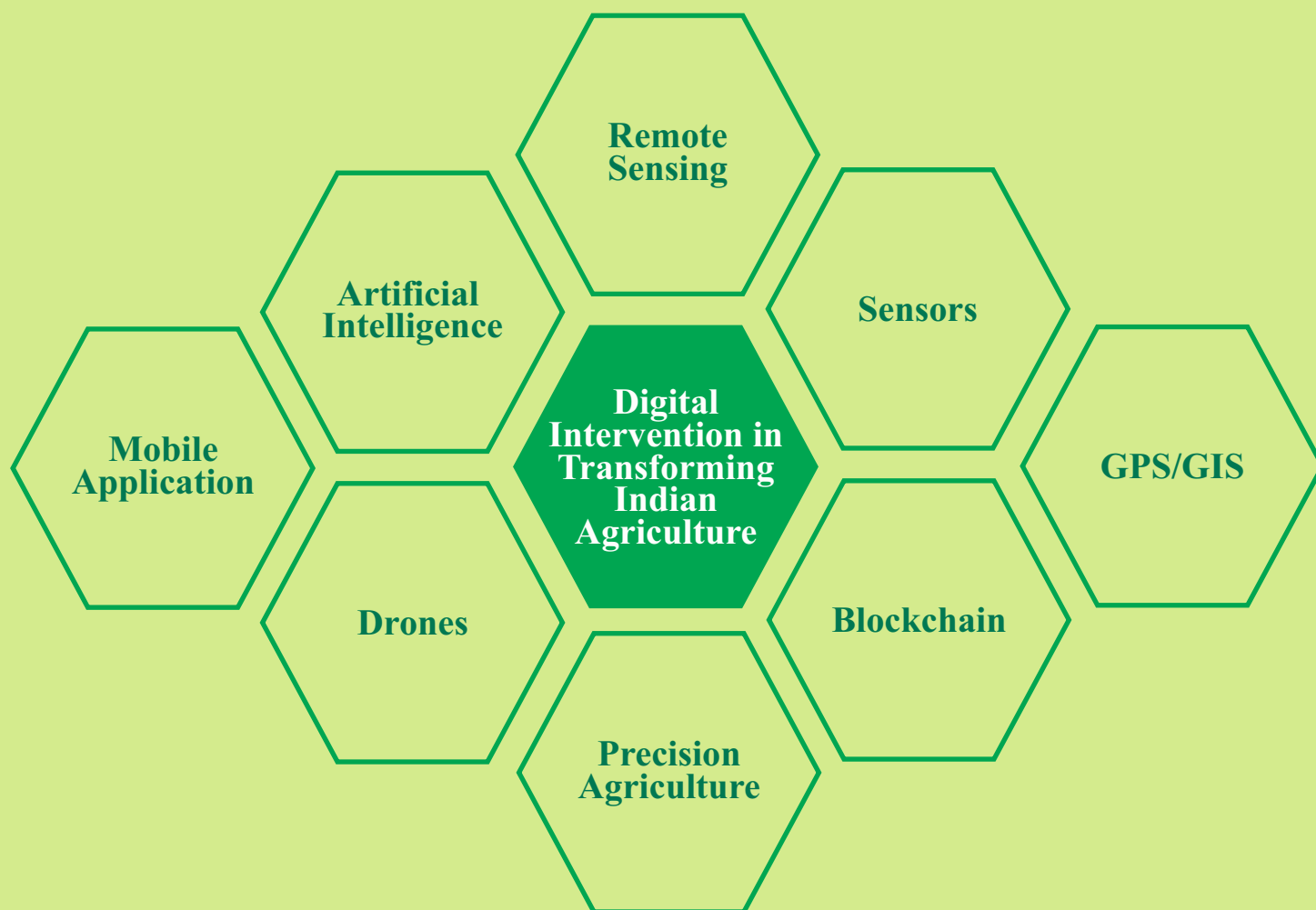




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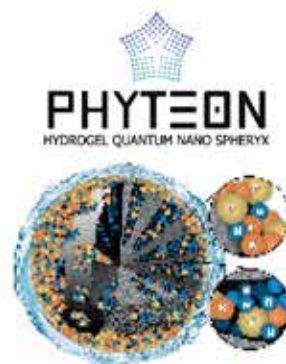
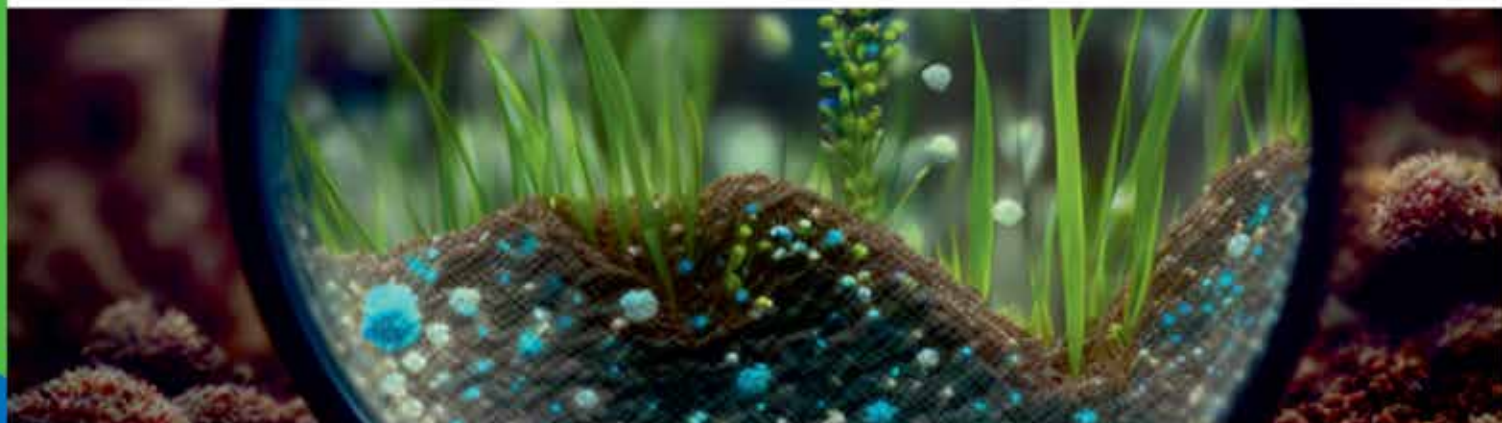


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Frank Notes

Transforming Indian Agriculture

India is the most populous country in the world with a geographical area of about 329.7 million ha. Population will continue to rise. The country has progressed well towards agricultural production, ensuring food and nutrition security to the teeming population. Production of food grain and horticulture crops in 2023-24 reached a level of 332.3 million MT and 353.2 million MT compared to 329.7 million MT and 355.5 million MT in 2022-23, respectively. Per cent growth in GVA of agriculture and allied sectors which was 4.7% in 2022-23 slipped to 1.4% in 2023-24. Therefore, contribution of the sector in GVA also declined from 18.2% to 17.7% during the period. Further, agriculture sector used to contribute about 50% in GVA in 1950s as other sectors of the Indian economy were not so spread. Evolution of fertilizer responsive high yielding varieties in late 1960s was the landmark in the history of Indian agriculture and the success of the same is the testimony of the facts as envisaged. However, challenges in the sector have been emerging and the country will have to keep pace of production in line with the need of the burgeoning population which may be around 167 crore by 2050.

There is no escape but to increase agriculture production by addressing the challenges being encountered in the sector. The challenges such as dwindling soil and water resources; deterioration of soil health; low fertilizer and water use efficiency; decline in crop response to fertilizer use and stagnation in farm productivity; adoption of same cropping system especially in Indo Gangetic plains; stagnant net cultivated area; adverse effect of climate change; etc. are cropping up. There is no doubt that Green Revolution has paid high dividends, but with the pros and cons. The second Green Revolution is the need of hour which can only be possible with systematic outcome-based approach to adopt the best sustainable farming practices to address the emerging challenges of agriculture.

Intervention in transforming Indian agriculture is of paramount importance through promotion of digital tools. The pace of spread of internet users in rural areas has been picking up and has even surpassed the urban areas. Even rural women are

making use of internet. There are good opportunities to tap such potential through encouragement of rural masses to utilize digital tools for farm operations in agriculture.

Application of remote sensing, sensors, GPS/GIS, cloud computing, artificial intelligence, machine learning, deep learning, block-chain, robotics, data analytics, smart phones, drones, etc. in agriculture may be a step towards transforming Indian agriculture to bring second Green revolution in the country. Use of digital technologies is critical for precision agriculture..

Companies in the private, cooperative and PSU sectors have been engaged in providing agri-based information on efficient use of fertilizers and water, crop surveillance, advance technologies, market prices, weather information, etc. with the help of digital tools. Quite a good number of agri-based mobile apps have been developed and farmers are getting information in real-time. Large numbers of agri-tech start-ups are based in India and various venture capital funds, and angel investors have long supported the sector. Satellite-based crop monitoring and drone technology are also being promoted.

Among the NPK use, contribution of N is about 67%. Both over-use or under-use of N in agriculture is detrimental to either crops or environment or both. Therefore, N management strategy needs to be given more emphasis. Efforts are continuing towards checking status of N in leaves through digital applications for precision N management. Availability of high quality satellite data has been considerably enhancing the fields of N estimate by remote sensing. Amalgamation of crop simulation modelling and remote sensing can be of great help in enhancing site-specific N management. Radiative transfer model, based on spectral reflectance data may be inverted to determine canopy chlorophyll content from spectral simulation model, can be utilized to estimate N requirement of a crop.

Digital tools such as DSSIFER, Nutrient-Expert, and KISAAN 2 in conjunction with Soil Health Card (SHC) Portal and Kisan Sarathi provide tailored,

India has the opportunity in transforming agriculture through mobilisation of digital tools towards climate resilience, sustenance of soil health, and ensuring food and nutrition security to the burgeoning population on sustainable basis.

site-specific fertilizer recommendation, leveraging ICT to enhance farming efficiency for sustainable agriculture. www.soilhealth.dac.gov.in have the facilities for registration of soil samples, recording test results of soil samples, and generation of SHC containing fertilizer recommendation. A soil test crop response mobile app provides fertilizer recommendations for a specific yield target for Maharashtra farmers in different crops.

Digital agriculture has the potential to transform rainfed farming by offering ways and means to overcome the challenges of climate change, soil degradation and water scarcity.

Realizing the vital scope, Government of India announced a Digital Agriculture Mission which aims to create digital ecosystems for farmers, improve efficiency of government programme, and support evidence-based policy making. The mission includes digital public infrastructure (DPI) to integrate with state and central digital infrastructure to provide services to farmers such as information on soil health, livestock and fisheries; AgriStack for a farmer-centric DPI to provide farmers with a digital identity (farmer ID); and Krishi Decision Support System for combining remote sensing data on weather, soils and crops to create soil profile maps. Further, Jio Agri (Jio Krishi) platform was introduced in early 2020 to digitalize the agriculture ecosystem. To provide farmers with real-time data and the necessary advice, NITI Aayog has teamed up with International Business Machines to create a crop production forecast model supported by AI. It aids in enhancing crop output, soil quality, agricultural input control and early disease outbreak warning. Government is also giving financial support to agri-tech firms.

Fertilizer industry is a major contributor to the growth and development of Indian agriculture. Major fertilizer players have adopted digitization for enhancing efficiency in production; evaluation and dissemination of advanced technologies and agronomic practices among the farmers. Industry in real-sense has been engaged in transforming of

agriculture and will continue to do. Towards transforming agriculture, fertilizer industry has been giving due attention on R&D and developing and promoting new products such as *neem* coated urea, sulphur coated urea, Nano urea, Nano DAP, Nano zinc and Nano copper, specialty fertilizer products etc. Industry is also promoting use of drones for application of fertilizers and agro-chemicals. Various advanced farm technologies are also taken to farmers' doorstep to improve their farm productivity and sustain soil health on sustainable basis.

As the awareness grows, India has the opportunity to take a lead in transforming agriculture through mobilization of digital tools, setting a global example in sustainable farming that balances productivity with ecological preservation, climate resilience, and ultimately fostering food and nutrition security for the future generations

Soil is an essence containing living organisms and non-living components. For a growth of at least 4% in agriculture on annual basis, productivity of soil has to be sustained. Use of digital tools with soil health card portal has been helping in recommending nutrient doses more precisely, enabling to sustain soil health. Further, adoption of integrated nutrient management comprising fertilizers, bio-fertilizers, organic manures, recycling of agricultural wastes by the farmers needs impetus.

To commemorate the **Global Soil Conference on Caring Soils beyond Food Security: Climate Change Mitigation & Ecosystem Services**, being organised by Indian Council of Agricultural Research, International Union of Soil Science and National Academy of Agricultural Sciences at NASC Complex, New Delhi during November 19-22, 2024, this special issue has been brought out on Digital Agriculture. The issue covers the leading articles on Digital sensing of crop N content on site-specific N management; Digital technologies for optimal plant nutrient management; Digital agriculture in rainfed farming; Embarked to a digital green revolution; Leveraging generative AI for site-specific fertilizer recommendations; ICL-leaf scanning technology; Fasal: Revolutionizing agriculture through AI and IoT, etc. It is hoped that this special issue will be helpful to those connected to agriculture including research scientists, policy makers, extension agencies and of course the farmers. ■

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Digital Sensing of Crop Nitrogen Content for Site-specific Nitrogen Management: A Review

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Abstract

Nitrogen serves as an essential nutrient for plant growth, significantly influencing crop performance and nitrogen use efficiency (NUE). Both deficit and excess supply of N in agricultural systems is detrimental to either crops or environment or both. Therefore, accurate assessment of canopy N content in crops is crucial for optimizing agricultural productivity, improving NUE, and reducing environmental impacts. Conventional approaches for N assessment based on soil /plant sampling and laboratory analysis, although precise, tend to be time-consuming, labour-intensive and often limited in spatiotemporal domain. Remote sensing platforms, such as satellites, drones, and ground-based sensors, provide real-time, non-invasive methods for capturing spatially distributed data on crop N status. This article analyses the principles, techniques, and factors that affect the digital estimation of canopy N through parametric, non-parametric, and physically-based methods. This review examines the integration of ground-based, UAV-based, and satellite-based platforms for data acquisition, emphasising the importance of spectral indices and radiative transfer models (RTMs) in modelling canopy N status. Additionally, advances in artificial intelligence and machine learning enable the development of predictive models that can process large datasets and improve the accuracy of N estimation. Potential of digital innovations, and current challenges in precision N management has also been highlighted.

Key words: Nitrogen management, remote sensing, machine learning, modelling

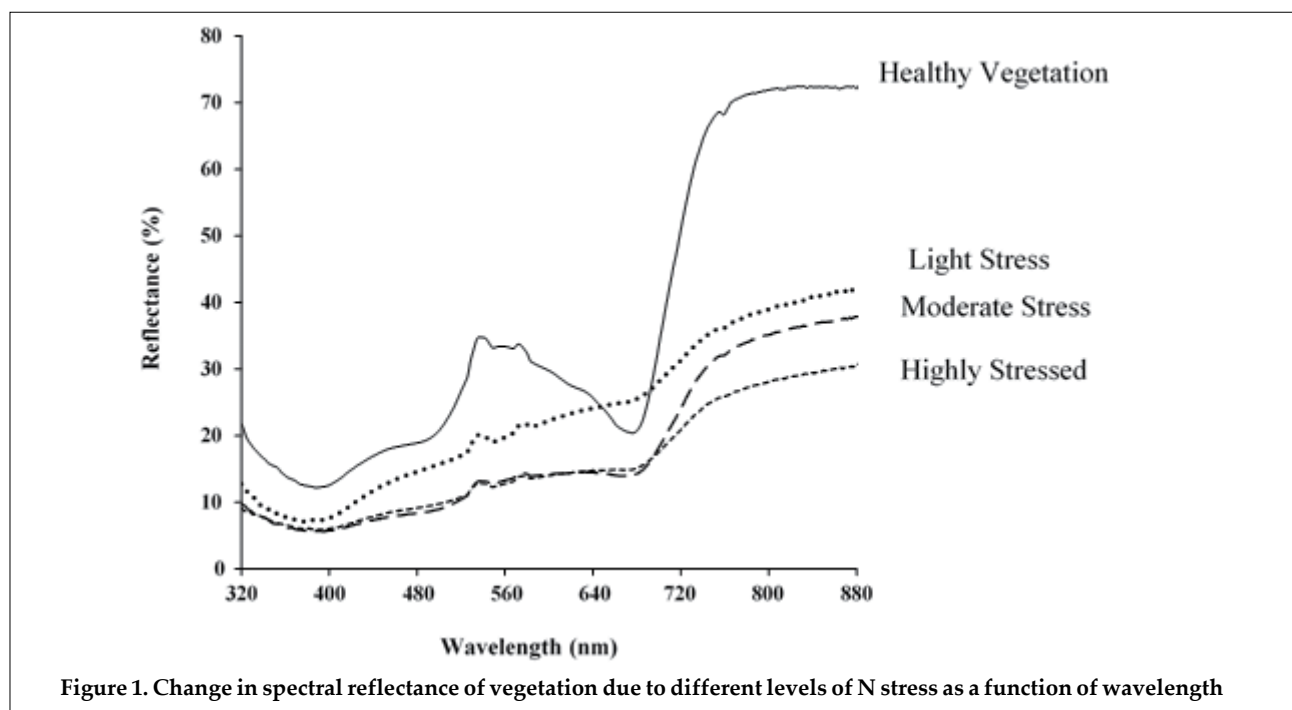
Introduction

Among the major nutrients, N is the most important mineral element constituting 1-5% of the dry matter of the plant and 75% of the chloroplast. Being a part of chlorophyll, it is directly involved in several metabolic activities (Evans, 1983; Seeman et al., 1987), physiological activities (Novoa and Loomis, 1981) and regulates several enzymatic reactions. It enhances the crop performance and vigour to a large extent (Bulisan and Warner, 1980; McDonald, 1992; Warraich et al., 2002). However, NUE is a critically important concept in the evaluation of crop production systems (Fixen et al., 2015). Smil (1999) estimated that harvested crops recovered 50% of all N input at the global scale. Calculated a higher value of 57% was also reported (Sheldrick et al., 2002). Similar values of 52% for Canada and 56% for the United States were also observed (Janzen et al., 2003; Howarth et al., 2002). For India, Ladha et al. (2005) estimated an in-season recovery of 48% from all sources of N. Cassman et al. (2002) reported a per cent recovery of 18% of N in wheat in India under unfavourable weather condition, whereas, value may be as high as 49% under favourable weather. However, Yu et al. (2022) found that global average RE_N was 39% in cereals, with 42% for both rice and wheat and 36% for maize through meta-analysis. This clearly indicates a declining trend of N input use efficiency for cereal production systems across the years over the globe.

One innovative way to deal with low NUE is the site-specific nutrient management (SSNM) method, which was developed in the 1990s for small-scale cereal

production systems in Asia (Dobermann et al., 2002, 2004; Buresh et al., 2010; Pampolino et al., 2012). It aims to address large variability among farms and fields in their seasonal plant nutrient needs (Dobermann et al., 2002). SSNM involves field specific N management strategies that includes quantitative knowledge of field specific variability in crop N requirement and expected soil N supplying power. The fundamental underlying assumption of this concept is to establish an optimum synchronization between supply and demand of N for plant growth (Giller et al., 2006) through four key principles called the 4 Rs viz. right time, right rate, right place and right product. Corrective N management methods rely on diagnostic tools to assess in-season soil or crop N status and N-management decisions (amount and timing) are made based on in-season data. The SSNM has been widely applied for rice, maize and wheat in both Asia and Africa (Dobermann et al., 2002; Sapkota et al., 2014; Saito et al., 2015; Shehu et al., 2019; Rurinda et al., 2020).

Accurate estimation of crop N status is the first and foremost important in agricultural research particularly for SSNM. Although conventional laboratory-based leaf N analysis is very precise, but it is more laborious, time consuming, costly and depends on accuracy of sampling. Again, N needs may vary spatially across fields and landscapes. On the other hand, remote sensing offers a resource efficient means to model plant N content in a spatially continuous manner and at regular time intervals. Thus, it is possible from remote sensing to continuously monitor the crop health at broader spatial scales. Remote sensing-



based canopy chlorophyll content estimation can be done efficiently using: (a) several spectral indices or (b) process based radiative transfer models *via* proximal, airborne or satellite platforms. The spectral indices related to chlorophyll or other biophysical parameters are regressed to observed/estimated values to predict the N status of plant. The parametric regression models, non-parametric linear regression models and recently the non-parametric non-linear machine learning models have been successfully applied to N estimation. Although these methods are quite reliable and accurate, they have no physical background, and the predictive capability of the model is dependent mostly on the quality of the training dataset. The physical based, radiative transfer models (RTM) have a sound understating about the process involved. Therefore, they are more robust in predicting the plant biophysical variables including the chlorophyll. RTMs like PROSAIL (PROSPECT +SAIL) can simulate the canopy optical properties based on a limited set of biochemical constituents and structural parameters in the wavelength range of 400 to 2500 nm (Jacquemoud and Baret, 1990). An inversion of these models based on look-up-table (LUT) or artificial neural networks (ANN) can predict the biophysical parameters accurately (Dhakar et al., 2021).

Keeping above discussion in mind, this review article comprises of several sections like principals, techniques for digital monitoring of canopy N in crops including data acquisition, data retrieval

(using parametric, non-parametric and physically based methods) and the factors affecting the retrieval of canopy N in crops to have a comprehensive overview of canopy N estimation using digital technologies.

Principals of Digital Monitoring of Canopy N

The spectral reflectance of vegetation has a unique feature, having a marked contrast between maximum absorption of visible spectra (0.4-0.7 μ m), (due to presence of chlorophyll molecules which absorbs 70-90% of incident radiation in this region) to maximum reflectance in NIR region (as much as 60% of incident radiation) due to presence of mesophyll cells. This contrasting reflectance pattern is captured through several vegetation indices (VIs), where reflectance values at multiple wavelengths/wavebands are added, subtracted, multiplied or divided to yield a single value representing crop health, and vigour (McKinnon and Hoff, 2017). However, the red-edge region in between is also greatly affected due to structural and compositional change in plant leaf under N stress. These changes bear characteristic information on plant N status *vis-à-vis* crop health (Zheng et al., 2022). The N rate is negatively correlated to spectral reflectance of visible region (460-710 nm), whereas, it is positively related to NIR reflectance (710-1220 nm) as reported by Zhu et al., 2006 (Figure 1). Under N-stress, the red edge, or the spectral region between the red absorption feature and high NIR reflectance, changes shape and position characteristically (Barnes et al., 2000).

Table 1. Commonly used canopy reflectance vegetation indices (broadband and narrowband) for monitoring crop N status (Source: Adapted from Padilla et al. 2018; Chen et al. 2019)

Index	Equation using reflectance bands
Normalized difference vegetation Index (NDVI)	$\frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}}$
Green normalized difference vegetation Index (GNDVI)	$\frac{\text{NIR} - \text{Green}}{\text{NIR} + \text{Green}}$
Ratio vegetation index (RVI)	$\frac{\text{NIR}}{\text{Red}}$
Chlorophyll index (CI)	$\frac{\text{NIR}}{\text{Green}}$
Chlorophyll vegetation index (CVI)	$\frac{\text{NIR}}{\text{Green}} \times \frac{\text{Red}}{\text{Green}}$
Soil adjusted vegetation index (SAVI)	$\frac{\text{NIR} - \text{Red} + \text{L}}{\text{NIR} + \text{Red} + \text{L}}$
Optimized soil adjusted vegetation index (OSAVI)	$\frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red} + 0.16}$
Red edge normalized difference vegetation index (RENDVI)	$\frac{\text{NIR} - \text{Red edge}}{\text{NIR} + \text{Red edge}}$
Canopy Chlorophyll content index (CCCI)	$\frac{\text{RENDVI} - \text{RENDVimin}}{\text{RENDVimax} + \text{RENDVimin}}$
Red edge index (REI)	$\frac{\text{NIR}}{\text{Red edge}}$
Ratio	$\frac{\text{RENDVI}}{\text{NDVI}}$
MERIS terrestrial chlorophyll index (MTCI)	$\frac{\text{NIR} - \text{Red edge}}{\text{Red edge} - \text{Red}}$

Broadband and narrowband vegetation indices can also help in N canopy content estimation and thus N recommendation. For an example, Chen et al. (2010) reported a new VI, double-peak canopy N index (DCNI) that can predict the plant N concentration (%) with a R^2 of 0.72 for maize and 0.44 for wheat. A list of most commonly used VIs for N management are presented in **Table 1**.

Techniques for Digital Monitoring of Canopy N in Crops

Data Acquisition

The quality data acquired by ground based, airborne, and satellite remote sensing provide a wide range of options for monitoring the canopy N in plants (**Figure 2**). The variability in resolution of data provided from these sensors determines the area, coverage, and accuracy of N estimation from plants. Moreover, the data retrieval techniques and inversion modelling play a crucial role in achieving accurate N status.

Ground-Based Platform: Spectroradiometers are hyperspectral remote sensing instrument for proximal sensing that collects spectral reflectance from a target (vegetation, soil, etc.) in the wavelength range of 350 to 2500 nm at every 1nm intervals. Unlike multispectral sensors or even green

seeker, crop circle or Yara-N sensors, it collects information over a wide range of wavelength thus provide a huge information about target. Spectral reflectance of vegetation in visible (380-700 nm) is largely controlled by absorption due to plant pigment (chlorophyll, carotenoids and anthocyanins), whereas, the reflectance in NIR (700-1300 nm) is largely due to leaf/canopy structure and spectral reflectance at SWIR region (1300-2500 nm) is controlled by presence of water, lignin, cellulose and proteins (Berger et al., 2020). N content in leaf largely affect the chlorophyll content and mesophyll composition and thereby the absorption and scattering in visible and NIR region (Zheng et al., 2022). Use of proximal sensing, particularly for N-management has been investigated in several crop around the world as well as in India (Tripathi et al., 2017; Croft et al., 2020; Sullivan et al., 2004). It offers a reliable, real-time and non-destructive method for identifying, quantifying, and mapping plant stresses, thereby has a great potential for site-specific management of resources over time-consuming and expensive laboratory analysis (Khanal et al., 2020).

UAV-Based Platform: Such systems have advanced remote sensing and precision agriculture to the next level. Application of drones in crop monitoring represents significant opportunities to collect field



Figure 2. Techniques for canopy N content estimation: (A) Traditional laboratory-based N estimation (Kjeldahl apparatus), (B) Field experimentation for N management, (C) Chlorophyll (SPAD) meter, (D) Ground based/proximal (Spectroradiometer) remote sensing, (E)

data more easily, quickly, and cost-effectively than traditional methods. UAV-based advanced technology is seen as the future of remote sensing in precision agriculture (Tsouros et al., 2019). With advancement of lighter, more compact sensors and growing carrying capacity of UAVs, drones equipped with sensors have become a popular platform for monitoring crop N. These UAVs enable the rapid collection of high-resolution ground data, offering exceptional high spatial, spectral images adapted for a specific purpose and an appropriate revisit time, making them ideal for research at small to medium scales. UAVs are currently equipped with a range of sensors, including digital RGB cameras, multispectral and hyperspectral cameras, infrared thermal imagers, chlorophyll fluorescence sensors, and LIDAR sensors (Zhang et al., 2021).

Lebourgeois et al. (2012) used two sensors (RGB and NIR-G-B cameras) mounted on a UAV to assess N status in sugarcane by calculating simple ratio pigment index (SRPIb) which showed high correlation with leaf N content (R^2 of 0.7). Similarly, Schirrmann et al. (2016) discovered that the red-to-green ratio from UAV RGB imagery had a good correlation (R^2 of 0.68) with plant N content in winter wheat, but only at the heading stage. Fu et al. (2020) investigated the potential of RGB-based VIs, colour parameters, and textures derived from UAV-based RGB images for estimating N status in winter wheat. Their findings revealed that the partial least squares regression (PLSR) model, achieved the highest estimation accuracy for plant N content. These findings highlight the effectiveness of UAV equipped with multispectral cameras in plant N studies. However, hyperspectral imaging spectrometers combine the strengths of both

spectroscopic and imaging technologies, making them ideal for large-area applications. UAV-acquired hyperspectral imagery, with its narrow bandwidth and wide continuous spectral range, can capture subtle changes in crop spectral reflectance, making it ideal for precise monitoring of nitrogen levels. The increasing payload capacity of UAVs has shifted research toward lightweight, cost-effective sensors. Hyperspectral imaging systems like the UHD185-Firefly, Cubert S185, and Micro-Hyperspec (Headwall Photonics Inc., USA) are already being employed for N monitoring in agriculture (Zhu et al., 2018; Wang et al., 2021). Li et al. (2019) demonstrated that using UAV-based hyperspectral images linked to a radiative transfer model, specifically through multiple lookup tables tailored to different growth stages, can effectively estimate canopy N density (CND) in winter wheat. The results indicated good estimation performance, with R^2 values of 0.83 and 0.69 for field and UAV hyperspectral data, respectively, confirming the potential of this approach for high-throughput monitoring of plant N status. UAV remote sensing, unaffected by atmospheric conditions, offers reliable access to high-quality spectral data, making it a valuable tool for crop N studies.

Satellite-Based Platform: Satellite remote sensing can readily offer the spatial detail of the canopy N status over a large area with other advantages like timeliness, receptivity, reliability and at a free of cost or economical prices. As N-demand in crop often vary substantially across fields and landscapes, satellites may be one of the best tools for assessing the spatial variability of N. Ability of satellite-based remote sensing to cover broad areas fast and in a recurring manner makes it a perfect

Table 2. Use of satellites and satellite-based indices for N management in crops

Satellites	Resolution	Crop	Indices used	References
SPOT	20 m	Maize	NDVI, Green NDVI	Han et al., 1998
		Wheat	Variance inflation factors of the selected bands	Castaldi et al., 2016
QuickBird	2.88 m	Maize	NGNDVI	Bausch and Khosla, 2010
		Wheat	NDVI, GNDVI, SAVI	Genc et al., 2009
		Wheat	RVI, NDVI, DVI, GNDVI	Shou et al., 2007
IKONOS	4 m	Wheat	NDVI, GNDVI, RVI and OSAVI	Jia et al., 2012
		Rice	RVI and NDVI	Zhang et al., 2006
		Maize	GNDVI, NDVI and NRI	Sullivan et al., 2004
RapidEye	5 m	Wheat	CCCI, EVI, GNDVI, etc.	Fabbri et al., 2020
		Rice	RETCARI/REOSAVI, MTCI, NDPI, etc.	Huang et al., 2017
WorldView-2	2 m	Rice	NDPI, MTCI, CCCI etc.	Huang et al., 2017
FORMOSAT-2	8 m	Rice	NDVI, EVI, RVI, CI, PSRI, etc.	Huang et al., 2013
			RVI, DVI, SR, VARI, etc.	Huang et al., 2015
			CI, TCARI, MCARI, etc.	Huang et al., 2017
Sentinel-2	10 m	Wheat	NDVI	Santaga et al., 2021
	10 m	Wheat	NDRE, NDRE2, REP, MCARI, MTCI, EVI2, NDVI	Bossung et al., 2022
	10 m or 20 m	Maize	SR, NDVI, NDRE, TCARI, MCARI 1, MCARI 2, etc.	Sharifi, 2020
	10 m	Wheat	MCARI 1, MCARI 2, REIP, mSR, mSR2, SR, etc.	Zhao et al., 2019
Envisat	1km	Grasslands and forests	MTCI	Loozen et al., 2018

feedback tool for reviewing N management decisions early in the season and even before visual symptoms appear. Based on the relationship between NDVI, LAI and plant chlorophyll, Blondlot et al. (2005) proposed a methodology called *Farmstar products* to manage N fertilizer application in wheat using SPOT satellite. Shou et al. (2007) used QuickBird satellites to derive RVI, DVI, NDVI, and GNDVI at booting stage to simulate N content in winter wheat. They found that among several VIs, NDVI and RVI had higher R^2 -values or even better than single band reflectance values for prediction of chlorophyll and N content. RapidEye images were also successfully used by Magney et al. (2017) to calculate NDRE at peak LAI stage to map final wheat N uptake with a R^2 of 0.81 and RMSE of 15.94 kg ha⁻¹. However, they concluded that, use of RapidEye satellite images are more faithful to evaluate the canopy N (kg ha⁻¹) than plant N concentration, canopy N is a function of both N concentration and LAI (Baret et al. 2007). Sun et al. (2018) observed that Hyperspectral LiDAR can also be used to predict canopy N content of rice, with a R^2 of 0.74 and a RMSE of 2.80 mg g⁻¹, and the results were also in line with ASD Spectroradiometer (R^2 of 0.73).

Several precision farming decisions support systems (CropSat, Agrosat, Agrisat, etc.) use the correlation between remotely sensed NDVI and N uptake to recommend N to farmers and end users. More practically, satellite images can be utilized for mapping a stable management zone when yield data are not sufficient. Elbl et al. (2018) used Sentinel-2 and SPOT images to

generate variable rate application (VRA) of N, and found that VRA can improve NUE by 6% than conventional practices. Using an automatic segmentation of RapidEye derived images, Georgi et al. (2018) suggested an algorithm to delineate stable management zones for precision N management. VRA of N can increase the energy use efficiency and net return of N application. According to Kayad et al. (2021), VRA of N enhanced the maize yield by 31% and there was decrease in N-application by 23%. A list of studies on satellite remote sensing in the N-management of several crops is presented in Table 2.

Data Retrieval

Several plant N retrieval methods are developed over the years from the remotely sensed spectral data. Berger et al. (2020) have divided these techniques into six main groups. These are parametric regression methods that connect plant N content with vegetation indices, band reflectance, band derivatives, or other related products; chemometrics or linear nonparametric regression methods; machine learning methods or non-linear nonparametric methods; physically-based models or radiative transfer models (RTM); sun-induced fluorescence-based methods (SIF); and hybrid or combined techniques.

Parametric Regressions Methods: Parametric regression models are most commonly used in biophysical and biochemical parameters retrieval methods from spectral signatures (Berger et al., 2020). Models work when the

relationship between independent and dependent variables is known beforehand. Several narrowband VIs are regressed with plant N using spectral reflectance from visible, red, NIR and red edge (Herrmann et al., 2010; Chen et al., 2010; Clevers and Kooistra, 2012; He et al., 2016; Jay et al., 2017). However, inclusion of NIR and SWIR reflectances into vegetation indices can improve the canopy N retrieval due to strong correlation of these bands with plant protein content (Herrmann et al., 2010). The correlation between spectral bands or their derivatives with N content can be used to derive the N content of plant. Several studies demonstrated that, at the leaf and canopy level N content can be estimated with VIs at reliable accuracy using hyperspectral remote sensing data (Hansen and Schjoerring, 2003; Zhu et al., 2008; Inoue et al., 2012). Parametric regression of VIs with plant N content, although, has a reliable accuracy and advantages, have many drawbacks such as the inversion process is ill-posed, use limited information by combining few bands information, model overfitting problem, etc.

Chemometrics or Linear Nonparametric Regression Models: Unlike the linear parametric models, chemometrics (linear nonparametric regression model) does not reduce the spectral information by computing VIs, but transform it into several new features. Several techniques are used like linear regression, multiple linear regression (MLR), step-wise multiple linear regression (SMLR), partial least square regression (PLSR), etc. Linear regression (LR) examines whether there is a substantial link between crop N indicators and certain VIs, univariate linear regression and its nonlinear transformation have shown positive results, and they play a key role in plant N status retrieval. Yi et al. (2010) observed a good agreement between LR based models and the observed N content in rice, with an R^2 of 0.775, RMSE of 0.494 and relative prediction error of 18.70%. Chen et al. (2019) combined VIs and computed a N sufficiency index (NSI) and predicted N nutrition index (NNI) non-destructively with a R^2 ranging from 0.53 to 0.56. Using the thresholds of NSI, they also reported an accuracy of 57-59% for predicting N status of crops. MLR is preferably used for N estimation from spectral data under situation when phenological information is missing or data are collected through multiple crop growth stages. Dunn et al. (2016) found that 738 nm, 1362 nm, 1835 nm and 1859 nm spectral bands in SWIR region are highly important for assessing N uptake by plant using MLR. In SMLR, a predetermined collection of wavebands is used as predictive variables. Miphokasap et al. (2012) reported a higher correlation with N using SMLR models in full spectral domain (*i.e.* from 400-2500

nm) compared to models based on the narrowband VIs. Sensor noise has limited chance to be cancelled out because SMLR techniques do not condense spectral data to retrieve majority of the important information (Jacquemoud et al., 1995). Karande et al. (2014) evaluated the NDVI, modified simple ratio (mSR) and NDRE index values to detect N stress in wheat crop using MLR and SMLR. NDRE was found highly significant ($P < 0.01$) for N stress in SMLR and used to predict N requirement of the crop at early stages (35-45 DAS). Moreover, SMLR approaches may produce high predicted accuracies, although occasionally at the expense of overfitting and heavy computational burdens, especially when an excessive number of variables are used (Yu et al., 2013; Zhou et al., 2018).

In the set of chemometric techniques for analysing N from hyperspectral data, PLSR has shown to be the most widely used method, while all other methods directly use the narrowband VIs (Berger et al., 2020). Tavakoli and Gebbers (2019) found that PLSR can be used to estimate N content with high R^2 (0.77–0.91) and low RMSE (0.25–0.14) for single-date data in wheat using a digital camera. According to Hansen et al. (2003), using PLSR to fit N status produced results that were superior to those of exponential regression, with the R^2 raised by 23%. PLSR is frequently used in N research because it combines the benefits of aspects of principal component analysis (PCA) and SMLR by considering the covariance of the relevant biochemical variables. PLSR can be more appropriate than PCA for making predictions because, in contrast to PLSR, the latent variables produced by PCA only consider the variance in the feature space and not the covariance between the independent and target variables. Unfortunately, due to potential interference from specific wavebands, PLSR approach may not always yield the best results (Inoue et al., 2012). To get around these restrictions, some improved PLSR techniques, such as interval PLSR, have been created.

PCA has been used to delineate N fertility management zones in several cereals. However, PCA is most frequently used in hyperspectral remote sensing, as a spectral dimensionality reduction tool. In principal component regression (PCR), principal components can be used to calculate regression coefficients for biophysical or biochemical vegetation traits. Yang et al. (2016) estimated the leaf N content of rice using PCA and obtained a R^2 of 0.952 at tillering and 0.931 at shooting stages with laser-induced fluorescence technology. Chen et al. (2013) used PCA to develop NNI of corn and found that the PCA-NNI can explain 79% variability of conventional NNI with RMSE of 0.10 during validation. Yi et al. (2010) also observed a good agreement between PCA based PC-ANN models

and observed N, with an RMSE of 0.347 and relative error of prediction of 13.14%.

Major advantage of using the PLSR, PCA and SMLR is that they can successfully address collinearity issue between parameters. Co-linear spectral variables are reduced to a few uncorrelated latent variables to ensure no overfitting (Yang et al., 2016; Zhang et al., 2021). Chemometric methods can provide more accurate N estimation and they are very much reliable for N prediction using hyperspectral data compared to the narrowband VI or other linear parametric models due to the exploitation of the full spectral information. However, local calibration and verification limits the applicability of the chemometric models to wide scale (Verrelst et al., 2019). The PCR and PLSR can overcome the multi-collinearity as against SMLR or MLR, which are inherently associated with these problems.

Machine Learning Methods: Machine learning (ML) methods have emerged as powerful tools for predicting canopy N content. These models can capture complex, nonlinear relationships between spectral data and N levels, often leading to more accurate predictions (Verrelst et al., 2019). Artificial neural network (ANN) and back propagation neural network (BPNN) are one of the most commonly used models for crop N status monitoring using remote sensing data (Zhang et al., 2021).

Another group of ML model includes support vector machine (SVM), which is a kernel-based regularized regression algorithm. Yao et al. (2015) found SVM to be the most stable among ML models namely conventional regression analysis, SVM and ANN in terms of computational and prediction accuracy and complexity level for prediction of wheat leaf N content. In SVM, main focus is the kernel function. Wang et al. (2017) reported that multiple-kernel support vector regression (MK-SVR) is superior in prediction of N status at multiple crop growth as it can combine local as well as global kernel function. Based on SVR-based radial basis function (RBF) kernels, Miphokasap and Wannasiri (2018) estimated leaf N% in sugarcane and found greater correlation coefficients than SMLR models. Thus, SVM is highly effective for solving multi-dimensional data problems analytically (Zhang et al., 2021).

Gaussian processes regression (GPR) is another promising ML model. It is a part of kernel-based techniques that rely on a strong Bayesian formalisation and thus enable a formal treatment of error propagation and uncertainty quantification (Camps-Valls et al., 2019). Zhou et al. (2018) examined GPR models with a focus on the effect of spatial resolution on separating leaf N signals and background signals in rice canopies. They showed that GPR produced the best prediction of leaf N concentration by contrasting the findings with PLSR and VIs.

Widely used approach of ANNs makes use of error back propagation through the network of perceptron. A disadvantage of ANNs is that they are prone to overfitting, meaning that they strongly depend on input quality and may struggle with unknown values outside the range in which they were trained (Kimes et al., 2000). Problems of underfitting and in particular overfitting are, however, generally applicable to all ML models. ANNs were applied by Yi et al. (2010), who used the advantages of a PCA with an ANN approach and successfully determined N concentration of rice from spectral reflectance.

The random forest regression (RF) is another data mining method which combines several sets of decision trees. RF have several advantages, like it can integrate several decision trees, rank the relative importance of variables, minimize data redundancy, highly stable and having a vast application prospect (Zha et al., 2020, Chlingaryan et al., 2018). Liang et al. (2018) also reported that RFR algorithms largely improved the prediction of N content compared to two VI-models. Singh et al. (2021) used various ML regression models for prediction of wheat N status from hyperspectral data and found that de-resolve plus first derivative spectral pre-processing technique along with RF and GPR ($R^2 > 0.85$) was superior in predicting N status of wheat than any other combinations. Soltanikazemi et al. (2022) also found that RF was the best-performing model compared to SVR when estimating leaf N from Sentinel-2 satellite imagery. Their results further support the effectiveness of RF in handling complex datasets for N estimation in agricultural fields. The RFs are fastest in training and prediction and they are also less prone to overfitting and can be regarded as robust to outliers and noise.

Recent studies also have demonstrated that nonlinear nonparametric models, particularly convolutional neural networks (CNNs), significantly outperformed traditional linear regression models in estimating canopy N content. This advantage is especially evident when dealing with large and complex datasets, such as those obtained from UAV-based multispectral imagery. CNNs excel in capturing intricate relationships and patterns within high-dimensional data, allowing for more accurate predictions of canopy N levels (Pullanagari et al., 2021; Gallo et al., 2023).

Although, ML models may be more complex to implement than PLSR approaches, they can deliver explicit estimates of uncertainties and can provide higher mapping qualities as found by several studies (Verrelst et al., 2019). Comparison studies from several literatures proved that for N prediction, ML frequently produced a higher accuracy than linear nonparametric techniques (Miphokasap and Wannasiri, 2018; Yao et al., 2015; Zhou et al., 2018).

Use of Physically Based Methods for N Estimation: In order to determine the N content of crops from

observed spectral data, radiative transfer models (RTM) use optimisation algorithms for inversion. Primary categories of the object of study are leaf radiative transfer models and canopy models, depending on scale. The PROSPECT is the most widely used model at leaf scale (Jacquemoud and Baret, 1990) and at the canopy scale, SAIL model is used mostly for areas with continuously dispersed uniform vegetation. RTM use the structural and physicochemical properties of plants and leaves as input parameters and simulate the corresponding spectra in forward mode. As RTMs are physically based, they are more robust and readily transferable. The PROSAIL is the combination of PROSPECT and SAIL model. It is a physically based model and most commonly used to retrieve plant biophysical properties including leaf and canopy chlorophyll content, water content and LAI through model inversion (Croft et al., 2020; Danner et al., 2017; Sun et al., 2018) because of its simplicity, robustness, and availability. PROSPECT model accounts for absorption and scattering processes based on sensitivities to leaf/canopy structure and biochemistry (Jacquemoud and Baret 1990; Ollinger, 2011). Input parameters that influence the simulation of canopy spectral reflectance $R(\lambda)$ from visible (350 nm) to short wave infrared (2500 nm) using the PROSAIL model are presented in **Table 3**. In the forward mode, model simulates the spectra from biochemical parameters provided in it, whereas in backward mode, model can predict LAI, chlorophyll and equivalent water thickness in canopy.

Several PROSAIL model inversion techniques have been reported in literature, like, numerical optimization (Meroni et al., 2004), genetic algorithm (GA) (Mridha et al., 2015), artificial neural networks (ANN) (Kravchenko, 2009), look-up table (LUT) (Sehgal et al., 2016), principal component inversion (PCI) technique (Satapathy and Dadhwal, 2005) and support vector regression (SVR) (Tuia et al., 2011). With these different inversion strategies, PROSAIL has been proven as an efficient tool to retrieve biophysical and biochemical parameters of crops, grassland, forests, and other vegetation types (Darvishzadeh et al., 2012). Retrieval of parameters from multispectral and hyperspectral remote-sensing data is the main application (85% of all PROSAIL-based studies) of this model. Retrieval of canopy structure parameters like LAI and leaf angle,

biochemical parameters like chlorophyll and leaf water content, as well as growth parameters such as leaf dry matter have received greater interest by researchers.

The PROSAIL describes the crop growth process physically, which is more stable in the inversion mode but it is time-consuming. Combined with the look up table (LUT) approach, PROSAIL model is computationally more effective than the conventional optimisation methodology. The LUT-based inversion method computes a cost function, e.g., root mean squared error (RMSE) and try to minimize it (Danner et al., 2017). Several studies have used LUT-based methods across the solar domain (Danner et al., 2017; Weiss et al., 2000). Despite long-standing stability and dependability of RTM in the inversion of physicochemical parameters, different configurations of the model by users may result in equally reasonable findings, necessitating the application of *a-priori* knowledge to constrain the model. However, ill-posed nature of model inversion is a common limitation in all physical models because similar spectra correspond to different combination of canopy parameter. Numerous studies have demonstrated that multispectral remote sensing images, such as MODIS, Sentinel-2 and Landsat series images, could be applied to accurately estimate leaf chlorophyll content (LCC) (Zarco-Tejada et al., 2019).

Interactions between biochemical and structural canopy parameters (e.g., LAI and LCC) may add some uncertainties in the retrieval, the measured signal not only depends on the leaf biochemistry but also on the number of leaves within the sensor field of view (Baret et al., 2007). Alternatively, canopy integrated biochemical parameters, obtained by multiplying the leaf biochemical content by the LAI, can generally be estimated more accurately (Clevers and Kooistra, 2013; Jacquemoud et al., 1995), while still representing physically-sound quantities (Baret et al., 2007). Leaf level chlorophyll content (C_{ab}) of sugar beet is poorly retrieved from LUT based PROSAIL inversion with a R^2 of 0.26 and RMSE of 8.93 ig cm^{-2} (Jay et al., 2017). However, retrieval accuracy was improved significantly in canopy chlorophyll content (CCC) with a R^2 of 0.76 and RMSE of 0.24 g m^{-2} . Lunagaria and Patel (2019) used LUT-based iterative optimization inversion method for estimation of

Table 3. Input parameters of PROSAIL model for simulating reflectance spectra

Category	Parameters in PROSAIL model
Biophysical parameters	Chlorophyll a+b concentration (C_{ab}), equivalent water thickness (C_w), dry matter (C_m), leaf structure parameter (N), leaf inclination angle (θ_l) and LAI
Soil parameter	Soil spectral reflectance, $\tilde{n}_s(\lambda)$
Other parameters	zenith (θ_v) and azimuth (ϕ_v) viewing angles, zenith illumination angle (θ_s) and fraction of diffused incident solar radiation (SKY).

wheat canopy chlorophyll concentration. They found a very high correlation (0.87) between observed and simulated value at 1% level of significance. However, RMSE of chlorophyll retrieval was $15.62 \text{ } \mu\text{g cm}^{-2}$ due to overestimation of the higher chlorophyll values. Very recently, Sun et al. (2022) also concluded that retrieval accuracies of the leaf chlorophyll (Cab) were increased by use of the priors of LAI (RMSE of Cab from 7.67 to $6.32 \text{ } \mu\text{g cm}^{-2}$). Rivera et al. (2013) also concluded that, CCC *i.e.* LAI $\times$ LCC were more accurately estimated from Sentinel-2 imagery, than LCC probably due to the fact that LAI influences the whole spectral range, while LCC sensitive spectral range is limited to the beginning of the red edge.

Factors Affecting the Retrieval of Canopy N in Crops

Retrieving canopy N in crops using remote sensing technologies is influenced by several key factors impacting the accuracy and efficiency of N detection.

Data Acquisition Angles

VI's used in N status studies are usually based on vertically captured data (Zheng et al., 2022). However, variations in viewing angles due to experimental conditions and the anisotropic nature of vegetation reflectance can reduce the accuracy and reliability of N content estimates using these indices. Numerous studies have demonstrated that multi-angle measurements are more effective than vertical measurements for estimating the structural characteristics of ground objects, particularly vegetation. He et al. (2016) observed that reflectance in the visible, red edge, and NIR bands decreases progressively from zenith angles of -60° to 0° , with relative changes in reflectance may vary up to 265% in the visible band and from 89% in the NIR band. Thus, developing zenith angle insensitive VI's can improve the prediction accuracy, and model stability. Higher viewing angles can extract crop biochemical information more effectively than nadir orientations, with significant impacts on canopy reflectance, particularly in the red and NIR bands, making indices based on these bands more sensitive to angle variations. VI's such as the normalized difference red edge (NDRE), and the green band chlorophyll index (CIgreen) include zenith angle insensitive bands and offers a robust N estimation particularly to zenith angle variations (Lu et al., 2019).

Canopy Structure

Estimation accuracy for leaf chlorophyll and N is often disturbed by plant canopy structure (Liu et al., 2023). Structure of the plant canopy, including LAI, plant height, and canopy density, can significantly influence N retrieval (Pan et al., 2023; Liu et al., 2023). Variations in these structural properties alter how light interacts with the canopy, affecting reflectance signals captured by sensors. Although, empirical models are easy to implement, they are not robust to capture the canopy structural effect (Wang et al., 2017). Firstly, under N stress the LAI and N content decreases in plant synergistically; secondly, changes of these canopy parameters alter the reflectance spectra of plant canopy drastically. According to Li et al. (2013), spatial heterogeneity of the canopy can mask N signals due to differences in LAI and canopy coverage.

Leaf Nitrogen Distribution

Distribution of N within the canopy plays a crucial role in its detection. N content often varies between upper and lower leaves. In crops with a high degree of leaf stratification, it becomes difficult to assess N content uniformly, leading to retrieval errors. Most studies that treat the canopy leaves as a single entity tend to focus on the upper leaves, often overlooking the vertical variability within the canopy. At the jointing, flowering, and filling stages, leaf N decreases from top to bottom, while during the booting stage, it first increases and then decreases. Additionally, capturing crop reflectance spectra vertically makes it difficult to effectively detect information from the lower canopy layers due to the influence of leaf cover at various growth stages. However, improved results in estimating canopy N content have been achieved by acquiring reflectance spectra vertically or from multiple angles to account for canopy stratification (Zheng et al., 2022).

Crop Type and Growth Stage

Different crops and their growth stages exhibit distinct N requirements and reflectance characteristics. As crops mature, their biochemical and structural properties change, influencing the N detection accuracy. So, temporal changes in crop growth stages must be accounted for, as the spectral response to N varies over time. However, integrating multi-temporal vegetation indices with key phenological indicators, developed dynamic model holds clear biological

relevance. This approach not only aids in monitoring crop N levels but also greatly improves the capability for early prediction of N status (Zheng et al., 2022). Several other factors like spectral properties and sensor type (e.g., hyperspectral, multispectral), soil background (Zhu et al., 2008), illumination conditions (Clevers and Kooistra, 2013), can also distort the reflectance signals, complicating nitrogen retrieval processes.

Conclusion

Digital imaging, particularly remote sensing, has emerged as an effective tool in precision agriculture. The accuracy and dependability of remote sensing for quantifying canopy N are contingent upon data quality, which is influenced by the spectral, spatial, and radiometric resolutions of the sensors. Additionally, an increased temporal frequency of observations is advantageous for effective N management. Availability of high-quality satellite data at no cost is significantly enhancing the field of N estimate by satellite remote sensing. Amalgamation of crop simulation modelling and remote sensing can significantly enhance site-specific N management in agriculture. Radiative transfer model based on remote sensing may be inverted to determine canopy chlorophyll content from spectral reflectance data, a crucial indicator of N status, which, when combined with a crop simulation model, can be utilised to estimate the N requirements of the crop. Incorporation of digital technologies in precision N management can enhance NUE, promote sustainability by minimising environmental footprint, and reduce fertilizer costs.

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Abstract

Combining detailed soil quality databases with advanced technologies like sensors, data analytics, and AI can improve nutrient management through accurate, site-specific recommendations, thereby optimizing nutrient use and supporting sustainable, climate-resilient agriculture necessary for global food security targets. Automation in soil sampling, including the use of unmanned ground vehicles, hydraulic devices, and drones, significantly enhances efficiency, accuracy, and safety in soil analysis and plant nutrient management. Accurate agricultural information and innovative technologies like ICT and geo-spatial tools are vital for efficient resource management and sustainable farming in response to declining crop productivity and increasing population demands. Customized fertilizers, developed through GPS/GIS-based soil fertility mapping and nutrient indexing, enhance site-specific nutrient management (SSNM), improving nutrient use efficiency and crop yield. Selecting the optimal interpolation technique, such as ordinary kriging, inverse distance weighting, or spline, is crucial for accurately assessing soil physico-chemical properties in unsampled areas, as demonstrated in a case study from eastern Madhya Pradesh. Various digital tools like DSSIFER, Nutrient Expert, and KISAAN 2.0, along with platforms like the Soil Health Card portal and Kisan Sarathi provide tailored, site-specific fertilizer recommendations and agricultural guidance, leveraging ICT to enhance farming efficiency and sustainability in India. The COVID-19 pandemic has highlighted the importance of non-contact soil testing methods, and advances in spectroscopy and IT-based technologies offer rapid, precise, and environmentally friendly solutions for soil analysis, essential for efficient nutrient management and sustainable agriculture. The development of a site-specific soil resource database using advanced sensors and sensing technologies is essential for precision agriculture, enabling efficient resource use, rapid soil nutrient analysis, and data-driven decision-making to optimize crop and soil management. The Agricultural Internet of Things (AIoT) leverages AI, machine learning, and IoT devices to transform agricultural operations by optimizing input application, enhancing farm profitability, and promoting soil sustainability through precision farming technologies. Adopting digital agriculture technologies, such as AI, machine learning, and ICTs, is crucial for enhancing farm profitability, reducing agrarian distress, and promoting sustainable soil and nutrient management. To meet national goals by 2047, a unified approach to soil health management leveraging geo-spatial technologies and smart nutrient management is essential for optimizing inputs, maximizing profits, and promoting sustainable agriculture.

Key words: Automation, decision support system, GPS/GIS, ICT integration, precision agriculture

Introduction

In India, despite extensive research on soil properties, much of it has focused on physical, chemical, and biological aspects in isolation, overlooking their interconnected roles in soil functions and crop productivity. To bridge this gap, it is essential to create comprehensive databases of key soil quality indicators tailored to various soil types, cropping systems, and management practices across different agro-ecoregions. When combined with smart technologies like advanced sensors, data analytics, and artificial intelligence, these databases can transform plant nutrient management by providing precise and location-specific recommendations. These technologies collect real-time data on critical factors such as soil nutrient levels, moisture content, and plant health, which are then analyzed to optimize nutrient uptake, minimize waste, and reduce environmental impact.

Moreover, GIS and GPS technologies allow for the precise management of small units within fields, further enhancing nutrient management efficiency. This integration of smart technologies and soil research is vital for developing sustainable, climate-resilient crop production systems, crucial for achieving global goals like the United Nations' 'zero hunger' by 2030 and addressing food and nutritional security in a rapidly growing population.

Nutrient Management Approaches

Nutrient management in India is characterized by nitrogen overuse, potassium neglect, and phosphorus over application, revealing flaws in farmers' fertilizer practices and leading to nutrient imbalances. The declining partial factor productivity of fertilizers can be mitigated by addressing complex nutrient interactions. The widespread use of DAP in Indian agriculture likely contributes to negative nutrient interactions with micronutrients like Zn, Fe, and Cu, while also disrupting the nutrient ratio.

Blanket fertilizer recommendations by State Governments are based on broad crop responses, ignoring soil variability and nutrient supply capacity. These simplified guidelines are popular with line departments but fail to address site-specific needs. Another common approach is fertilizer application based on personal or peer perceptions, influenced by factors like fertilizer and commodity prices, water availability, market access, and risk perception. This often results in nutrient imbalances, especially when farmers rely on progressive peers' practices without considering their own resources. A more accurate method is soil-test-based fertilizer recommendations, which use soil analysis, correlation, and calibration to provide tailored advice.

In one subset, the targeted yield method, was pioneered by Ramamoorthy and colleagues, proving that Liebig's law of the minimum applies equally to N, P, and K (Ramamoorthy et al., 1967). This method not only suggests soil test-based fertilizer doses but also predicts achievable yields with proper agronomic practices (Dey, 2016; Dey and Santhi, 2014; Kumar et al., 2021; Krishna Murthy et al., 2023) but also improve nutrient use efficiency (Nisar et al., 2022; Rani et al., 2022; Sharma et al., 2023)). Fertilizer adjustment equations derived from this approach have been validated through frontline demonstrations across India, showing higher response ratios and benefit-cost ratios in diverse agro-ecological regions (Dey and Srivastava, 2013; Majumdar et al. 2014; Singh et al., 2015c; Soren et al., 2017). The targeted yield concept balances "fertilizing the crop" and "fertilizing the soil," providing a scientific basis for balanced fertilization. It assumes a linear relationship between grain yield and nutrient uptake, allowing for precise fertilizer estimation based on soil nutrient contributions.

Over 4,000 frontline demonstrations by All India Coordinated Research Project on Soil Test Crop Response (AICRP-STCR) centers have shown the superiority of STCR-IPNS recommendations over blanket approaches and traditional practices, resulting in higher yields and returns. Demonstrations under the Tribal Sub Plan (TSP) in states like Assam, Bihar, Chhattisgarh, and others also confirmed that even farmers with minimal agricultural knowledge could achieve the yield targets within $\pm 10\%$ variations using STCR technology (Dey, 2015, 2016). Of late, STCR has developed fertilizer prescription equations for secondary nutrients like sulphur and algorithms linking leaf colour chart, SPAD, and CM 1000 meter values at critical growth stages with yield in the rice-wheat system. Additionally, soil testing protocols for organic farming, including the characterization of organic phosphorus pools, have been established.

STCR also introduced fertilizer recommendations for drip fertigation (Praveena Katharine, 2014, 2017). Another important subset, SSNM, developed in the 1990s by IRRI and national partners across Asia, addresses the limitations of blanket fertilizer recommendations in large areas.

Research underscores the importance of indigenous knowledge in creating agricultural technologies to mitigate climate vulnerabilities. For example, in the plateau region, a method where powdered cowdung is mixed with soil after sowing rice seeds and followed by land leveling boosts nitrogen mineralization. This practice enhances nutrient uptake by young plants by improving soil water retention and accelerating microbial activity (Dey and Sarkar, 2011).

Sampling Strategy

Sampling is the first step of soil fertility evaluation, mapping and soil health card (SHC) generations. 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. Additionally, 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. Moreover, 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 for pin-pointing/correcting sources of error (Dey, 2019a).

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 enhancing crop yields with better quality and 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. 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, 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 the understanding of their own lands. The added advantage of participatory directed sampling process is that it captures localized irregularities better and hence, decision arrived at from this process is superior.

Automation in Sampling

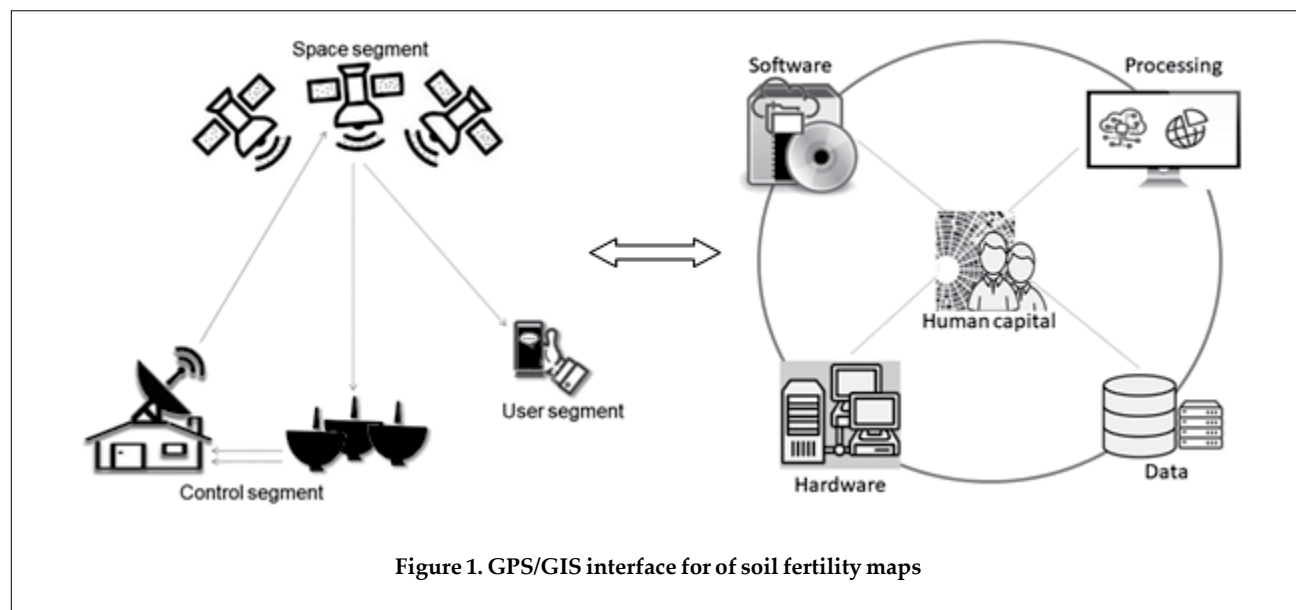
Soil sampling is the stepping stone for evaluating soil fertility and making strategic decisions on plant nutrient application. Soil analysis and plant nutrient recommendation depend on the small amount of sample collected. The COVID-19 pandemic called for paradigm shift towards current method of sampling 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, drone-aided soil mapping procedure has to be simple and easy to adopt.

Use of GPS/GIS-based Soil Fertility Mapping for Development of Customised Fertilizers

In the era of globalization, accurate and dependable agricultural information is essential for informed decision-making. To efficiently manage natural resources, a comprehensive database is necessary, especially as India faces the challenge of meeting the food and fiber needs of a growing population with existing land. As total factor productivity and fertilizer response ratios decline, embracing innovative technologies is crucial to reverse these trends. This includes adopting ICT, integrating externalities into economic decisions, strengthening local governance, and developing sustainable land management guidelines (Dey, 2020). Moreover, efficient nutrient management through geo-spatial technologies like GPS, GIS, and remote sensing is critical (Dey and Bhattacharyya, 2021). GIS, with its advanced tools, enables precise agricultural practices by monitoring changes and optimizing inputs at a granular level, allowing for the management of specific field areas rather than the entire field as a single unit (**Figure 1**).

The concept of balanced use of fertilizers to promote SSNM can be achieved through customised fertilizers. The customised fertilizer formulations can be derived from basic data of STCR and clustering of response zones through GPS/GIS-based fertility mapping helps 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 customised 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-Indian Institute of Soil Science, Bhopal in collaboration with mainly AICRP on 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 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. These fertilizers are area and crop specific.

The technology developed has been adopted by Indo Gulf Fertilisers (now Indorama), Coromandal International Limited and Nagarjuna Fertilizers and Chemicals Limited (Dey, 2019b). These fertilizers are included in FCO, 1985 and now there are 30 customised fertilizers.

Use of Soil Fertility Mapping for Interpolation: A Case Study from Madhya Pradesh

It is vital 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 compared and analyzed (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, sulphur, and zinc, from 2150 different locations (0–15 cm). For inverse distance weighting and spline, exponent value of 1, 2, and 3 were used, and these values were decided from the RMSE value. The ranges of 5–30 closest neighbouring points were selected for interpolation methods. Out of total 2150 samples, 10% points were preserved for validation using root mean square error root mean square error (RMSE) test. Overall, all methods gave similar RMSE values. On this study, ordinary kriging (exponential) performed well for pH, K, and S, whereas IDW 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

Decision support system for integrated fertilizer 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, and Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University (Dey, 2016). In cases where STCR

recommendations are unavailable for a particular soil-crop situation, the software can generate prescriptions using blanket recommendations based on soil test values. Using this software, fertilizer 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, soil testing laboratories can generate and issue the analytical report and recommendations in the form of SHC (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 same yield goal for his location and formulates a fertilizer management strategy required to attain the same. 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 SHC portal developed by the Ministry of Agriculture & Farmers Welfare, Government 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 SHC along with fertilizer recommendations. It is a workflow-based application with major modules such as (i) soil samples registration; (ii) test result entry by soil testing labs; (iii) fertilizer recommendations; (iv) SHC generation along with fertilizer recommendation and suggested amendment; 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 provides alerts to farmers about sample registration and generation of SHC through SMS and email. Based on test results, these recommendations are 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.

Mobile App

Bilingual (Marathi and English) STCR mobile app for fertilizer recommendations of Maharashtra was developed in collaboration with National Informatics Centre (NIC), Pune (Dey, 2019b). Based on resource endowment capacity of the farmers, the App helps to realize the targeted yield of crops. Farmers can get the precise fertilizer recommendations based on soil test value and for a specific yield target. The STCR prescription equations for sugarcane, wheat, upland paddy, transplanted paddy, pearl millet, *Kharif* sorghum, dryland *rabi* sorghum, finger millet, fodder maize, Bt cotton, groundnut, soybean, sunflower, pigeon pea, green gram, chickpea, okra, brinjal, cabbage, cauliflower, potato, tomato, turmeric, chilli, onion, garlic, marigold, bitter gourd, banana, and maize have been included in the app.

Mobile app, named fertilizer calculator, estimates fertilizer needs in sugarcane cultivation (<https://icar.org.in/mobile-app?page=5>) using soil test results (N, P, K) and FYM data to calculate the required

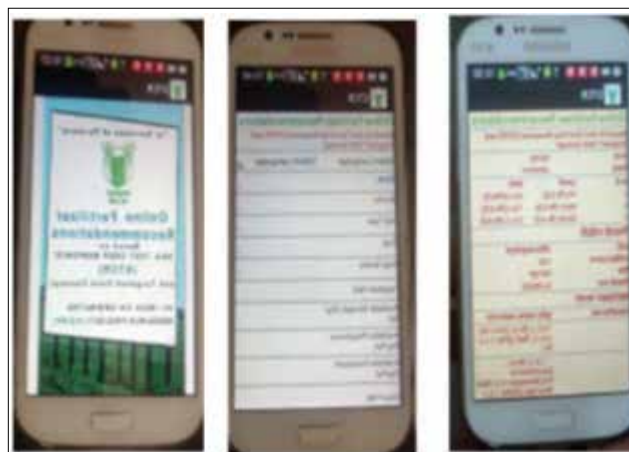


Photo 1. Snapshot of mobile app

amounts of Urea, DAP, and MOP for targeted yield in both plant and ratoon crops. A snapshot of mobile app is depicted in **Photo 1**.

KISAAN 2.0

Krishi Integrated Solution for Agri Apps Navigation (KISAAN 2.0) is designed to support e-agriculture and promote smartphone-based farming in India.

This app consolidates over 300 agriculture-related applications developed by ICAR Institutes into a single Android app. The goal is to simplify farming for Indian farmers by offering a convenient, unified platform. KISAAN 2.0 provides a user-friendly interface in multiple Indian languages, allowing farmers to easily access a wealth of agricultural knowledge including plant nutrient management as well as recommendation of soil amendments.

Kisan Sarathi

An innovative ICT-based platform, developed by ICAR, is designed to revolutionize agriculture by seamlessly connecting farmers with the latest technologies and expert knowledge. Powered by the interactive information dissemination system (IIDS) under the Digital India Corporation (DIC) and supported by the Ministry of Electronics and Information Technology (MeitY), Government of India, Kisan sarathi serves as the system of agri-information resources auto-transmission and technology hub interface. This intelligent online platform offers multimedia, multi-way connectivity, enabling farmers to access a vast knowledge base and engage with numerous subject matter experts. By focusing on local agricultural needs while maintaining a national perspective, Kisan Sarathi aims to empower farmers with the tools and information they need to thrive in an evolving agricultural landscape.

Other DSS

A web-based fertilizer recommendation system was developed using the STCR approach and geo-referenced soil fertility maps for Tumkur district, Karnataka. The SHC, generated by entering geo-coordinates via smartphones, was evaluated against actual soil test values for pH, EC, N, P, and K demonstrated high accuracy, with online values closely matching actual test results (Dey, 2019b). A copyrighted DSS for fertilizer prescription of FCV tobacco in the northern light soils of Andhra Pradesh was developed and is now widely used.

Soil Spectroscopy for Rapid Evaluation of Soil Fertility

In the backdrop of COVID-19 pandemic, non-contact/ minimum-contact soil testing methodologies had assumed 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 for 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 a 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 (International Centre for Research in Agroforestry; presently known as World Agroforestry Centre) collaborative project, K availability indices were also ascertained through MIR spectroscopy besides traditional mineralogical

approach. 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).

Use of spectroscopy for soil analysis 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 partial least squares regression (PLSR) techniques performed better than the other two regression techniques for all the soil properties except for available potassium and EC, where the support vector machine regression model performed slightly better.

Good predictions for the independent validation data set were obtained for per cent of clay, silt & sand and soil water retention at permanent wilting point and field capacity, 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. It 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 labour-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, farmers need to collect soil samples, transport the samples to the laboratory and got it analysed, 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 potentially be 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

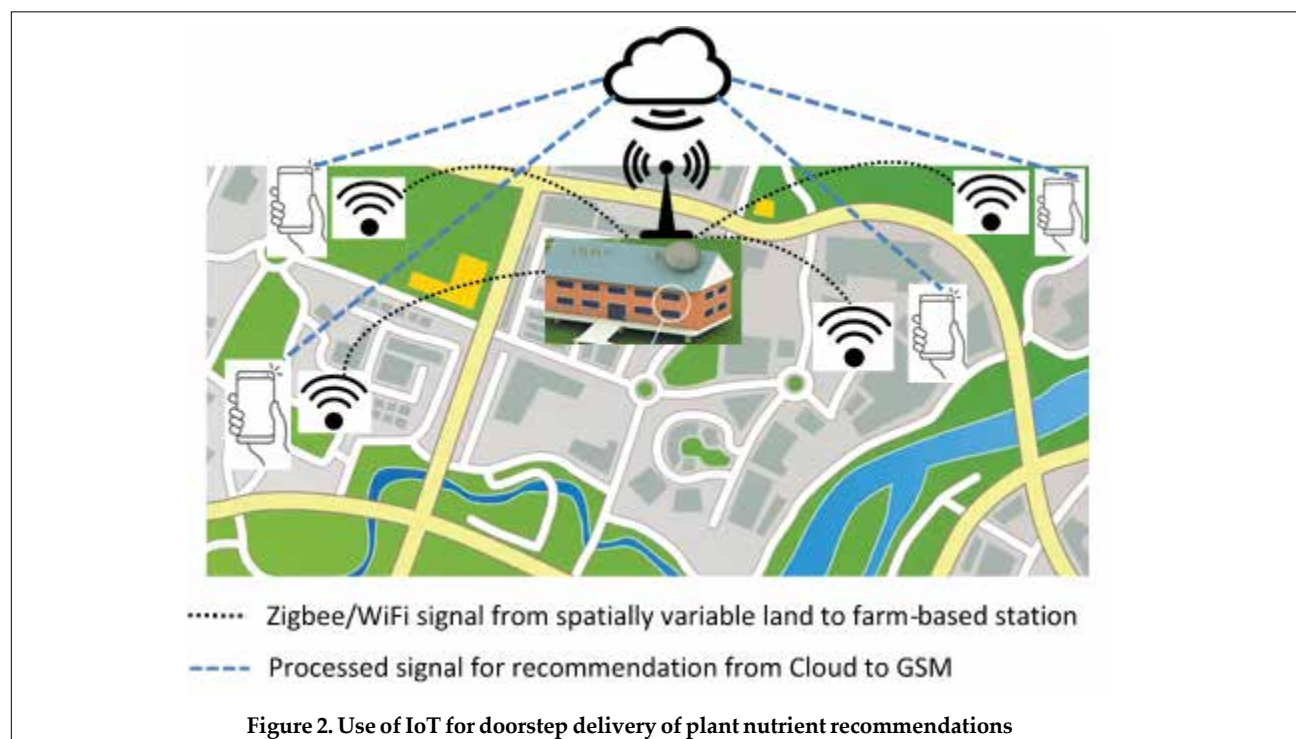
precise and efficient resource management. Nanotechnology can support precision farming and forestry practices by providing high-resolution imaging, monitoring, and sensing capabilities. Efforts should also be made towards development of hand held cost effective NDVI sensors to reproduce the results 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 is 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 preparation to sowing, input application and final harvesting. This is made possible by advancements in artificial intelligence, machine learning, cloud and mobile connectivity. Field characterization through internet-connected devices such as drones, remote sensing, and hand-held sensors for geo-tagging each parcel of land, along with the development and delivery of farm management plans via cloud-based networks, will enhance farm profitability and soil sustainability (Dey and Bhattacharyya, 2021). It is also necessary to maintain proper cloud-delivered security services to alleviate potential security threats in precision farming. Because of their portability and flexibility to specifically designed electrical systems, Internet of Things (IoT) based solutions might be developed fairly easily (Taylor et al., 2019).



Enumeration of spatial variability and the introduction of variable-rate technology (VRT) for applying plant nutrients, amendments, and other farm inputs—using automated rate settings on equipment through IoT (**Figure 2**) — lead to reduced input costs by optimizing usage and energy savings by decreasing the number of field passes.

Smart Technology vis-à-vis Increased Efficiency of Inputs

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 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, 2019a). 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 (Dey, 2019b). 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 taking slope, depth and texture into consideration.

Conclusion and Way Forward

To realize the nation's aspirations by 2047, we must transition from isolated efforts to a unified and integrated approach in soil health management. There is an urgent need for adoption of efficient nutrient management harnessing geo-spatial technologies like

GPS, 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 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, as enshrined in Target 15.3 of SDG-15, should be the guiding principle 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. 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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Digital Agriculture in Rainfed Farming

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Abstract

Rainfed agriculture, which depends solely on natural rainfall, constitutes the majority of global agricultural land. This paper explores the integration of digital agriculture technologies in rainfed farming systems, addressing the unique challenges posed by climate variability, soil degradation, water scarcity and resource constraints. Current state of digital agriculture in rainfed farming has been reviewed in this paper, examining the potential benefits and limitations of technologies such as precision agriculture, IoT, remote sensing, big data analytics, and mobile applications. Socio-economic and infrastructural barriers to the widespread adoption of digital agriculture in rainfed regions have also been discussed.

Key words: Digital agriculture, rainfed farming, IoT, precision agriculture, mobile apps, remote sensing, digitization, digitalization

Introduction

Rainfed farming is primarily dependent on rainfall, and suffer lack of groundwater for agriculture and allied activities (Gautam et al., 2007; Gajjala et al., 2023). It is very important to the country's economy and food security (Srinivasa Rao et al., 2015). Further, it is the livelihood of small and marginal farmers in the country. It produces 40% of food grains, which supports human population and livestock. Rainfed agriculture is practiced under a wide range of soil types, agro-climates, topography and rainfall conditions ranging from 400 mm to 1600 mm per annum. Rainfed regions are characterized by complex climatic challenges, manifested as water scarcity for rainfed crop production (Gautam et al., 2007; Kanwar, 1981). Rainfall is highly unreliable, both in time and space, with strong risks of dry spells at critical growth stages even during good rainfall years. Rainfed crops are prone to breaks in the monsoon during the crop growth due to water stress. Digital agriculture, defined as the use of digital tools and technologies to enhance agricultural productivity and sustainability, offers potential solutions to these challenges.

Emerging digital technologies have the potential to change traditional agricultural practices. The Food and Agriculture Organization of the United Nations describes this change as a "digital agricultural revolution", which could help ensure agriculture meets the needs of the future global population (Liang et al., 2003). Others call the change Agriculture 4.0/5.0 (Jiang et al., 2024), indicating a fourth/fifth major agricultural revolution, although the precise

dates of these are unclear (Tang et al., 2002). Agricultural revolutions over history have involved periods of technological transformation and increased farm productivity (Amerttet et al., 2024). The transformations of agricultural technologies over the past, have been the offshoots of broader technological advancements (Jennifer and Sarah, 2020). Combustion engine and development of automobile were instrumental to the rise of the tractor; advances in genetics gave upsurge to modern plant breeding technologies, such as hybrid seeds; and rise of modern chemistry accorded rise to synthetic pesticides and fertilizers. Similarly, development of digital technologies and rise of big data analytics are having a major influence on the growth of new agricultural technologies. These data-driven precision technologies are dubbed by some as Agriculture 4.0, reflecting the impact on agriculture of what is commonly referred to as the fourth industrial revolution, characterized by the rise of digital technologies (Rose and Chilvers, 2018). This paper aims to provide a comprehensive review of the role of digital agriculture in rainfed farming, highlighting both the opportunities and challenges associated with its implementation.

Challenges in Rainfed Farming

Rainfed agriculture has greater resilience due to its diverse farming activities. Further, it has plenty of problems and challenges due to complex conditions (Sheoran et al., 2022; Srinivasarao et al, 2015; Kanwar, 1981). The rainfed lands suffer from a number of biophysical and socio-economic

constraints which affect productivity of crops and livestock. These include low and erratic rainfall, land degradation and poor productivity (Katyal and Das, 1993); low level of input use and technology adoption and low draft power availability (Mayande and Katyal, 1996) and inadequate fodder availability, low productive livestock, resource poor farmers and inadequate credit availability.

Land degradation in rainfed areas has resulted from climatic variations and unplanned over-exploitation of natural resources by human activities, and increasing pressure of human and livestock population. It has become unavoidable to cultivate even the marginal lands. Pasturelands are degraded due to overgrazing caused by both increase in livestock population and decrease in area under grazing due to encroachment for cultivation and urbanization. As a result, more and more forests are being used for grazing purpose. At present, nearly 70% of rainfed area is affected by wind erosion and sand deposition. Rainfed soils are generally of poor quality (low fertility, high erodibility, fragile, shallow and susceptible to loss of physical integrity). These have very weak buffering and resilience capacity. Saline-alkali soils in arid and semi-arid areas acidic soils in sub-humid and humid areas are generally observed in such areas. The soils are mostly coarse textured, highly degraded with low water retentive capacity, multiple nutrient deficiencies, and thus are not conducive for intensive cropping.

Rainfed agriculture relies entirely on natural rainfall and it is vulnerable to several constraints, including that most of the farmers are resource-poor, soils deteriorate, poor crop production in most cases (Rosegrant et al., 2002; Wani et al., 2009). Repeated droughts present a major challenge to rainfed agriculture. Prolonged water stress; especially at critical stages of development, degraded soil and resources (Srinivasarao et al., 2011; Srinivasarao and Vittal, 2007). There is poor organization of the marketing system in the villages, including lack of proper regulation and profitability. These sectors are dominated by intermediaries and defined by dubious marketing platforms (Dixit et al., 2013). Out of an estimated 142 million ha net cultivated area, about 86 million ha (60%) is rainfed. Even after reaching the full irrigation potential, nearly 50% of the cultivated area will remain rainfed (Paroda, 1997). The average land holding is likely to be 0.08 ha from the present 0.15 ha, which would be uneconomical for farming. Rainfed farmers are economically weak with little ability to withstand risk. Out of the 97 million farm holdings, 76% are small (<2 ha) and marginal,

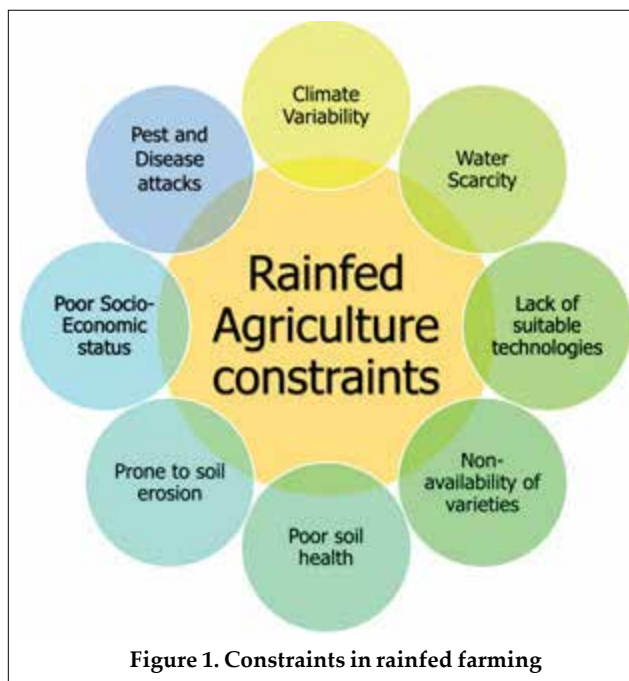


Figure 1. Constraints in rainfed farming

cultivating only 29% of the total arable land. The holdings are unconsolidated and scattered (Sharma and Singh, 2006). Climate is one of the major factors influencing crop growth. Favourable weather is essential for good harvests. Weather abnormalities like cyclones, droughts, hailstorms, frost, high winds, extreme temperature and insufficient photosynthetic radiation, etc. may generally lead to very low or even no yields. Hence, characterization of agro climates is a pre-requisite to know the potential of a region, especially under dryland conditions for improving and stabilizing the productivity (Rao et al., 1999). Constraints faced by the sector is depicted in **Figure 1**.

Digital Agriculture Technologies in Rainfed Farming

Global agriculture faces various challenges to meet the demand for food and fibers in the coming years because it needs to maintain overall productivity without further polluting soil, water and other agroecological systems (Finger et al., 2019; Cole et al., 2018). Widespread operational inefficiencies could be corrected by the use of digital agriculture technologies (Goswami et al., 2023). Agriculture has always been in a constant state of change in order to become more economically efficient and to overcome changing agronomic challenges such as plant diseases or weather extremes (Kuska et al., 2024). Emerging digital technologies have the potential to change traditional agricultural practices. Digital farming is an approach to farming that uses digital technologies, such as sensors,

drones, global positioning system (GPS) mapping, and machine learning to optimize agricultural production (Shamshiri et al., 2018; De Clerca et al., 2018; wikipedia, 2022; BASF, 2024).

Digital farming allows farmers to collect and analyze data on soil quality, crop health, weather patterns, and other variables in real-time, enabling them to make more informed decisions about planting, irrigation, fertilization, and pest and disease control. Agriculture is now evolving through both digitization and digitalization. Digitalization is the process of using digital technology to improve agricultural processes and operations to increase efficiency and create new value. Whereas, converting information in analog format (such as paper documents, photos or audio) into digital format (such as digital files, databases and e-books), information can be easily stored and shared. This is expected to lead to more efficient use of resources and higher yields. The process of digitalization is depicted in **Figure 2**. Digital farming (also referred to as smart farming or agriculture 4.0) is expected to address the challenges using information communication technologies to collect and analyze data to support efficient farming processes (OECD, 2019; Bacco et al., 2019). Digital farming has the potential to transform agricultural systems to be more sustainable (Shang et al., 2021). Digital technologies have become increasingly popular in agriculture (Johanna et al., 2021).

The scenario of digital farming is rules and algorithms, human and artificial intelligence, the eye of the knowledgeable farmer and the outsourced 'eye' via GPS, science-based and practical experience all this will form a new synthesis, so to speak, in a future integrated

digital food economy encompassing the agricultural and food sectors. Digital technologies of various orientations, characteristics and degrees of maturity used in different agricultural production segments are being tested or some are available as prototypes (Härtel, 2022). Digital agriculture encompasses a broad range of technologies that can be applied to rainfed farming. The data-driven approach helps farmers save time and money, and makes more efficient use of crop inputs while measurably improving crop yield and quality. The precision farming market is witnessing steady growth with revenues projected to increase consistently over the next decade at a CAGR of 12.2%. Precision farming market statistics related to hardware, software and services for 2023 to 2033 has been show in **Figure 3**.

The precision farming market generated USD 10.5 billion revenue in 2023. Approximately, 40.46% of respondents utilize sensors for monitoring machine conditions, enabling timely maintenance and minimizing downtime. Unmanned vehicles, including autonomous tractors and other autonomous machinery, are widely adopted. Nearly 89.31% of respondents utilize these advanced tools for tasks such as planting, cultivation, and harvesting. Around 32.06% of respondents utilize microclimate sensors to monitor environmental conditions such as temperature, humidity, and air quality, ensuring optimal living conditions for livestock. Nearly, 12.98% of respondents utilize milking robots, which automate the milking process and provide benefits such as increased milk yield, reduced labour costs, and enhanced animal welfare. GPS guidance systems with automatic control (autosteer) for fertilizer/chemical application saw a significant rise from 78% to 90%, indicating a growing reliance on automated navigation systems in agricultural machinery (Trishita, 2024). This section reviews the most relevant technologies and their applications.

Precision Agriculture

Precision agriculture involves the use of GPS, sensors, and data analytics to manage field variability and optimize inputs. In rainfed farming, precision agriculture can be used to monitor or measure soil moisture, temperature, and nutrient levels using sensors across different parts of a field, allowing farmers to apply water and nutrients more efficiently (Szeles et al., 2024). Applying machine learning (ML) tools to analyse soil and weather data can help farmers to choose the best

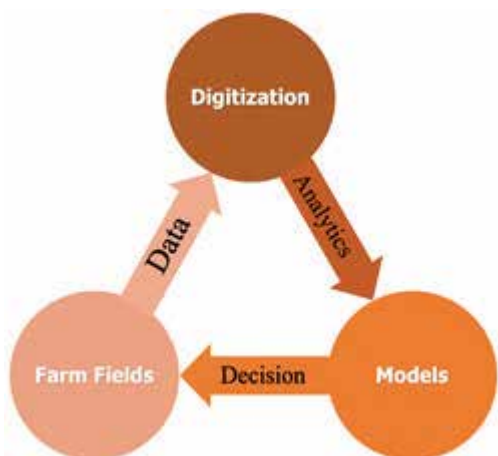
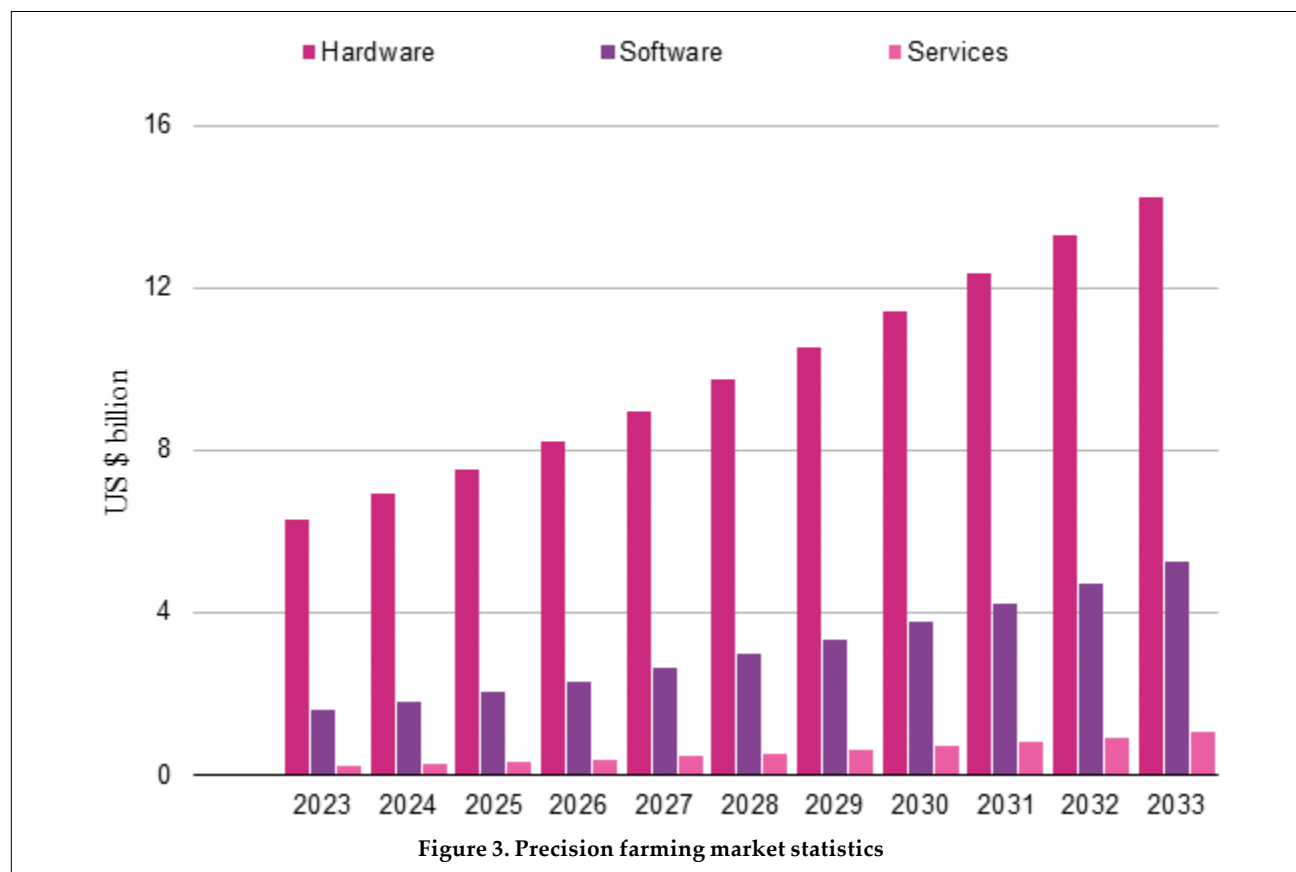


Figure 2. The process of digitalization



times to plant and schedule farm activities for minimizing the risk of crop failure (Tilekar et al., 2024; Palermo et al., 2024). Precision agriculture enables site-specific management of crops, reducing input costs and environmental impact. Drones are used for monitoring crop health, assessing water stress, spraying crops with precision and optimizing input usage (Shamshiri et al., 2024). A list of relevant applications is given in Table 1.

Internet of Things (IoT)

The basic concept of internet of things (IoT) is the pervasive presence around us of a variety of things or objects such as radio-frequency identification (RFID) tags, sensors, actuators, mobile phones, etc. through unique addressing schemes, are able to interact with each other and cooperate with their neighbours to reach common goals (Atzori et al., 2010). IoT involves connecting devices and sensors to the internet, enabling real-time monitoring and control of farming operations. Key applications in rainfed farming include real-time monitoring, automated irrigation and livestock management. IoT devices can monitor soil moisture, temperature, and weather conditions thereby providing farmers

with real-time data to make informed decisions. Although rainfed farming relies on natural rainfall, supplemental irrigation systems controlled by IoT can help during periods of drought or inadequate rainfall. IoT can also be applied to manage livestock health and productivity in mixed farming systems common in rainfed regions. Smart irrigation systems automatically adjust water delivery based on soil moisture and weather conditions. IoT-based application development platforms have the potential to run farm management tools capable of monitoring real-time events when integrated into interactive innovation models for fertigation. Their capabilities must extend to flexible reconfiguration of programmed actions. IoT platforms require complex smart decision-making systems based on data-analysis and data mining of big data sets. Data is processed in a decision-making system based on learning prediction rules in conjunction with the Drools rule engine. The platform can be remotely controlled, and offers a smart farming open data network with shared restriction levels for information exchange oriented to farmers, fertilizer provider, and agricultural technicians that should provide the farmer with added value in the form of better decision making or more

Table 1. Application of precision agriculture and its solutions			
S. No.	Technology	Solution	Reference
i.	Agtrinsic	Agtrinsic is a scouting and harvesting analytics app that uses AI for routing of scouts and monitoring of disease pressure.	https://agtrinsic.com
ii.	Agmatix	Through its agronomic trial management SaaS solution, Agmatix allows researchers, agronomists, and farmers to simplify trial data collection straight from the field. Feature of on-farm experimentation enables users to create and manage side-by-side plot trials directly in the app.	https://www.agmatix.com
iii.	Operations Center	John Deere's Operations Center Mobile (formerly My Operations) takes remote management of the field operations and equipment to the next level. The app is truly helping proactively manage, improve logistics and productivity.	https://www.deere.com/
iv.	xarvio Field Manager	xarvio Field Manager from BASF uses the latest satellite image recognition and cutting-edge agronomic modelling to give most reliable advice. Features include field specific risk status for disease and insect risks; important crop growth stage notifications; optimal spray timing notifications; field specific weather information; hourly spray weather forecast; optimal timing and variable application maps for fertilizer.	https://www.xarvio.com/
v.	AgriSync	It enables farmers and advisors to connect and resolve support issues on the farm. Farmers can connect with multiple advisors from different companies to submit and receive support in real-time via video.	https://www.agriscyncer.com
vi.	Agworld	The app enables growers, crop consultants, farm staff, precision specialists, and operation managers to truly work as one. It improves workflow and increases production efficiency. Agworld is integrated with Microsoft Power BI analytics platform.	https://www.agworld.com/au/
vii.	AgVend	AgVend's integrated Grower Portal is a custom-branded information and commerce app. It provides the growers with the ability to pay invoices, access historical orders, request product prices, and more.	https://www.agvend.com
viii.	BeCrop	It is a proprietary technology developed by Biome Makers, integrating genomics, AI, and ag data to identify the microbial biomarkers and provide a meaningful explanation of soil function in agriculture, including biodiversity, crop vulnerability and nutrition.	https://biomemakers.com/
ix.	Farm Dog	Farm Dog is the productivity platform for profitable agronomists. The one-stop portal provides ones. Business with those tools that save their time in the field and in the office, improve the communication with the clients, and provide the data management solutions that the business requires.	https://farmdog.ag
x.	FarmQA	FarmQA is a digital toolset for agronomy that includes crop scouting, treatment recommendations, map layers, and complete reporting functionality.	https://farmqa.com
xi.	GeoPard Agriculture	It is a cloud-based mobile app for precision ag data with business intelligence capabilities. GeoPard Variable Rate prescription maps are used for fertilizing, crop protection, seeding, irrigation, desiccation, and optimization of crop inputs and yield while preserving resources.	https://geopard.tech
xii.	Agvance Grower 360	Grower360 gives growers timely access to their information, creating a better relationship with ag retailers by enhancing the customer experience.	https://agvance.net/products/grower360
xiii.	Drop Control	Know the exact condition of farm using Drop Control, a web/mobile solution that allows to follow the weather and soil moisture conditions, and control the irrigation/fertigation system efficiently.	https://wiseconn.com/us/our-solution/
xiv.	Sirrus App	Sirrus app helps agronomists and farmers collaborate on farming decisions by making field data accessible and easy to collect. Users can scout crops for pest pressures and easily record and collect observation photos.	https://sirrus.proagrica.com/sirrus-suite/sirrus/

efficient exploitation operations and management (Baseca et al., 2019). A list of promising IoT applications is given in **Table 2**.

The worldwide market for IoT applications in agriculture demonstrates significant growth across various segments from 2020 to 2026. In the precision crop farming segment, the market value surged from \$7,285.3 million in 2020 to \$8,280.6 million in 2021 and is projected to reach \$13,134 million by 2026. Similarly, the livestock monitoring and management

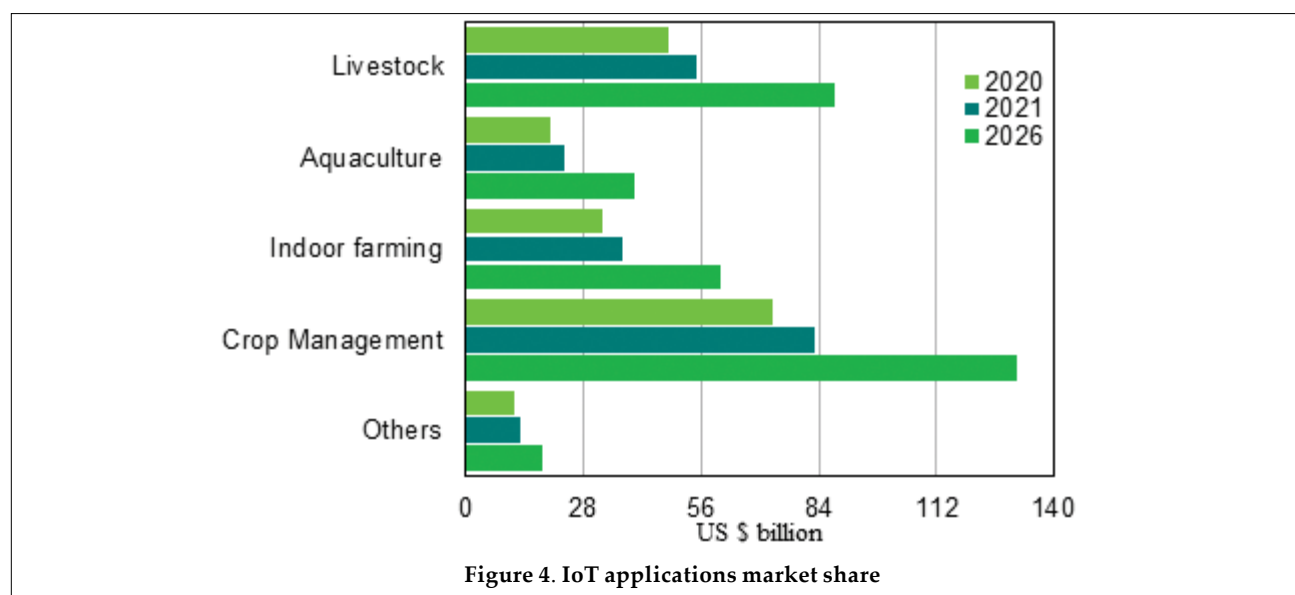
segment witnessed notable growth, with market values rising from \$4,834.1 million in 2020 to \$5,503.3 million in 2021 and an anticipated increase to \$8,797.6 million by 2026. Indoor farming also experienced substantial growth, with market values increasing from \$3,234.1 million in 2020 to \$3,707.4 million in 2021 and projected to reach \$6,086.9 million by 2026. Additionally, the aquaculture segment demonstrated significant growth **Figure 4** with market values rising from \$2,011.1 million in 2020 to \$2,327.2 million in 2021

Table 2. Solutions offered by IoT applications

S.No	Applications	Solution	Reference
i.	Slakes	The Slakes app allows users to easily and accurately measure wet aggregate stability – a key indicator of soil health. The app uses a smartphone camera to take a picture of three dry soil aggregates before and after exposing them to water for 10 minutes.	https://soilhealthinstitute.org/our-work/initiatives/slakes/
ii.	Agrobit	A mobile app for agricultural photogrammetry, allowing farmers to digitally model crops using smartphones. This technology provides detailed insights into crop health and development, enhancing precision agriculture practices.	https://agrobit.com/en/
iii.	Airbots	It is autonomous agri drones for enhanced crop spraying and monitoring. This technology supports efficient pesticide and fertilizer application, and the drones can also gather valuable crop performance data.	https://airbotsaerospace.com/
iv.	Phytech	The Phytech mobile app is a production optimization solution that integrates plant-data, AI-based recommendations, IoT network, and hydraulic monitoring and automation.	https://www.phytech.com
v.	Cropler	AI-powered remote photo monitoring for enhanced field management. Cropler's technology allows for accurate crop health tracking and data-driven agricultural decisions.	https://www.cropler.io/
vi.	Ribes	It has visual plant recognition and autonomous vehicles for constant crop monitoring, providing critical data for berry farmers to increase yields and reduce costs.	https://www.ribestech.com/
vii.	Soil Scout	Soil Scout offers a solution with wireless underground sensors for real-time soil condition monitoring to enhance crop growth	https://soilscout.com/solution/wireless-soil-moisture-sensor
viii.	Semios	Semios allows remotely monitor and manage weather, pest pressure, water, and plant stress in one convenient place to produce a better crop. Get early warnings and instant feedback on frost, disease, and pest management. Gain insight into your daily and weekly operations.	https://semios.com

and forecasted to reach \$4,016 million by 2026. Other segments also showed growth trends, with market values increasing from \$1,152.5 million in 2020 to \$1,285.1 million in 2021 and anticipated to be \$1,818.7 million by 2026. Overall, IoT application market in agriculture is witnessing robust global

expansion, driven by the increasing adoption of technology-driven solutions to optimize farming practices and improve efficiency across various agricultural segments. The global IoT in agriculture market was valued at US \$ 13.61 billion in 2022 and is projected to be worth around US \$ 33.57 billion



by 2032 with a registered CAGR of 9.50% from 2023 to 2032.

Remote Sensing and Satellite Imagery

Remote sensing technologies provide valuable insights into the health and condition of crops and soil over large areas. Satellite imagery can detect signs of stress in crops, such as nutrient deficiencies

or water scarcity, allowing for early intervention. The introduction of more compact technological solutions, such as autonomous drones, light detection and ranging (LiDAR) sensors, high-resolution cameras, small-scale robots, and long-range wireless transmitters, has led to a shift in precision agriculture and smart farming methods towards digitization (Shamshiri et al., 2024). Geographic information system (GIS) tools help in

Table 3. GIS and Remote sensing-based technologies

S.No.	Technology	Solution	Reference
i.	Aurea Imaging	It offers crop intelligence to monitor and treat individual trees and crops, leading to precision farming and sustainability.	https://aureaimaging.com/
ii.	Taranis Scout	Taranis Scout app allows to take imaging, do analytics, and provide comprehensive reporting to the field with automatic issue detection and quantified alerts delivered anytime, anywhere.	https://www.taranis.com
iii.	Panorama	Panorama features an API that allows other industry data platforms to create a connection to the precision planting system, allowing the data to flow seamlessly from the 20120 monitor to any platform. It allows precision planting dealer to provide remote technology support.	https://panorama.ag
iv.	AGMRI	AGMRI, a crop intelligence app, is ideal for farmers, agronomists, and crop specialists. It is an AI platform that combines ultra hi-res imagery with machine learning and computer vision to deliver a complete and uninterrupted "row-level" detail view of every acre and every field all season long.	https://www.intelinair.com
v.	Ceres Imaging	It employs aerial imagery and machine learning to provide detailed crop health information, assisting in optimized yield and water usage.	https://ceres.ai/portfolio-insights
vi.	Insights	Using various types of imagery and state-of-the-art intelligence algorithms, Insights virtually scouts the field and alerts about crop health concerns (plant insights) and irrigation issues (irrigation insights) before they become problems.	https://valleyinsights.prospera.ag/
vii.	Orbit	It is an AI-driven field scouting mobile application, leveraging the variable rate fertilizer application feature, Orbit optimizes fertilizer distribution across varying segments of land, promoting cost-efficiency. Orbit evaluates a field's yield potential against a comparable one by utilizing NDVI data and phenological stages, providing insights for enhanced agricultural productivity.	https://www.doktar.com/
viii.	Farm Command	Farm Command is a digital farm data management app helps quickly analyze, visualize and share information from anywhere. Features include an in-cab tool; field-centric weather data and forecasts; imagery-derived map layers; automatic crop health change detection; simplified operational planning; scouting tool; harvest tool; and more.	https://www.farmcommand.com
ix.	Fire Map	Fire Map that enables growers to monitor active fires within a 20-mile radius of any location in the world. Agrology's Fire Map delivers data in 3D, enabling users to zoom in and out to see the exact location of fires and users can select up to three locations at once.	https://www.agrology.ag
x.	RoboCare	Advances early disease detection in greenhouses using hyperspectral imaging and AI their solutions enable proactive responses to potential crop health issues.	https://robocare.tn/?page_id=9
xi.	Automated FruitScout	Automated Fruit Scout is an industry leader in agriculture process automation such as precision crop load management. Fruit Scout's easy-to-use mobile app leverages its computer vision technology, enabling growers to scientifically determine their optimal crop load, and saving them from wasting labour and inputs (water, fertilizer).	https://fruitscout.ai
xii.	Agerpoint Capture	With the Agerpoint Capture app, users can easily create digital twins of plants, crops, trees, and the natural world. These 3D models help to measure and analyze the ground truth.	https://www.agerpoint.com

mapping soil types, terrain, and rainfall patterns, which can be used to plan crop rotation and optimize land use. Regular monitoring of crop health, growth stages, and water stress is possible using satellite imagery and aerial photography. These technologies help monitor weather patterns, soil moisture levels, and potential climatic changes. GIS and remote sensing (RS) techniques offers several solutions for sustainable crop production which include genotype/crop species identification, landscape and farm-level sustainable management of farming system, and also formulation of better policies (Basso and Antle, 2020). Different studies have demonstrated the benefits of optimally incorporating these technologies as a viable means for sustainable crop production (Bahn et al., 2021; Pauschinger and Klauser, 2021; Mondejar et al., 2021). A list of use case applications in agriculture are given in **Table 3**.

Remote sensing technologies in agriculture aim to ensure profitability, sustainability, and environmental protection. The market is also benefiting from access to real-time data on crop, soil, and ambient air conditions, as well as other relevant information such as hyper-local weather forecasts, which is expected to grow to raise revenues during the forecast period 2023-2030. The global remote sensing technology for agriculture market was valued at US \$ 1.81 billion in 2022 and is expected to reach the value of USD 3.28 billion by 2030, at a CAGR of 7.70% during the forecast period of 2023 to 2030. "Hardware segment" is expected to dominate the market due to driving farming communities to use efficient agricultural methods. In addition to the insights on market scenarios such as market value, growth rate, segmentation, geographical coverage, and major players, the market reports curated by the Data Bridge Market Research also include in-depth expert analysis, geographically represented company-wise production and capacity, network layouts of distributors and partners, detailed and updated price trend analysis and deficit analysis of supply chain and demand.

Agri Data Analytics

Data analytics involves processing large datasets to extract useful insights for decision-making. The analytics comprise volume, variety, velocity, and veracity components (Osinga et al., 2022). Predictive analytics in agriculture are tools that use a variety of statistical methods including data mining, predictive modeling, and machine learning that analyze an array of current and historical agricultural, biological, climate, and

hydrological data from various sources to make predictions about future outcomes on the farm. These predictions provide farmers with actionable insights that can help develop models to improve agronomic performance, manage inputs, optimize resource use, predict market conditions and plan for better crop production. Therefore, historical data and machine learning algorithms are used to forecast crop yields, identify risks, and suggest optimal planting times. It provides actionable insights based on real-time data, helping farmers manage resources more effectively. Artificial intelligence (AI) and data processing have become integral components of modern technology. Advanced data processing techniques, AI can efficiently analyze massive volumes of data, extract valuable insights, and identify meaningful patterns that would otherwise be difficult for humans to detect (Smith 2020; Dharmaraj and Vijayanand, 2018). AI and machine learning algorithms for predictive modeling and decision support (Aworka et al., 2022), integration of Blockchain technology for transparent and traceable supply chains (Kamilaris et al., 2019), and the development of biotechnology solutions for crop improvement and pest management (Steinwand and Ronald, 2020) are pertinent example of data analytics.

Data-driven technologies like remote sensing, smart sensors, and IoT-based devices constructed over AI/ML algorithms have become a fundamental aspect of agriculture that assists farmers with critical decision-making (Acharya et al., 2023). Data-driven tools can assess risks associated with climate variability, pests, and market fluctuations, enabling farmers to make informed decisions. Big data analytics can help optimize the use of inputs such as seeds, fertilizers, and water, reducing costs and environmental impact. The insights of data analysis led to development of app and decision support systems for field continuous monitoring, understanding crop performance and field variability, which can improve farmer decision making (Kayad et. al. 2021). Companies like FarmWise, FarmBot, and John Deere's FarmSight use machine learning to analyze data, predict yields, and optimize farm operations. Data analytics platforms like AgVue, FarmShots, and Gro Intelligence provide data analytics and insights for informed decision-making. Cloud-based, proprietary software and interfaces developed by FarmShots create high-resolution images, which can be displayed in multiple formats for rapid and accurate indication of field

conditions. A list of promising platforms which provides data analytics-based solutions is given in **Table 4**.

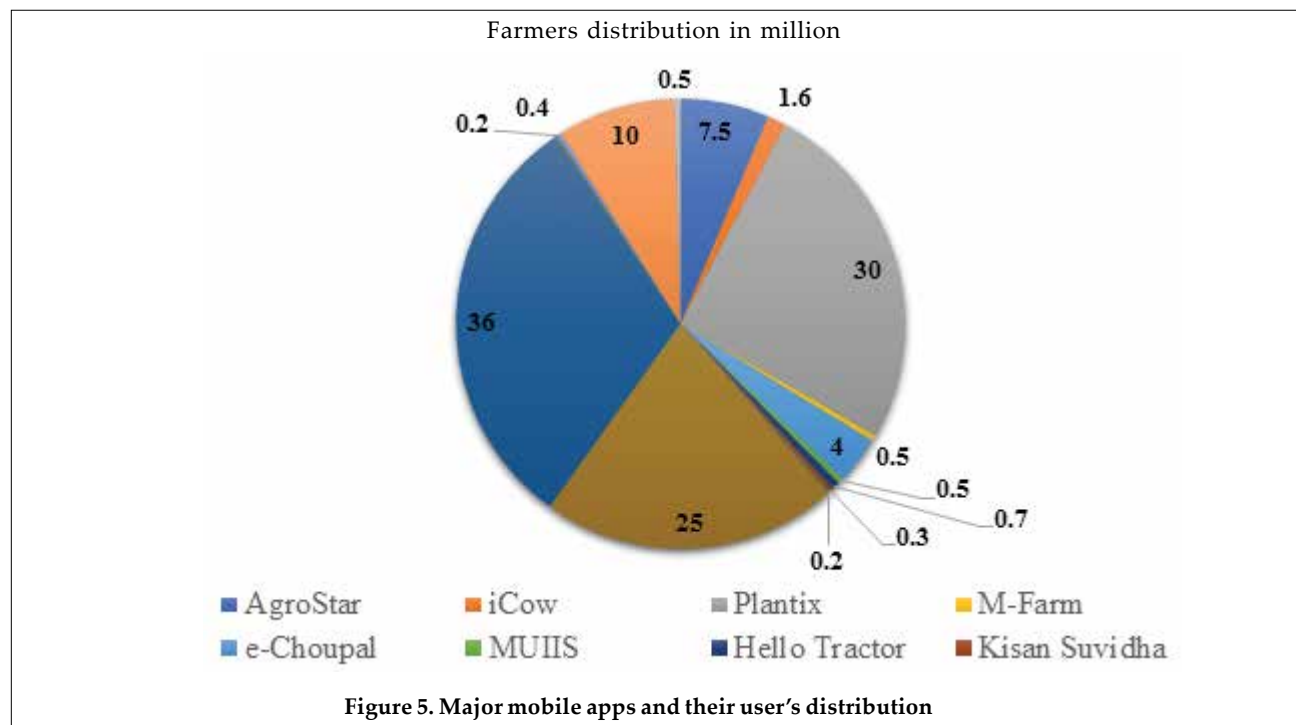
Mobile Applications

Mobile technology has become an essential tool for farmers, particularly reaching the stakeholders. Mobile apps provide farmers with access to critical information, such as weather forecasts, market prices, and best practices. Digital platforms can deliver extension services remotely, offering advice on crop management, pest control, and sustainable

farming practices. Mobile apps can connect farmers with buyers, improving market access and enabling better price negotiations. Devices that provide real-time updates on equipment and crop status thereby aiding in better farm management. It ensures traceability of crops from farm to market, which can enhance the market value of the products. Such applications facilitate fair trading and farmers get timely payments for their produce. It provides farmers with accurate weather forecasts, helping them plan planting, irrigation, and harvesting activities. The firms, IBM and Texas A&M AgriLife are collaborating through the IBM Sustainability

Table 4. Platforms providing data analytics-based solutions

S. No.	Technology	Solution	Reference
i.	SWAT Records	Soil, Water, and Topography (SWAT) is a multi-user, crop record-keeping solution for farmers and crop consultants. It create jobs for spraying, seeding, fieldwork, and harvesting.	https://swatmaps.com/ecosystem/swat-records/
ii.	Farmer's Business Network	Utilizing data analytics and machine learning, FBN helps farmers make informed decisions to optimize crop management.	Farmer's Business Network
iii.	Full Harvest	The platform connects farmers with food companies to sell surplus produce, reducing food waste.	https://www.fullharvest.com/
iv.	GROWERS and GROWERS Retail	GROWERS, a FREE app for farmers enable them to work directly with their retailers to request farm input products digitally, streamlining, and organizing the entire process. In addition, GROWERS Retail allows retail counterparts to respond to farmers' requests creating new ways for retailers to drive customer loyalty and sales growth as more farmers embrace technology.	https://growers.ag/retailers/
v.	AGvisorPRO	AGvisorPRO connect remotely and in real-time with individuals both for hire and for free. The app improves the connection between farmers, independent consultants, retailers, manufacturers, equipment dealerships, and the government.	https://getagvisorpro.com
vi.	Climate FieldView	It is an integrated digital agriculture tool that provides farmers informed operating decisions to optimize yields, maximize efficiency, and reduce risk.	https://climate.com
vii.	Aeroview InField	With the Aeroview InField app, farmers gain insights from high-res drone data, leading them directly to stressed trees on the farm. Easily identify, manage, and act against pest and disease threats. Users can track pest, disease, irrigation, and weed problems.	https://blog.aerobotics.com/infield-irrigation-zones
viii.	GSI Connect	GSI Connect optimizes the quality and profitability of dried grain and eventually connects customers with their entire grain system.	https://www.grainsystems.com
ix.	FieldAlytics Engage	The FieldAlytics Engage app enables growers to see upcoming activities on their fields, review and approve work orders, view field spatial data, assess the latest weather reports, and view current grain market information from a single dashboard.	https://www.ever.ag/fieldalytics/
x.	Gripp	Gripp enables the digitizing and scaling of agricultural operations by providing a chat-styled tracking platform for seamless connectivity among large teams and the hundreds of assets they work with on an ongoing basis.	https://grippcustomfarmingcorp.com
xi.	E4 Vision	E4 Vision 2.0, which help growers make quick decisions on one go. One of the most notable features of 2.0 is the soil recommendations tool. Customers will be able to have a quick reference to the data maps, reports, and new recommendations all at one place.	https://www.e4cropintelligence.com/
xii.	Bushel Farm	Bushel Farm (formerly FarmLogs) gives farmers both a ground-level and big-picture view of their farm's operational and financial performance. Powerful automation within the tool transforms farm records into valuable insights that farmers can use to plan and make decisions on their own or share with their grain buyers, agronomists, bankers, insurance providers, and other trusted farm partners.	https://bushelfarm.com



Accelerator to deploy and scale Liquid Prep, a tech solution that provides “when to water” decision support to farmers, in arid regions of the United States. Deltares teamed up with IBM developed a tech solution “Aquality/app” that helps farmers monitor nitrate levels and give insights into nutrient losses and local water quality. The effectiveness and efficiency of mobile apps and their impact on agricultural information dissemination to farmers have been validated (Mondejar et al., 2021). Several apps are well accepted by the farmers and their distribution is depicted in **Figure 5**. According to Bu and Wang (2019), incorporation of App-based agricultural services in crop production with climate-smart agricultural practices could be the main driver of greener and cleaner sustainable crop production, which is one of the agenda for sustainable global development. Therefore, many start-ups, consulting, and even private persons are already using the possibility of non-code chatbot development (Arawjo et al., 2023), to develop topic specific chatbots. The current progress in AI, and especially development like large language models (LLMs), can help to accelerate automation in agriculture (Matheus et al., 2024). A list of major mobile applications, which are providing solutions to the farming community is given in **Table 5**.

Socio-Economic and Infrastructural Barriers to Adoption

While digital agriculture holds great promise, several barriers hinder its widespread adoption in

rainfed farming regions like high costs and limited availability of digital tools, such as smartphones and sensors, prevent many farmers from adopting these technologies. Many farmers lack of digital literacy and skills needed to use digital tools effectively, limiting their ability to benefit from digital agriculture. Poor infrastructure, such as unreliable internet connectivity and inadequate power supply, hampers the deployment of digital agriculture solutions. Traditional farming practices and skepticism about new technologies can slow the adoption of digital agriculture. Inadequate policy support and regulatory frameworks can inhibit the growth of digital agriculture, particularly in rainfed regions. Digital literacy or access to training opportunities may benefit some farmers from the increased productivity and efficiency enabled by digital tools, others struggle to afford or access the necessary technology and training. This can divide and widen socioeconomic inequalities within rural communities, reinforcing disparities between large commercial farms and small-scale or subsistence farmers (Shamshiri et al., 2024). Economic condition, availability of technological infrastructure, technical knowledge, age of farmers, type of organization, reliability of technology, and concerns about security and privacy are important elements in adopting digital agriculture (Dibbern et al., 2024). The third barrier is lack of infrastructure, considering the resources associated with the availability of Internet and electronic equipment (Strong et al., 2022; da Silva et al., 2023). The barrier deals with a lack of knowledge,

Table 5. Major mobile apps providing solutions to the farmers			
S.No.	Mobile App	Solution	Reference
i.	mKisan	A digital platform providing weather forecasts, crop advice, and market access to farmers	https://mkisan.gov.in/
ii.	CropX	It is an easy-to-use integrated hardware and software system that connects farm data, real-time conditions, and agronomic recommendations, all while keeping farm data in one place for easy tracking and sharing	https://cropx.com
iii.	Agmarknet	Agmarknet portal is a Government of India portal on agricultural marketing backed by a wide area information network connecting agricultural markets.	https://agmarknet.gov.in
iv.	DGFT	Foreign trade policy with the main objective of promoting India's exports	www.dgft.gov.in/CP/
v.	PMFBY	Pradhan Mantri Fasal Bima Yojana is the government sponsored crop insurance scheme	https://pmfby.gov.in
vi.	e-NAM	National Agriculture Market (eNAM) is a pan-India electronic trading portal for agricultural commodities.	www.enam.gov.in/web/
vii.	Weatheragro	Latest weather and report of prices of agriculture commodities.	www.weatheragro.com
viii.	Kisanbandi	e-Market place for farmers.	www.kisanbandi.com
ix.	yieldsApp	yieldsApp's AI technology provides farmers with field-specific, recommendations for pest, disease, and nutrient management. The platform enables transparency and traceability to their farmers.	https://www.yieldsapp.com
x.	Meghdoot weather app	Meghdoot, a joint initiative of India Meteorological Department, Indian Institute of Tropical Meteorology and Indian Council of Agricultural Research aims to deliver critical information to farmers through a simple and easy to use mobile application.	https://apps.apple.com/in/app/meghdoot /id1474048155
xi.	FarmDrive	A digital platform providing farmers with access to credit, insurance, and market information.	www.farmdrive.com / FarmDrive/login.php
xii.	Traction Mobile	Traction Mobile is the ultimate tool for seamless field task management. Boost your productivity, save time, and gain efficiency by effortlessly handling connected machine tasks from phone. It can also assign equipment and personnel to each task, and approve or archive records.	https://tractionag.com/traction-mobile-app-now-available/
xiii.	Krishi Yantradhaare Driver	Agriculture Department, the Government of Karnataka has decided to establish Custom Hire Service Centre.	https://play.google.com / store/apps/ details?id= com.avani.chsc.driver.chscdriverapp&hl =en_IN&gl=US
xiv.	Libra Cart	Libra Cart from Agrimatics is a full-featured tablet and smartphone-based grain cart weighing and data management system. Automatically capture harvest data and share with the touch of a button.	https://agrimatics.com/agrimatics-libra-cart

which is related to the absence of training and knowledge of digital/technological platforms on the part of farmers (Bhardwaj et al., 2023; da Silveira et al., 2023; Richter et al., 2023). The barrier is also directly related to issues linked to the farmer's educational background and age, which are also barriers associated with the adoption of digital agriculture (Caffaro et al., 2020; Kanovska, 2021).

Future Thrust

The future of digital agriculture in rainfed farming is promising, but several steps are needed to ensure its success. Investing in education and training to improve digital literacy among farmers is crucial for the widespread adoption of digital tools.

Governments and development organizations should prioritize infrastructure improvements, such as internet connectivity and power supply in rainfed regions. Policymakers should create an enabling environment for digital agriculture, including providing incentives for innovation and ensuring that technologies are accessible to all farmers. Digital agriculture solutions should be designed with sustainability and scalability in mind, ensuring they are affordable, user-friendly, and adaptable to different farming contexts. The introduction of the fifth-generation mobile network (5G) is reshaping and redefining digital agriculture, initiating new possibilities for farming mechanization and automation.

Conclusion

Digital agriculture has the potential to transform rainfed farming by offering new ways to overcome the challenges of climate variability, soil degradation, and water scarcity. Farmers can improve productivity, manage risks, and enhance the resilience of their farming systems by leveraging technologies such as precision agriculture, IoT, remote sensing, big data, and mobile applications. Digital transformation in agriculture and rural areas is a policy priority at global level (Trendov et al., 2019; World Bank, 2017, 2019). Digital technologies are often seen as an opportunity to enable sustainable futures in agriculture and rural areas (Rijswijk et al., 2021). However, realizing the full potential of digital agriculture in rainfed farming will require concerted efforts to address socio-economic and infrastructural barriers, build capacity, and create supportive policies. Caution is not to be trapped in an exaggerated precision. Based on an examination of the daily functioning of the various components of yield mapping, it finds that digital farming is often 'precisely inaccurate', with the high volume and granularity of big data erroneously equated with high accuracy (Visser et al., 2021). Many articles with a technological focus emphasize the potential positive impacts of digital agriculture, but this emphasis may be the result of hype rather than concrete evidence that digital agriculture will deliver on its promises (Klerkx and Rose, 2020) and has raised skepticism among critics (Clapp and Ruder, 2020). Nevertheless, academics and policy-makers are describing an ongoing paradigm shift in food production a radically new model of producing food (Lajoie-O Malley et al., 2020), where data-driven decisions help reduce the use of harmful or scarce inputs (McBratney et al., 2005; Rossel and Bouma, 2016). With the right investments and strategies, digital agriculture can play a crucial role in ensuring food security, reducing poverty, and promoting sustainable development in rainfed regions of the world.

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Indian Agriculture : Embarked to a Digital Green Revolution

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Abstract

Agriculture directly or indirectly employs over 50% of the population in India and has a share of 18.2% of the Gross Domestic Product (GDP) at current prices and provides food security to nearly 1.43 billion people. Therefore, technology and the digitalisation of agriculture play a role of a catalyst to improve resource use management and increase production. According to the NITI Aayog research on artificial intelligence, agriculture must expand at a rate of 4% or higher to maintain an annual growth rate of 8–10%. Digitisation is crucial for achieving this level of success. The NITI Aayog indicated in a report that by 2025, AI in agriculture would worth \$2.6 billion at a compound annual growth rate (CAGR) of 22.5%. India is on its way to becoming a digitally advanced nation. The country is already home to one of the world’s largest and most rapidly growing bases of digital consumers. India has over 820 million active internet users, with more coming from rural areas. It is digitising activities at a faster pace than many mature and emerging economies. Digital interventions such as smart farming and precision agriculture are helping to improve the output of conventional agricultural systems and drive them towards efficiency and sustainability. Data-driven technologies like remote sensing, smart sensors, and internet of things (IoT)-based devices constructed over AI/ML algorithms are fast becoming a fundamental aspect of new age agriculture assisting farmers with critical decision-making. This digitalised green revolution is strengthening farmers in terms of farm management by improving crop yield, pest control, soil health and mitigating climate risks. However, implementing these innovative technologies is permeated by challenges and obstacles. There are issues related to awareness, learning and adaptation by farmers, privacy and data security as these technologies can generate sensitive information about farmers, their farms, and practices.

Key words: Digital agriculture, precision agriculture, green digital revolution, smart farming

Introduction

Globally, digital solutions are already driving the next level of farm productivity by reducing operational costs and enabling less resource-intensive growth. Various surveys have revealed that agtech usage differ across regions globally. A survey conducted by McKinsey, 2022 involving 5,500 farmers in 2022 across Asia, Europe, North America, and South America reveals that agtech adoption varies markedly across geographies, and that hesitant adopters are particularly concerned about unclear return on investment and high prices. Asia includes China and India; Europe includes France, Germany, Netherlands and Spain; North America includes Canada and the US; South America includes Argentina and Brazil;(n =5676). Highlights of the survey are presented in **Table 1**.

(Asia includes China and India; Europe includes France, Germany, Netherlands and Spain; North America

includes Canada and the US; South America includes Argentina and Brazil;(n =5676)

Agtech product adoption is lowest in Asia, with only about 9% of farmers using or planning to use at least one agtech product; adoption varies between countries in this region as well. Agtech adoption is not uniform across regions and, in some cases, there is substantial variation between countries within region both in terms of the percentage of farmers using agtech.

- ◆ Though agtech adoption is slow, farmers are open to innovation.
- ◆ There is a transition toward more sustainable, less resource-intensive food systems, with precision agriculture as a key enabler.
- ◆ Regulation will likely play an increasingly important role in accelerating growth in certain agtech submarkets.

Table 1. Currently using or planning to use one technology in next two years

Global	Europe	North America	South America	Asia
~39%	~62%	~61%	~50%	~9%
Farm-management software	Farm-management software and remote	Farm-management software	Remote sensing most popular	Farm automation and robotics

- ◆ Business models continue to evolve toward integrated solutions.
- ◆ There is substantial opportunity to improve product personalization and resolve the limited trust around data sharing.

Regulatory changes proposed over the past three to five years in various countries are likely to affect the direction of agtech adoption and innovation. Digital Green revolution is strengthening the farmers in terms of farm management by improving crop yield, pest control, soil health, etc. in real-time. We have thoroughly reviewed the digital adoption in terms of insights into the Indian agriculture (Balkrishna et al., 2023)

Important interventions in digital green revolution are the following:

i. Robotics: Automation in farm operations is playing a critical role due to declining labour availability and required precision in operations.

ii. IoT and Sensors: The ability to track produce and live animals, detect health issues and evaluate the environment inside the farm or the uptake of moisture from the soil in real-time is of huge value in addressing the major challenges of climate/sustainability, animal welfare and tracking in the food supply chain.

iii. Artificial Intelligence (AI) and Machine Learning (ML): AI may create a new avenue for extension agents, farming experts, consultants and professional experts, and more likely, it will alter how those profession functions. More accurate data will be available faster but will still need interpretation. This will change the jobs but not replace them.

iv. Drones: The ability of drones to go where manual operations would be difficult and see things not readily observed from the ground, creates real insights into pest protection, fertilizer and herbicide application, irrigation and harvest timing. Drones are going to revolutionised the farm operations and management. They are considered more efficient than the time-consuming conventional manual methods for spraying liquid fertilizers. However, this technology has to be picked up in India, where more than 80% of farmers are small and marginal having land less than 2 hectares. Drones in agriculture need to be given impetus to enhance and optimize various farming activities such as crop monitoring, crop spraying, soil analysis, and mapping. Drones equipped with sensors and cameras are used for imaging, mapping, and surveying farms. From the drone data, insights can be drawn regarding crop health, irrigation, spraying, planting, soil and field, plant counting, yield prediction, and much more. Drones can either be scheduled for farm surveys (drone as a

service) or can be bought and stored near farms where they can be recharged and maintained. After the surveys, drones need to be taken to nearby labs to analyse the data that has been collected, thereby helping leverage IoT in agriculture better.

v Blockchain: Blockchain can create transparency in a sector that's often failed to capture consumer confidence. Blockchain represents an opportunity for the food industry to regain its high ground. It is seen as a tool to address consumer concerns about provenance and food safety.

vi. Data Analytics: The power of data analytics is being used to unleash meaningful new insights for farmers and food producers.

vii. Cloud Connectivity: Cloud-based computing services use real-time connections to the internet to offer more flexible resources and economies of scale than available with conventional server-based or even edge options. The requirement for connectivity especially 5G represents a genuine challenge when many farms are yet to be connected. Governments understand that if farming is to be revolutionized, addressing connectivity is essential. Without it, the rural-urban divide will be exacerbated.

viii. Robotics in Agriculture: with increasing demand and shortage of labour across the globe, agriculture robots or commonly known as agribots are starting to gain attention among the farmers. Recent advancements in sensors and AI technology that lets machines train on their surroundings have made agrobots more notable. We are still in the early stages of an ag-robotics revolution, harnessing the full potential of the IoT in agriculture, with most of the products still in early trial phases and R&D mode.

ix. Computer Imaging: Computer imaging involves the use of sensor cameras installed at different corners of the farm or drones equipped with cameras to produce images that undergo digital image processing. Digital image processing is the basic concept of processing an input image using computer algorithms. Image processing views the images in different spectral intensities such as infrared, compares the images obtained over a period of time, and detects anomalies, thus analyzing limiting factors and helping a better management of farms.

x. AI in Digital Agriculture: One of the most significant contributions of artificial intelligence (AI) in agriculture is precision farming. By harnessing data from satellites, drones, sensors and IoT devices, farmers can obtain real-time insights into soil health, weather patterns, crop growth, and pest infestations. This enables them to optimize resource usage, minimize wastage, and make informed decisions regarding irrigation, fertilization, and crop protection.

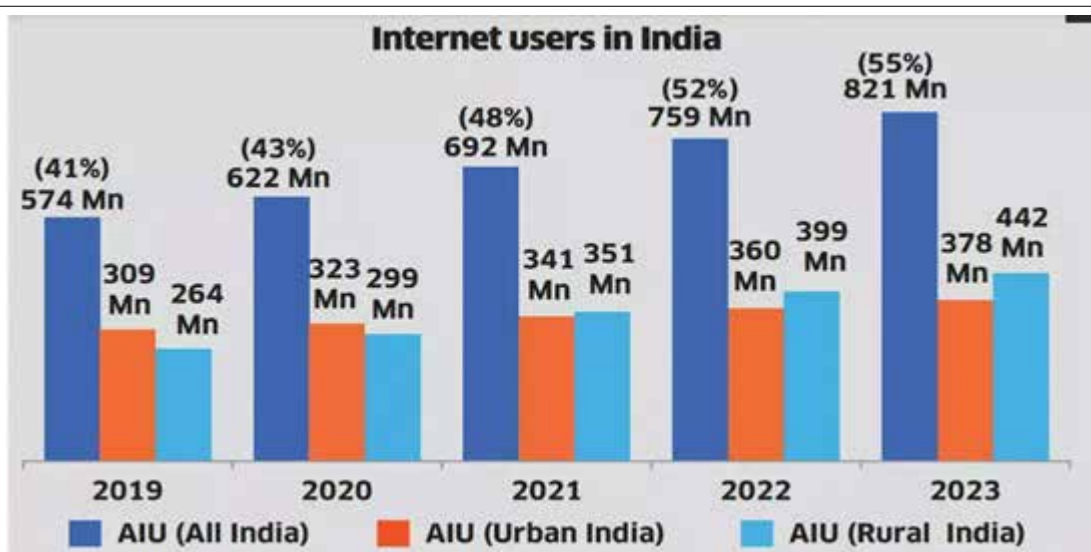


Figure 1. Internet users in India (Source : Internet in India Report 2023 by Internet and Mobile Association of India (IMAI) and KANTAR)

AI-powered predictive analytics further empower farmers to anticipate market trends, mitigate risks, and maximize yields, thereby enhancing profitability and sustainability. India has a rich history of agricultural prowess, with the Green Revolution of the 1960s drastically boosting food production and alleviating hunger. However, sustainability of these practices has come under scrutiny due to issues such as soil degradation, water scarcity, and chemical dependency. To address these challenges and ensure food security for future generations, it is imperative to leverage cutting-edge technologies like AI and big data analytics.

Digital Agriculture Initiatives in India

Digital agriculture, which encompasses the use of technology and data-driven solutions to enhance agricultural practices, is rapidly transforming farming worldwide. In India, this transformation is gaining momentum. As of 2023, approximately 30% Indian farmers have adopted some form of digital technology in their agricultural practices. Despite being a global agricultural powerhouse, India's agriculture sector is plagued by inefficiencies and challenges that hinder its potential. Adoption of digital technologies can address these issues by enhancing productivity, optimizing resource use. Use of internet users in the country is on rise in rural areas and the data given in **Figure 1** supports the growth in digital revaluation.

India's agricultural sector is undergoing a significant transformation with the integration of digital technologies. The Digital Agriculture Mission 2021–2025 aims to modernise agriculture through advanced technologies like AI, remote sensing, drones, etc.

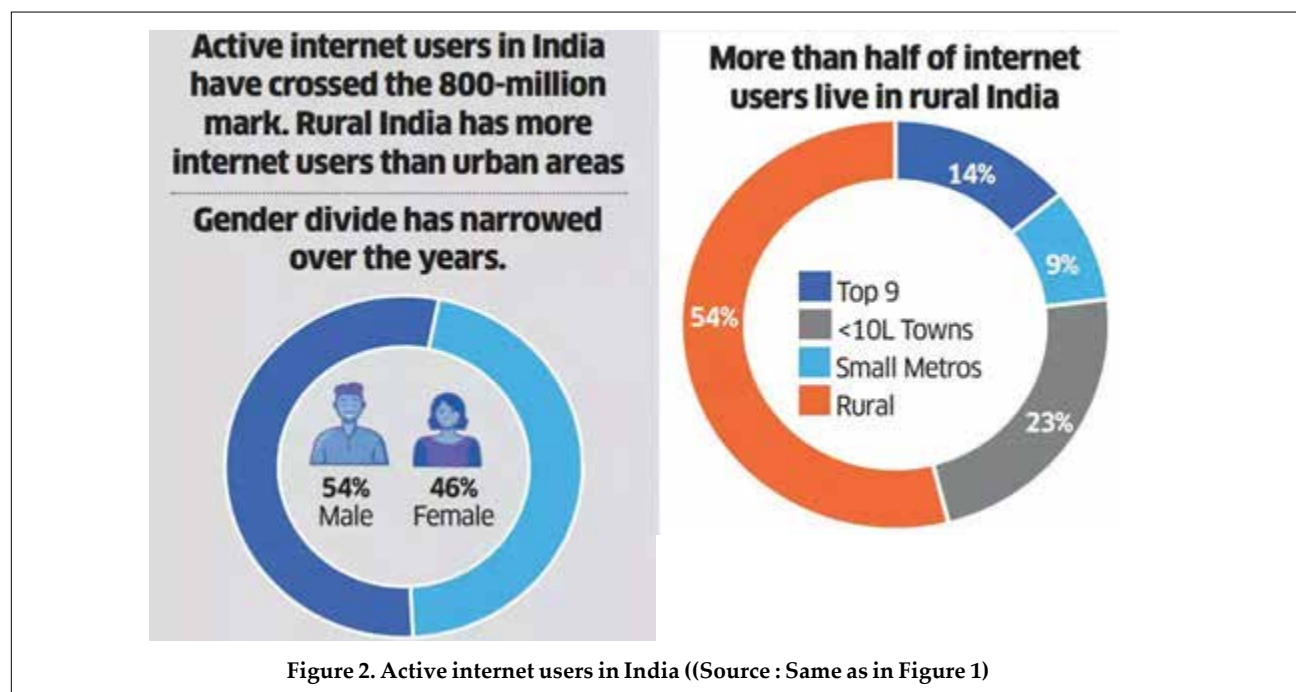
Further, as per the Budget Announcement for 2023–24, the Government has taken various initiatives to build Digital Public Infrastructure (DPI) for agriculture as an open source, open standard and interoperable public good. DPI will enable inclusive, farmer-centric solutions through relevant information services for crop planning and health, improved access to farm inputs, credit, and insurance, help for crop estimation, market intelligence, and support for growth of agri-tech industry and start-ups (Economic Survey, 2024).

Agri Stack is one of the prominent DPIs with three foundational registries (databases) i.e. farmers' registry/database, geo-referenced village maps and the crop sown registry/ database, along with several support registries/databases. Three foundational registries will enable digitally authenticable identities and non-repudiable digital assets for the farmer in the form of farmer IDs, geo-tagged farm plots and crop-sown data. Internet users are more in rural area compared to urban areas (**Figure 2**) which support having lot of scope of using advanced farming through digital gadgets.

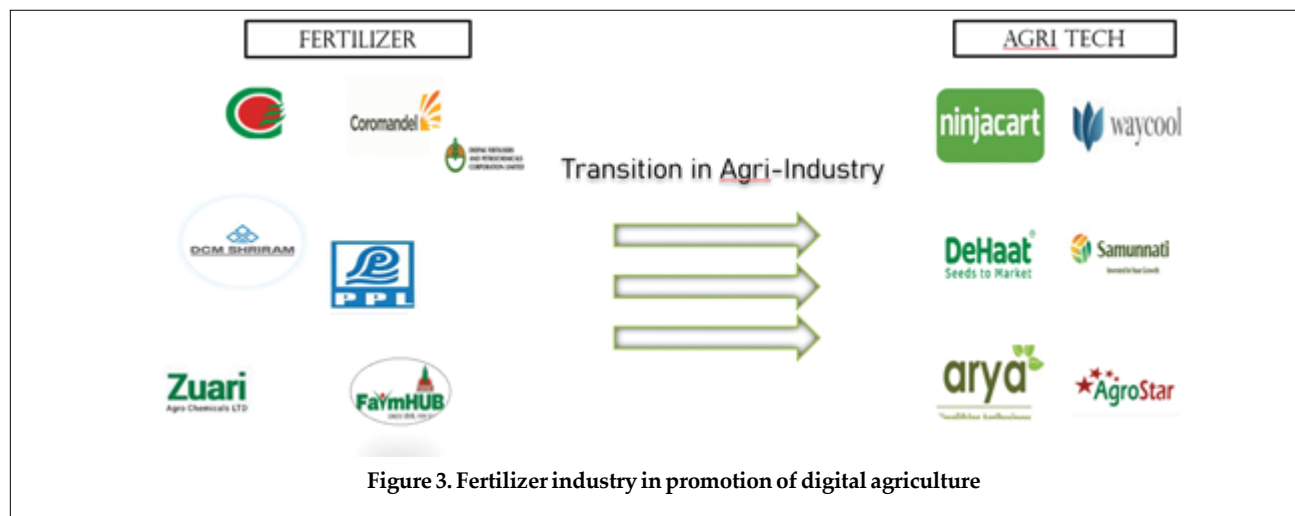
India has taken significant steps to embrace digital advancements in agriculture, aiming to revolutionize the farming landscape. The government introduced the 'India Digital Ecosystem of Agriculture' plan, centered around 'AgriStack,' a collection of technology-based interventions serving as the foundation for sector digitalization (Garg, 2021).

Major Initiatives

Public as well as private sector in India have taken up several initiatives to evolve innovative and required digital support to farm sector.



- ◆ The Krishi Decision Support System (Krishi-DSS) is another DPI, which aims to integrate and store in a standardized form relevant geospatial and non-geospatial data, such as remote-sensing data, weather data, soil data, crop signature library, reservoir data, groundwater data, and data pertaining to Government schemes.
 - ◆ The Digital Agriculture Mission 2021–2025 aims to encourage and speed up projects based on innovative technologies, including AI, blockchain, remote sensing, robots, and drones.
 - ◆ Over 1,000 agri-tech start-ups are based in India, and various venture capital funds, loan funds, and angel investors have long supported the sector. These start-ups have innovative ideas that assist farmers in improving farming techniques and produce.
 - ◆ To provide farmers with real-time data and the necessary advice, NITI Aayog has teamed up with International Business Machines (IBM) to create a crop production forecast model supported by AI. It aids in enhancing crop output, soil quality, agricultural input control, and early disease outbreak warning.
 - ◆ In August 2019, Cisco created an Agricultural Digital Infrastructure (ADI) solution to improve farming and knowledge exchange. This played an essential role in the data pool that the Department of Agriculture developed under the National Agri Stack.
 - ◆ The Jio Agri (Jio Krishi) platform was introduced in February 2020, and it digitalised the agricultural ecosystem along the entire value chain to empower farmers. The platform's primary function leverages data from standalone applications to offer counsel. Advanced features of it use data from various sources, input it into AI algorithms, and then deliver precise, individualised advice.
 - ◆ India is gradually embracing climate-smart farming methods, which will assist in altering the country's ecology and cutting greenhouse gas emissions from agricultural activities. For instance, the farmers in Gujarat's Dhundi village have begun employing solar electricity and other sustainable energy sources for irrigation.
 - ◆ Microsoft and the Indian government have teamed up to support India's small-holder farmers by running a pilot programme called 'Unified Farmer Services Interface'. The alliance aims to boost farmers' incomes through improved price management and increased agricultural yield using AI sensors. The collaboration would accelerate the use of AI in farming.
 - ◆ Six institutions are a part of the government's Sensor-based Smart Agriculture (SENSAGRI) programme. Drones would be utilised in this concept to scout over land areas efficiently, acquire priceless information, and instantly communicate the data to farmers.
 - ◆ The Government is also encouraging AI to revolutionise agricultural and farming trends and giving financial support to agri-tech firms.
- India is continually working to develop and



implement regulations that would improve the sustainability of its agricultural industry. Partnerships between corporations and the government can aid in developing a smart agriculture industry, given India's dynamic corporate structure. Digital marketplaces have become the predominant investment in digital agriculture technologies, overshadowing other offerings and reinforcing a disconnect between digital projects and rural needs (Roy, 2024). To reach goals like doubling farmer incomes and sustainable growth, the Indian government is undertaking these initiatives and programmes. The widespread adoption of digital agriculture in India would, therefore, require a multi-stakeholder strategy in which the government plays a significant enabler's role in the ecosystem.

Digital Technologies Critical for Precision Agriculture

GPS: It plays a pivotal role in capturing real-time data about the location and conditions of a farm to enable traceability and related operations.

Remote Sensing: Remote sensing is the process of acquiring information related to Earth's surface by measuring its reflected and emitted radiation without coming into direct contact with the object. Remote sensing techniques are applied to explore agricultural applications such as crop discrimination, crop acreage estimation, crop condition assessment, soil moisture estimation, yield estimation, precision agriculture, soil survey, agriculture water management, agro-meteorological and agro-advisories.

GIS: It combines GPS data with maps and other spatial information to view a farm's terrain and crop conditions

Variable Rate Technology: It enables customized application of fertilizers, agro-chemicals, etc. based on the needs of different areas of a field.

Soil Sensors : It monitors soil moisture, nitrogen levels, and other elements that promote crop growth

Crop Sensors: Crop sensors can measure aspects of plant health, such as chlorophyll levels and canopy temperature

Big Data Analytics: Information from different sources, such as weather patterns, crop yields, and market demands can be synthesized to provide insights for making decisions.

Fertilizer industries are also working on above digital technologies to gear up reaching to farmers digitally and making profitable agriculture.

Fertilizer Industry in Promotion of Digital Agriculture in India

Fertilizer Industry is promoting digital agriculture in India and the get the benefits of digital agriculture that is implementing these technological solutions enable reliable management and monitoring of farms (Figure 3). As farmers get a complete digital analysis of farms in real-time, they can act accordingly and do not have to apply excess pesticides, fertilizers and reduce overall water consumption.

Other major benefits include increase in agriculture productivity and lower production cost; inhibition in soil degradation; application of fertilizers in balanced proportion based on requirement and minimization of use of pesticides in crop production by promoting residue free farming; and promotion of effective and efficient use of water resources to uplifts socio-economic status of the farmers. Use of digital technology will reduce environmental and ecological impacts.

Zuari Farmhub Limited

In line with the objective of reaching the rural population more effectively and efficiently, Zuari

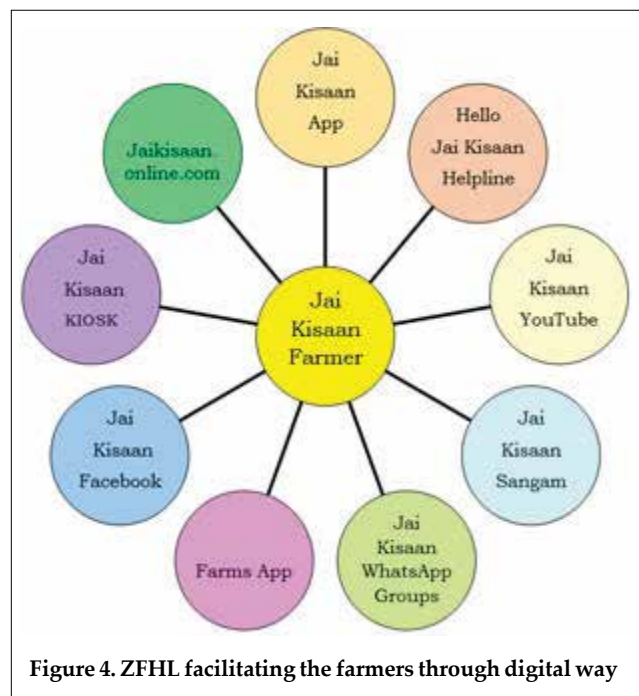


Figure 4. ZFHL facilitating the farmers through digital way

Farmhub Limited (ZFHL) has strategically embraced digital solutions. ZFHL has adopted various digital tools to provide need-based information to support the farming community throughout the agricultural cycle, from sowing to post-harvest technology and marketing. Future of digital agriculture looks promising in terms of increased farm mechanization and smart application of agri-inputs, and development of digital agriculture infrastructure expected to drive further adoption among farmers.

Present days of agriculture highlight the importance of digital agriculture, as it addresses challenges such as labour shortages, shifts in consumer preferences for food safety and quality, and disruptions in the supply chain. Overall, the impact of the pandemic is estimated to be positive, encouraging the global expansion of digital agriculture. ZFHL is intensively using digital tools for technology dissemination (Figure 4).

ZFHL Interventions in Digital Agronomy

- Village-wise soil fertility maps are developed, enabling the farmers to refer these maps for their soil health and sharing soil test recommendations through WhatsApp immediately after analysis along with recommendation for the crop
- Farmers are digitally connected for multi agri-solutions through Jai Kisaan App and Jai Kisaan Chatbot
- Farmers connect-Hello Jai Kisaan Help line and Jai Kisaan Kiosk Video connect.

- Connecting farmers through social media and Jai Kisaan App
- Sampoorna Solutions need-based weekly video through Farms App
- Sensor based tools, space imaginary, drone, surveillance bended support through digital agronomy.
- ZFHL manages 40 hectares of farm through Farms App, and completely monitors all farm operations, inputs and farm management.
- Farmers can interact with subject matter specialists through Jai Kisan Kiosk as shown live in Photo 1.

Sensor-based Tools, Space Imaginary, Drone, Surveillance-bended Support

ZFHL is working jointly with Israeli company CropX on Pilot scale and 25 sensors are installed at farmers' fields and at Adventz Agri Innovation centre. These soil sensors help in measuring soil moisture and help the farmers manage their irrigation systems more efficiently. Knowing the exact soil moisture conditions of their fields, farmers are able to generally use less water to grow a crop, enabling them to increase crop yields of better quality by improved management of soil moisture during critical plant growth stages. Efficient irrigation management can improve yields, grain quality, conserve water and energy, and reduce nutrient leaching. One of the easiest and most effective ways to improve irrigation efficiency is to implement soil sensor technology in irrigation scheduling.

For irrigation scheduling, it is important to understand the soil water content at which a crop begins to experience stress. In general, most crops begin to experience stress when soil water depletion/deficit is 30-50% of available water holding capacity. This is called management allowable depletion or irrigation trigger point. Quantification of soil water content is necessary for a variety of applications ranging from large-scale calibration of global climate models to field monitoring in agricultural and horticultural systems. A soil moisture sensor is a type of sensor used to measure the volumetric water



Photo 1. Farmer interacting with crop doctor

content of the soil. The main advantage of using soil moisture sensors to plan irrigation is more efficient water usage, thus reducing water consumption while allowing plant roots to grow deeper and avoiding over watering thereby reduced nutrient leaching in the root zone. Less water use can be modified to lower and higher thresholds to preserve ideal soil moisture saturation and reduce plant withering. An automatic watering mechanism can be set in motion with the aid of the sensor to water the crops whenever the soil moisture fails below a certain threshold.

CropX aggregates data from in and around the farm and transforms it into useful information to help farmers monitor the health of fields and crops. Information is easy to access and provides a holistic overview of the field conditions. It can help the farmers in savings of fertilizer, water and fungicides up to 20%, 50% and 20%, respectively, and also resulting in increase of crop yields up to 15%. It also results in reduction of farm management labour and saving of machine operation costs, and automatically imports real-time data from soil sensors, satellites, farm machinery, and other sources. This makes it easy to gather and manage all the data. With curated field data, histograms and statistics, it is able to quickly see direct insight into a variety of information about the fields: soil type, NDVI, SAVI, soil moisture index, insights and advice for irrigation, disease, nutrition and effluent management activities. Tracking and reporting activities are key for transparency in the agricultural supply chain and create additional value, such as providing consumers with low-carbon certified options or sharing best practices across large operations.

Insights of Soil Sensors: All in one device and easy to install having multiple soil measurements with physical robustness and agronomic insights, irrigation management, early control of pests and diseases and monitor nutrition with multiple depth measurements

Farms App ZFHL E-Com Platform: To meet the growing demand and bridge the demand-supply gap, ZFHL sells its speciality fertilizers and crop care products through an e-commerce portal called Farms App, delivering the products to farmers' doorsteps in 18 hrs with zero delivery charges with the help of India Post. The farms App accepts Agri-input in local languages and receives orders from all over the country (Postal pin codes).

Fertilizer Industry is a major contributor to the growth and development of Indian agriculture. All major fertilizer players have adopted digitalization for enhancing efficiency in production, evaluation and dissemination of new technologies and agronomic practices. The salient areas of transforming Indian agriculture by four other companies are also given.

To enhance agricultural productivity and efficiency, IFFCO employs AI-enabled drones, AI imaging technology and cloud computing. These innovations are revolutionizing farming practices by providing data-driven insights and enabling precision agriculture techniques. IFFCO has deployed 800 AI-powered drones to efficiently spray foliar plant fertilizers in small and medium-sized fields, covering almost 125 locations with more than 2,000 farmers at each location, as of February 2024. To meet the growing demand of the farmers for the specialty fertilizers, IFFCO sells its fertilizers through an e-commerce portal called IFFCO Bazaar, delivering products to farmers' doorsteps in the shortest time with zero delivery charges. The portal accepts input in 12 Indian languages and receives orders from all over the country (26,000 pin codes).

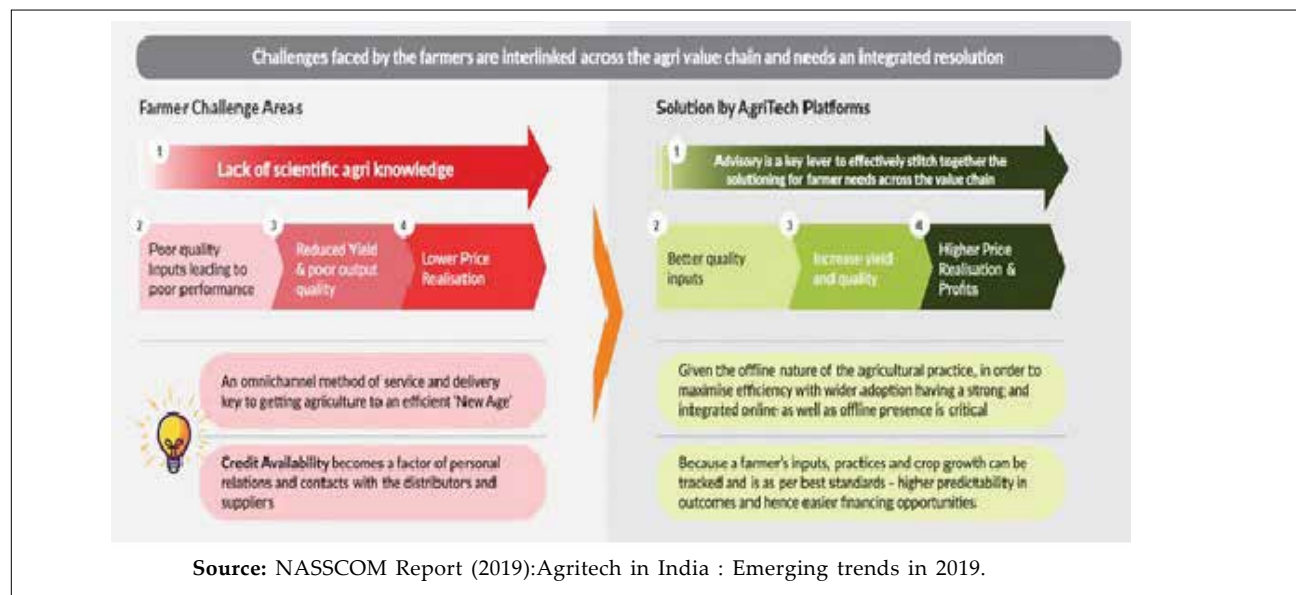
Coromandel International Limited has set up hi-tech poly house at its R&D Farm in Telangana to promote precision agriculture and accelerating innovation in new product development. Advanced field trials of innovative range of agri-inputs and solutions are conducted by use of latest technologies. Company has made foray into drone-based services having Dhaksha - one of the few differentiated players in drone technology and manufacturing in India, in its fold.

Chambal Fertilisers and Chemicals Limited launched uttamkrishi.com, a dedicated interactive website in Hindi, for the benefit of the farming community. It has a bottom-up approach to farming solutions as the website has been designed region-wise to address the local issues. Useful information on crops and agronomy are posted on the website. Farmers can access the information without any charge and can post queries, which are answered by company's experts.

Considering digitization a key to cultivating a competitive edge, enabling faster transitions from product testing and development to registration and sales, Mahadhan AgriTech Limited has adopted the tech solution in collaboration with Agmatix and successfully reduced their time to collate, verify, and analyse agronomic data. Such interventions are advancing sustainable agriculture and enabling higher yields by continually developing their products in smart and efficient ways.

Challenges and Opportunities

The boom of digital evolution in agriculture is still a long-held ambition and emerging technology must be engaged as a solution to all the radical problems of our farmlands. Consequently, it will aid to double the farmers' income and enhance crop production. Many challenges and opportunities are made possible for Indian agriculture to be technically transformed by giving boost to AgriTech platforms in improving crop yields per hectare of land (**Figure 5**).



In the wake of environmental challenges and the pressing need for sustainable agricultural practices, India stands at a pivotal juncture where technological innovation can pave the way for a transformative shift. AI and data-driven solutions can offer unprecedented opportunities to revolutionize India's agricultural landscape, ushering in a new era of productivity, sustainability, and resilience. In addition to enhancing agricultural productivity, AI and data analytics can play a crucial role in natural resource management and environmental conservation. By analyzing satellite imagery and geospatial data, policymakers can monitor deforestation, land degradation, and water pollution in real-time, enabling proactive interventions to preserve ecosystems and biodiversity. Furthermore, AI-powered models can optimize the allocation of water resources, facilitate afforestation efforts and mitigate the impacts of climate change on agriculture, thereby fostering resilience and adaptation in the face of evolving environmental challenges. Farmers also see opportunities presented by digitizing in the simplification of forecast, farm operation, market link, etc., Digitization can mean additional value creation for farms and it can contribute to improving farm productivity and income on regular basis.

Conclusion

Agri Tech is the future of farming, Digital interventions such as smart farming and precision agriculture are helping to improve the output of conventional agricultural systems and drive them towards efficiency and sustainability. This digitalised Green Revolution is strengthening farmers in terms of farm management by improving crop yield, pest control, soil health and mitigating climate risks. However, implementing these innovative technologies

is permeated by challenges and obstacles. For that, more scientific approach is required, advanced Agri Research needs to be focused and the newer agriculture technologies in precision agriculture should be farmers friendly and affordable to them so as to have reasonable prices. The data-driven technologies like remote sensing, smart sensors, and IoT-based devices constructed over AI/ML algorithms should be fundamental aspect of new age agriculture assisting farmers with critical decision-making. India has taken significant steps to embrace digital advancements in agriculture for doubling the farm income. India is coming forward to make it a farmers' slogan.

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Digital Agriculture

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Abstract

Digital tools and technologies have now been in use in agriculture to make Indian farming more resilient, profitable and sustainable. There are challenges in adoption of digital technologies in agriculture. However, there are opportunities which need to be tapped. Government of India has started laying lot of emphasis by approving Digital Agriculture Mission. The mission will bring the benefits of India's digital revolution to the agriculture sector, transforming it into a more efficient, transparent and farmer centric industry. Realizing the need, Indian Potash Limited has developed a mobile app in the name of IPL farmer samvad app and various need-based information related to agriculture are transmitted to farmers to improve their income. Farmers have started taking advantage of the same. In this paper, various areas of digital agriculture and IPL app have been discussed.

Key words: Digital agriculture, tools, mobile app, IPL efforts, Government initiatives, challenges, opportunities, benefits

Introduction

Global population is expected to increase to 9.6 billion by 2050 that lead to significant increase in the demand for food. At the same time, availability of precious natural resources like freshwater and productive arable land has been shrinking over the years. About 821 million people still suffer from hunger. If the UN Sustainable Development Goal of World with Zero Hunger by 2030 has to be achieved, then more productive, efficient, sustainable, inclusive, transparent, and resilient food systems are prerequisites (FAO 2021). The best ways to achieve sustainable agricultural development are to continue the process of innovation using contemporary genetic and information technologies to increase agricultural productivity while balancing economic, environmental, and social outcomes related to food and agricultural systems (Basso and Antle, 2020). Moreover, losses from farm to fork in the form of food waste can reach as high as 40% due to extended supply chains (Rozenstein et al., 2024). Several researchers have proved that the technological advancement in agriculture using new digital tools and technologies such as artificial intelligence (AI), drones, data analytics, remote sensing, sensors and cloud connectivity, etc. significantly increased the production efficiency and profitability along with potential to save precious natural resources and production cost to make the Indian farming more resilient, profitable and sustainable. Currently, emerging digital technologies have the potential to be the game-changers for traditional agriculture practices. These changes are popularly known as Agriculture 4.0, indicating its role as the fourth major agriculture revolution. The Government of India has approved the groundbreaking Digital Agriculture Mission, with a financial outlay of Rs. 2,817

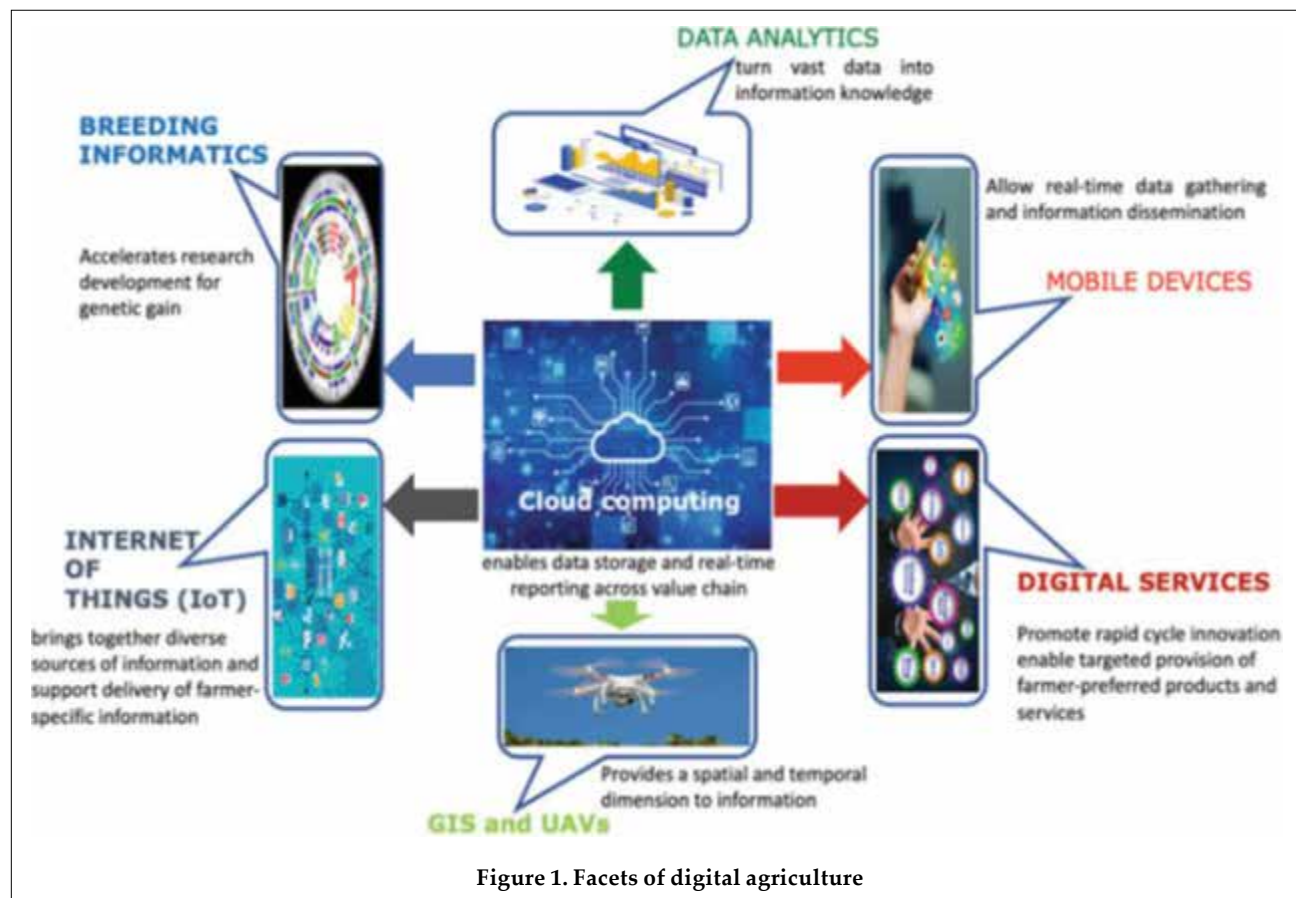
crore, including a central government share of Rs. 1,940 crore. This mission is poised to bring the benefits of India's digital revolution to the agriculture sector, transforming it into a more efficient, transparent and farmer-centric industry. Three main digital public infrastructures to be developed under this mission are AgriStack, the Krishi Decision Support System (DSS), and Soil Profile Mapping. These components will enable integration of data on farmers, crops, soil, and weather into a comprehensive digital framework, enhancing decision-making and service delivery.

Digital agriculture has the motto to make farming profitable and sustainable through using information-cum-communication technologies and data science, ensuring food and nutrition security, farm profitability and clean environmental under changing climate scenarios (Priyadarshan et al., 2024).

Facets of Digital Agriculture

In modern agriculture, advanced machines are used wherein agriculture economy ushered new heights. Current agriculture realizes information through digitalization. It integrates data collection, data transmission, data processing, digital control machinery, network and automation. These processes are coordinated by cloud computing with its various facets of digital agriculture. Cloud computing is the delivery of computing services including servers, storage, databases, networking, software, analytics and intelligence over the internet (the cloud) to offer faster innovation, flexible resources and economies of scale. Facets of digital agriculture-based on cloud are given in **Figure 1**.

- i. **Breeding Bio-informatics:** A modern breeding programme with advanced phenotyping and



genotyping technologies has the potential to create vast amounts of data and converts such data into valuable information in a time-sensitive manner.

- ii. **Data Analytics:** It is the process of exploring and analyzing large datasets to find hidden patterns, unseen trends, discover correlations and derive valuable insights to make predictions. It improves the speed and efficiency of agriculture operations.
- iii. **Mobile Devices (Smart Phones):** Equipped with various sensors are opening new opportunities for rural farmers who previously had limited access to up-to-date agriculture information like market, weather and crop disease news.
- iv. **Digital Services:** It refers to the electronic transfer of information including data and content across numerous platforms and devices like web or mobile.
- v. **Geographic Information System (GIS):** It is a computer system that analyzes and displays geographically referenced information. It uses data that is attached to a unique location. GIS is being merged with unmanned aerial vehicles (UAVs) to plan, construct and implement various agriculture practices.
- vi. **Internet of Things :** It describes the network of physical objects (things) that are embedded with

sensors, software and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet.

Tools and Technologies for Digital Agriculture

Robotics: From drones to autonomous tractors to robotic arms, the technology is being deployed in creative and innovative applications. The use of robotics can improve efficiency and productivity while reduce waste in agriculture activities.

Internet of Things and Sensors: IoT is utility of internet for various operational purposes. IoT becomes operational through sensors. Sensors are devices that detect and respond to changes in an environment. Inputs can come from a variety of sources such as light, temperature, motion and pressure. Sensors provide valuable information through a network and they can share data with other management component of system. The output of the sensor is a signal which is converted in to human-readable form such as characteristics, resistance, capacitance, impedance, etc.

Artificial Intelligence: The term intelligence refers to the capacity for knowledge, reasoning, abstraction and inference of meaning. The advancement of AI in

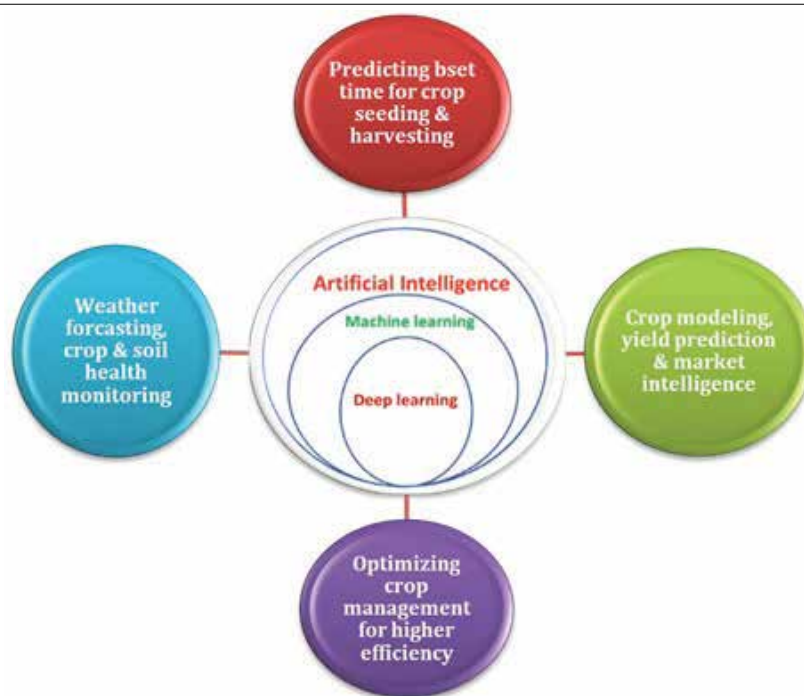


Figure 2. Role of artificial intelligence in agriculture

the past decade has offered great potential to augment the climate smart agriculture. AI plays a vital role in integrating and handling the huge data by conducting correlation studies to identify genomic targets associated with disease response traits. Role of AI in agriculture has been depicted in **Figure 2**. The tools including machine learning (ML), deep learning (DL) and predictive analysis can help in the analysis of big datasets to extract useful information about traits and their correlations of plant responses to stress conditions. The Ministry of Agriculture & Farmers Welfare, Government of India has employed AI methods to address various challenges in the agriculture sectors. Some of the initiatives are given below:

- ♦ *Kisan e-Mitra*, an AI-powered chatbot, assists farmers with queries about the PM Kisan Samman Nidhi Scheme. This solution supports multiple languages and is evolving to assist with other government programmes.
- ♦ National Pest Surveillance System tracks the loss of produce due to climate change. This system utilizes AI and ML to detect crop issues, enabling timely intervention for optimum management.
- ♦ AI based analytics has been using field photographs for crop health assessment and monitoring using satellite, weather & soil moisture datasets for rice and wheat crop.
- ♦ AI algorithms enable autonomous crop

management. When combined with IoT sensors that monitor soil moisture levels and weather conditions, algorithms can decide in real-time how much water to provide to crops.

Deep Learning : It is simply a neural network with three or more layers and is a subset of machine learning. These neural networks make an effort to mimic how the human brain functions; however, they fall far short of being able to match it, enabling it to learn from vast volumes of data. Additional hidden layers can help to optimize and refine for accuracy even if a neural network with only one layer can still make approximate predictions

Drones and Satellites: The drones record data in real-time, they lack the hard drives necessary to store the vast amounts of digital data that satellites are designed to hold until they can be recovered and used. In order to provide more accurate measurements on a particular location, drones can also use GPS.

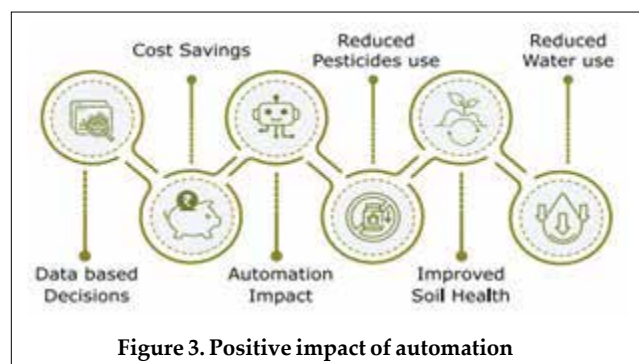
Blockchain: It ensures transparency and traceability in the supply chain, block-chain can help farmers secure better prices and reduce fraud. This technology builds trust among consumers and producers.

Data Analytics: Analyzing data collections to identify trends and make judgments about the information they contain is known as data analytics. Data analytics is increasingly carried out with the use of specialized hardware and software.

Cloud Connectivity: The capacity to connect two resources within a cloud, across clouds, and with on-premises data centers is called cloud networking. A cloud service provider must offer three main forms of connectivity: site-to-cloud, the connection between cloud resources, and on-premises hardware.

Automation: Automation can be achieved through implementation of the IoT. It is a network of physical items that are equipped with sensors, software and other technologies. These things are able to share real-time data with other linked devices and systems through networks because they are connected to the internet. With the development of agricultural sensor, wireless communication, cloud computing, machine learning and big data technologies, IoT technology has grown and is progressively being promoted and used in the field of protected agriculture. It is playing an important role in many areas of protected agriculture due to its capacity to help farmers test soil quality, climatic change, and crop health. Moreover, IoT system's cameras can capture crop diseases & insect-pests in the greenhouse in real-time, helping farmers to spot problems and use preventative measures into place. Super market managers use their computer or smartphone to monitor and forecast product status and demand in order to get things on the shelves. Users and customers can obtain details on the variety, origin, processing and other features of agricultural products by utilizing a QR code, barcode, etc.

Positive impact of automation in agriculture is illustrated in **Figure 3**.



e-commerce Software: This software gives the ability to sell the goods and services online. The front end, which is the website, makes it simple for customers to make purchases, while the back end allows to streamline all procedures from inventory to sales.

Farmers' Chatbots: The conversational virtual assistants using AI that automate conversations with farmers are known as chatbots. With the use of AI-powered chatbots, one can now understand natural language and communicate with users more personally. In agriculture also, this facility is in use and supporting the farmers in receiving answers to

their unanswered queries and providing recommendations as well.

Mobile-based Application: Agriculture mobile applications potentially deliver timely information to different subscribers such as farmers, traders and producers. The information delivered includes weather, rainfall, while some applications also help update the market data of commodity prices and facilitate the local buying / selling via hand held devices. Mobile apps are helping to boost overall business performance and reducing negative environmental impacts of farming. The main advantages of mobile apps for farmers are that they give timely information in response to the farmer's specific needs. Farmers can interact and get guidance from agriculture experts across the country via apps. Every knowledge related to crop and farming from sowing to harvesting stage is imparted to farmers for improving their farm productivity. Apart from this, farmers can also see nearby weather information and market prices, and warnings are also given in connection with aberrant weather conditions.

The mobile apps are working as a boon for farmers and transforming agriculture but still they have some gaps which need to be addressed. Either farmers are unaware about the app or they have very limited users, because most of them are not user friendly. Only few apps work at the ground level. Many applications are not in local which become a hindrance in the use of such apps. It has also been observed that most of the applications are area specific. Therefore, all farmers can not utilize the benefits of the application.

Efforts of Indian Potash Limited in Development of Mobile App

Indian Potash Limited (IPL) has developed a unique mobile app for the farmers viz; IPL farmer samvad mobile application (**Photo 1**).

IPL farmer samvad app is integrated with grassroots nurturing system (GNS) which is a comprehensive IT platform that can help manage grassroots-level samvad champ orchestration as well as targeted micro-communication, people connect programmes





Figure 4. GNS functional capabilities

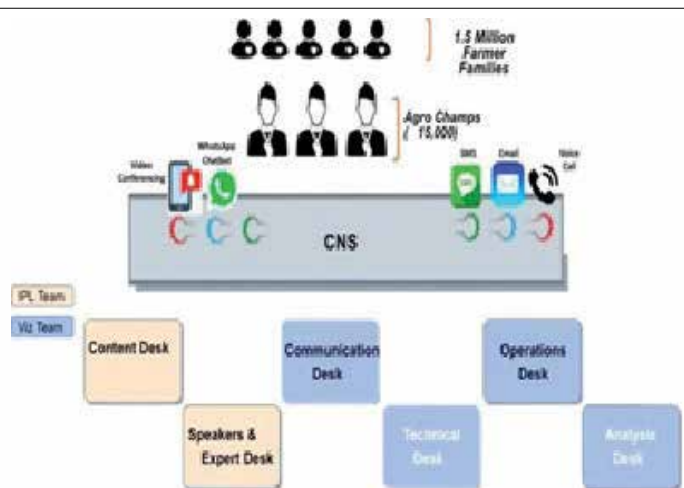


Figure 5. Component and execution model of GNS

including physical door-to-door meetups and digital video-conferencing programmes. GNS builds and nurtures a private social network, creating a matrix of samvad champs, their friends & families, and supporters with several modes of communication like an SMS gateway, voice calls, whatsapp & video conferencing facilities. Targeted multi-touchpoint engagements can be driven with the champs. GNS functional capabilities (Figure 4) and component of executive model (Figure 5) are given.

Content of IPL Farmer Samvad App

- i. **General Content (34 Crops)** : This includes pre-sowing to post harvest practices of a crop.
- ii. **Weekly Content (16 Crops)** : It includes week-based practices of a crop for better understanding and better farming.
- iii. **Stage-wise Content (12 Crops)** : It includes crop growth stage-wise practices for better enhancement of a crop and to provide farmer a good and deep knowledge.

Onboarding on Samvad App

- i. **Agri-expert: 50** : IPL has subject-matter experts for various crops and they do live video conferencing with farmers for clearing their doubts about their crops.
- ii. **Agritech Startups: 30 +** : In this section, farmer take information about the ongoing agricultural technologies and also get to know about the benefits of such technologies.
- iii. **Career: 10 +** : This section is built for farmers' families, especially for their children, who are preparing for any exam or engage in sports, etc. In this section, they get to know the latest information in their field by the field experts.

Key Engagements for Farmer Awareness

- ◆ Sending invitations through SMS, OBD/voice calls, or whatsapp audio/video messages to download IPL farmer samvad app.
- ◆ Sending invitation through SMS, OBD/voice calls, or whatsapp audio/video message for participation in video conferencing sessions for crop management-related sessions, awards & recognition programmes, and aspirational sessions by role models.
- ◆ Sending video conferencing session invitations by samvad champs through SMS or whatsapp audio/video message.

Online Events

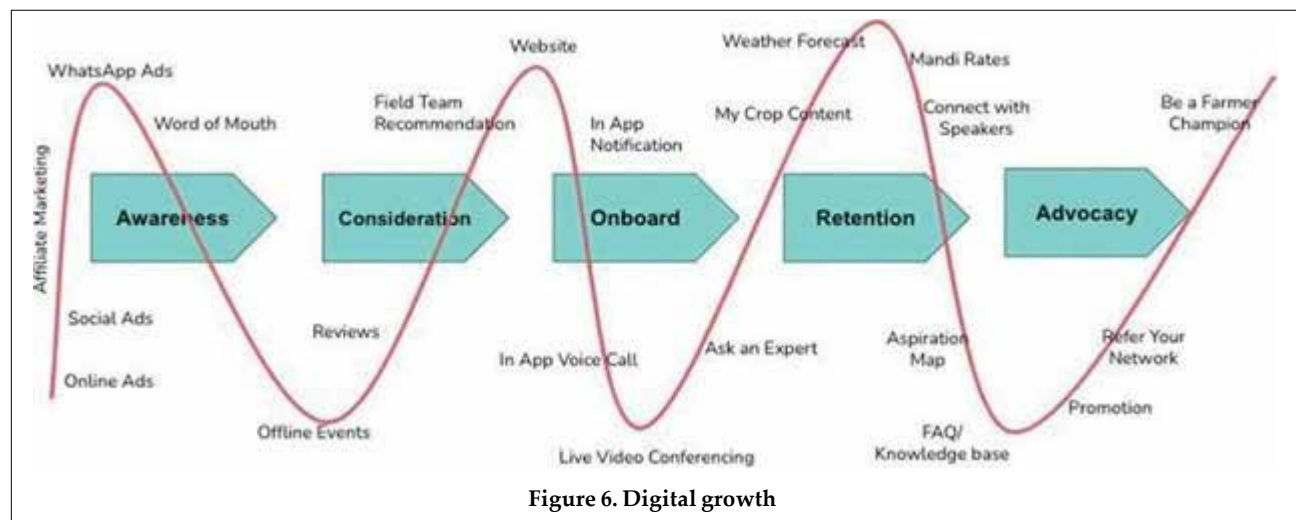
Video conferencing is a special event in our IPL farmer samvad app. It brings close interaction of farmers with the special experts of their fields and get new information related to their interest or ask questions with the experts through online mode. Every farmer can join who has downloaded the app.

Benefits of VCs

- ◆ 2-way interaction with the experts.
- ◆ Ask questions and get answers right away.
- ◆ Get updated by any upcoming technology, crop related knowledge.
- ◆ Many farmers can join at one time.

Till date, we have done total number of 200 VCs through the farmer samvad app.

Live mandi rates and weather forecast (7 days) are also part of the app for benefit of the farmers.



Farmer Engagement Journey

The engagement of the farmers towards digital journey of the IPL in connection with awareness, consideration on board, retention and advocacy is depicted in **Figure 6**.

There are 30,251 active users, 373 my crops and 578 queries related to the app are given in **Figure 7**.

User Acquisition

The layout, features, farmer onboarding signup login-profiting and programme information of the app are enumerated in **Figure 8**. Farmers awareness activities on digital agriculture are given in **Photo 2**.

Challenges and Opportunities

No doubt, there are challenges in taking digital agriculture for use by the farmers, however, there are opportunities to tap the same as given in **Table 1**.

Strengthening Digital Technologies for Sustainable Agriculture

- ♦ Realizing full coverage of communication networks

in rural areas; improve the construction of digital infrastructure in rural areas.

- ♦ Financial support for application of green & clean technologies.
- ♦ Promote the relevant knowledge to farmers in the field of e-commerce and to increase their entrepreneurial skills and innovative capacity, which will help to broaden their income channels.
- ♦ Investment in research and development of digitized, low-threshold, high-efficiency and green planting technologies.
- ♦ Develop inter-country, inter-regional communication, and bridging digital technology barriers so that, more people can participate in digitalization and work together to promote sustainable human civilization.
- ♦ Strengthen the digital extension programme with a vision to transform India into a digitally empowered farming community. Various projects



Figure 7. Success of IPL farmers samvad

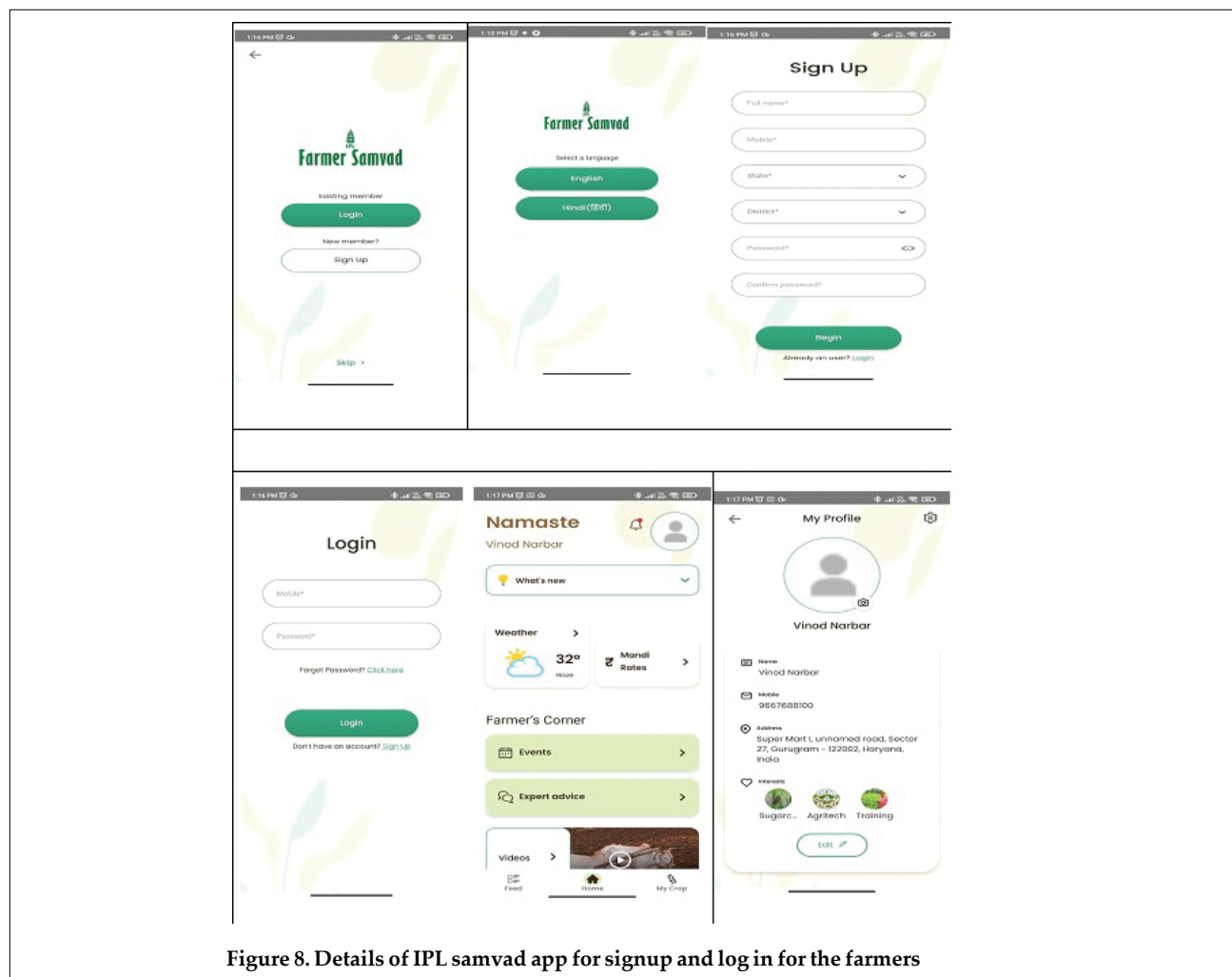


Figure 8. Details of IPL samvad app for signup and log in for the farmers

e.g. open data, soil health card, *mKisan* (*mFarmer*), farmer portal, agri-market app etc. have been launched for the farmers. Other programmes e.g. *KisanSuvidha*, *e-PusaKrishi*, *AgriApp*, *KrishiGyan*, *Agropedia*, *e-krishi*, *e-chaopal*, etc. based on digital information for farmers are in place in India.

Government Initiatives for Digital Agriculture

i. Digital Agriculture Mission: The Digital Agriculture Mission is designed as an umbrella scheme to support various digital agriculture initiatives. These include creating Digital Public Infrastructure (DPI), implementing the Digital General Crop Estimation Survey (DGCEs), and supporting IT initiatives by the Central Government, State Governments, and Academic and Research Institutions (MoA&FW, 2024).

ii. Digital Public Infrastructure: DPI for agriculture aims to provide comprehensive and useful data on farmers, comprising authenticated demographic details, land holdings and crops sown. It will include cultivators and tenant farmers, as per the policy of the State Government. It will also connect to relevant

DPI of the State Governments and Ministries of the Government of India to use data on farmers related to livestock, fisheries, soil health, other vocations, family details, and schemes and benefits availed, leading to innovative farmer-centric digital services in the agriculture sector. The three main DPIs to be developed under this mission are AgriStack, the Krishi Decision Support System and Soil Profile Mapping. These components will enable integration of data on farmers, crops, soil, and weather into a comprehensive digital framework, enhancing decision-making and service delivery. Implementation of DPI in agriculture will be coverage of farmers and their lands within three years. It will collect the details of 6 crore farmers and their lands. Also, it will conduct a digital crop survey for *kharif*-2024 in 400 districts of India. It enables issuance of Jan Samarth-based kisan credit cards in five states of India.

♦ **AgriStack:** The Ministry of Agriculture and Farmers Welfare has planned creating AgriStack is a collection of technology-based interventions in agriculture. It will create a unified platform for farmers to provide them



Photo 2. Farmer awareness activities on digital agriculture

Table 1. Challenges and opportunities in Deployment of digital agriculture

Challenges	Opportunities
Digital Divide: A significant portion of the rural population lacks access to smartphones and the internet. Bridging this digital divide is essential for equitable benefits. Lake of Infrastructure: Inadequate infrastructure, such as reliable electricity and internet connectivity, hampers the implementation of digital solutions. Lack of Education & Training: Many farmers lack the necessary skills to utilize digital tools effectively. Continuous education and training programmes are essential to empower them. Low level of digital literacy: It is to be noted that the application of digital technologies requires basic literacy and numeracy, specialized technical knowledge and computer skill. Farmers without such competencies will be marginalized in an increasingly digitally-driven society. Lack of basic literacy and numeracy is a significant barrier to using digital technologies.	Investment and Funding: Developing and implementing digital solutions requires substantial investment. Public-private partnerships can play a pivotal role in driving funding. Agri-Tech Startups: Various Indian startups, like Ninjacart and AgroStar, leverage technology to connect farmers with markets and provide agricultural solutions, showcasing the potential of digital agriculture. Government Initiatives: Programmes like Digital India and the <i>Pradhan Mantri Kisan Samman Nidhi</i> (PM-KISAN) aim to enhance digital literacy among farmers and provide financial assistance. Research and Development: Institutions like the Indian Council of Agricultural Research are integrating digital tools into research, helping develop climate-resilient crop varieties. Also they are focusing on the training and capacity building in using digital technologies in agriculture. There is a need to create social media platforms and for the farmers, such as 'Agri-Google,' 'Krishi Facebook,' 'Krishi-LinkedIn.' For these bottom-up approaches in policymaking, investments in physical investments, human and institutional capital and farmer-friendly e-platforms are necessary.

end-to-end services across the agriculture food value chain. AgriStack and Digital Crop Survey are important initiatives in digital agriculture under which a digital crop survey has started to ascertain the exact details of farmers' crops. A view of AgriStack is illustrated in **Figure 9**.

Krishi-Decision Support System (Krishi-DSS): This novel system capitalizes on geospatial technologies and correlated databases, with the primary objective of amplifying the evidence-based decision-making

capabilities of stakeholders within the agricultural domain. It is tailored to offer all-weather, high-resolution images for diverse applications including agriculture, forestry, soil moisture assessment, hydrology, and flood mapping. Krishi-DSS will be an invaluable tool for cultivating decision support systems in domains such as agriculture, bio-resources, environment, water resources, and disaster management.

Soil Profile Mapping: Under the Digital Agriculture Mission, detailed soil profile maps on a 1: 10,000 scale for about 142 million hectares of the country's

agricultural land are envisaged to be completed. A detailed soil profile inventory for about 29 million hectares has already been completed.

a. *The Digital General Crop Estimation Survey*: It will provide yield estimates based on scientifically designed crop-cutting experiments. This initiative will prove very useful in making accurate estimates of agricultural production.

b. *Unified Farmer Service Platform*: It is a combination of core infrastructure, data, applications and tools that enable seamless interoperability of various public and private IT systems in the agriculture ecosystem across the country.

iii. *e-Kisan Upaj Nidhi Yojanaa Digital Platform for Farmers*: The government launched an online digital platform named E-Kisan Upaj Nidhi Yojana to empower farmers with access to pledge finance against harvested commodities. This initiative enables farmers to store their agricultural produce with the Warehousing Development and Regulatory Authority (WDRA) and secure post-harvest loans from banks. It is a user-friendly digital gateway, developed collaboratively by the Department of Food and Public Distribution, Department of Financial Services, and NABARD. Integration of e-Kisan Upaj Nidhi and e-NAM enables farmers to leverage interconnected markets, extending benefits beyond governments MSP.

iv. *ICAR-CTRI Secures Patent for e-Crop Device*: Electronic crop (e-Crop), an IoT device for smart farming developed by ICAR-Central Tuber Crops Research Institute has been granted patent by Indian Patent Office. E-Crop is an electronic crop simulator that simulates crop growth in real-time based on weather, soil moisture and nutrient status; calculates nutrient and water requirements and generates agro-advisory for the crop at a daily time scale. This crop simulation model-based device gives periodical advices as SMS to the growers about water and nutrient (nitrogen, phosphorus and potassium) requirements. By narrowing the yield gap and improving nutrient use efficiency, the device contributes to reducing the carbon footprint associated with agricultural practices.

v. *CDP-SURAKSHA- SURAKSHA* stands for System for Unified Resource Allocation, Knowledge and Secure Horticulture Assistance and is a digital platform. The platform allows access to farmers, vendors, implementing agencies, cluster development agencies, and officials of the National Horticulture Board. It has features such as database integration with PM-KISAN, cloud-based server space from NIC, UIDAI validation, e-RUPI integration, local government directory, content management system, geotagging and geo-fencing. Once the demand has been raised by a farmer, the system will ask him to

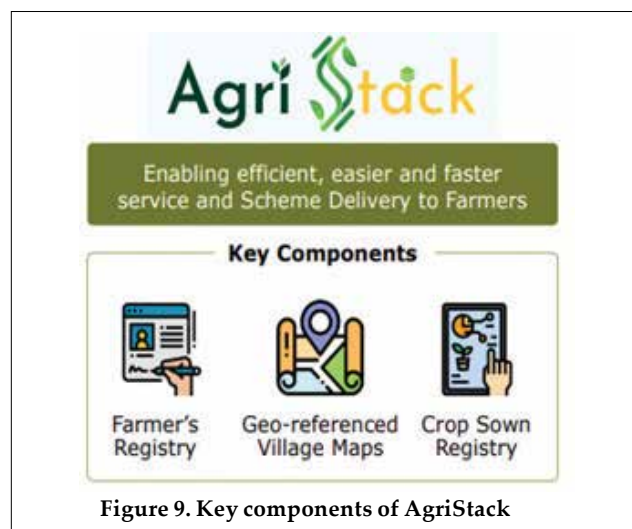


Figure 9. Key components of AgriStack

contribute is share of the cost of planting material. The subsidy amount paid by the government will appear on the screen automatically. This voucher will then be received by a vendor, who will provide the required planting material to the farmers.

vi. *Unified Portal for Agricultural Statistics (UPAg)*: It is an advanced agricultural data management platform designed to generate crop estimates and integrate with other systems generating agriculture statistics such as price, trade, procurement, stock, etc. The UPAg portal is part of the DPI for agriculture, focusing on harnessing data for growth, transparency, and agility in India's agriculture sector. This initiative aligns with e-governance principles and aims to enhance data-driven decision-making for policymakers, researchers, and stakeholders in the agriculture domain.

vii. *DiCRA Platform*: Data in Climate Resilient Agriculture (DiCRA) is the latest addition to the digital public goods registry. Powered by artificial intelligence, the platform is geared towards strengthening food systems and food security. Using remote sensing and pattern detection algorithms, DiCRA is able to identify farms that are resilient to climate change and those that are highly vulnerable. This five-year technical cooperation is envisaged to foster collective climate action and create innovative platforms and new product offerings to enhance economic empowerment in rural India. Such open data innovations can highlight best practices, optimize agriculture investments and shelter populations from risk.

viii. *e-RaKAM (e-Rashtriya Kisan Agri Mandi)*: It enables farmers to sell agricultural products through online auctions. Farmers can sell/buy agricultural products across India. It aims to centralize agricultural product transactions. It accesses to integrated logistics services in a larger market and reduce intermediary

costs by reduces dependence on middlemen in crop purchasing.

ix. e-NAM (National Agriculture Market): e-NAM provides an integrated platform for the farmers to know the food grain prices at various agriculture markets in the country. e-NAM helps the farmers to make proper decisions at different stages of the production process.

x. Digital Agriculture Division: The Government of India established the Digital Agriculture Division under the Ministry of Agriculture and Farmers Welfare to accelerate digital technologies in agriculture. This newly formed division emphasizes the creation of a central database related to farmers. The database is linked with the land record for proper synchronization of different agriculture related welfare schemes. It enables better and targeted service delivery to the farming community.

xi. National Digital Agriculture Ecosystem (NDAE): The objectives of NDAE includes the realization of higher income and profitability, access to correct information, better planning and execution of government initiatives, enhance resource efficiencies, location-specific extension services and generation of unique farmer IDs for individualization of service delivery. With the help of this ecosystem, farmers get accurate and updated information related to various aspects of farming such as which crop to grow, what type of seed to use, when to sow and what best practices to adopt to maximize yield and the marketing of agri-produce.

xii. Other Digital Initiatives:

These include *Kisan Call Centres*, *Kisan Suvidha App*, *Agri Market App*, *Soil Health Card (SHC) Portal*, *Agricultural Resources Information Systems (AgRIS)*, *Kisan Call Centres*, etc.

Benefits of Digital Agriculture

i. Agriculture Sustainability: Digital agriculture provides time effective decision support systems to optimum resource use for best crop management which can improve the agricultural productivity, profitability and sustainability to ensure future food security.

ii. Economic Viability: Accessing of market information and better price negotiations can increase farmer's income. This economic empowerment is crucial for rural development.

iii. Resilience to Climate Change: Digital agriculture can aid in adapting to climate change by providing real-time data on weather patterns and pest outbreaks, enabling farmers to respond proactively.

iv. Ease of Doing Farming: It offers automation in farm machineries for best and precise input management

and reduces demand for manual labour under their scarcity scenarios.

v. Intelligent Farming: Digital agriculture, use of remote satellite data and in-situ sensors improve the accuracy using freely available and high-quality satellite imagery and reduce the cost of crop, water and soil monitoring.

vi. Maintenance of Land Records: Using the technology, data related to a large number of landholdings can be appropriately tagged and digitized. It will not only help better targeting but also reduce the quantum of land disputes in courts.

Conclusion

Digital agriculture offers a transformative solution to many of the challenges faced by modern agriculture. By adopting these technologies, farmers can enhance crop productivity and quality of produce, and improve their livelihoods. While there are challenges in implementation, the benefits far outweigh the risks, making digital agriculture a cornerstone of sustainable food systems in India. Digital agriculture holds immense potential to revolutionize traditional farming by transforming it into a data-driven enterprise. With over 140 million farmers and diverse agricultural systems, integration of technology can address the complex challenges faced by Indian agriculture. By enabling precision farming, digital tools can significantly enhance crop productivity, ensuring that resources such as water, nutrients, and labour are optimized for maximum efficiency. Digital agriculture not only reduces operational costs but also increases profitability to the farmers. Moreover, by adopting sustainable farming practices, digital agriculture helps tackle pressing environmental concerns, making farming eco-friendly and resource-efficient for sustainability.

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A photograph of a man in a traditional conical hat and striped shirt, smiling and holding a wooden staff over his shoulder, standing in a lush green rice field. The background is a soft-focus view of the field and distant hills.

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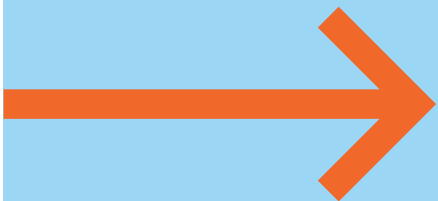
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Impact of Leveraging GenerativeAI for Site-Specific Fertilizer Recommendations to Small-Scale Indian Farmers: A Case Study from Khammam, Telangana

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Abstract

Smallholder farmers in India often face issues such as improper fertilizer usage leading to high input costs, reduced yields, and environmental degradation, particularly with the overuse of nitrogen fertilizers. In response, AI-driven tools like nutrient budgeting and precision agriculture offer promising solutions. This study examines the use of GenerativeAI (GenAI) to provide site-specific fertilizer recommendations for small-scale farmers in Khammam, Telangana as part of a broader effort to enhance agricultural sustainability and productivity. This research involved 776 smallholder farmers. Soil samples were collected and analyzed using advanced IoT-based soil testing technologies. Fertilizer recommendations were generated using GenAI, customized for each plot based on specific soil and crop conditions. The results showed an increase of 18% in average yields of crops with chilli production rising significantly by 46% in the intervened areas. Additionally, the study demonstrated reductions in input costs, particularly for pesticides, and improvements in overall soil health. The findings underscore the potential of GenAI to optimize resource use, enhance agricultural productivity, and promote environmental resilience in small-scale farming systems. These insights provide a framework for the integration of AI technologies into broader agricultural practices in developing countries, where climate variability and soil degradation pose significant challenges to sustainability.

Key words : GenerativeAI, soil testing, adoption, recommendations, crop production, a case study

Introduction

Agriculture is the foundation of India's economy, supporting over 60% of the population and contributing around 17% to the GDP while employing about 42% of the workforce (GOI, 2020). Despite its importance, smallholder farmers in India face significant challenges, particularly inefficient fertilizer use, which drives up input costs and contributes to environmental degradation. Studies have shown that improper fertilizer application increases production costs, placing additional financial strain on small-scale farmers (Chandrasekaran et al., 2023). Overuse of fertilizers also leads to diminished soil health, further reducing agricultural productivity over time. Smallholder farmers are crucial to global food security, yet they often lack access to timely, localized, and actionable agricultural information. This gap limits their productivity, profitability, and ability to adopt sustainable practices (Fabregas et al., 2019; Faure et al., 2012). In low- and middle-income countries, such as India, where farming technologies must be adapted to local environmental and plot-specific factors, absence of reliable guidance exacerbates these challenges (Fan et al., 2020; Davis et al., 2014). As a result, farmers struggle to manage risks effectively, leading to lower yields and reduced incomes. While agricultural extension services aim

to bridge this information gap, traditional systems often rely on extension agents who face significant obstacles in delivering tailored advice, especially in remote regions where soil conditions, climate, and crop varieties vary considerably (Gupta et al., 2023).

India's heavy dependence on nitrogen fertilizers, with consumption exceeding 30 million MT of total NPK nutrients annually, has led to widespread inefficiencies. Poor management practices result in nearly 50% of applied fertilizers going unused, allowing excess nutrients to leach into soils and water systems, causing significant environmental harm (Gupta et al., 2023). This inefficiency not only inflates production costs for farmers but also degrades soil quality, making farmers increasingly reliant on chemical inputs to sustain crop yields.

In the face of climate change, these issues are further compounded. Climate variability, including unpredictable rainfall and extreme weather events, affects nutrient uptake, rendering fertilizers less effective and increasing the likelihood of nutrient runoff. Long-term reliance on fertilizers has been shown to degrade soil structure and reduce resilience to climate-induced stresses, resulting in lower yields over time (Velayudhan et al., 2024). This poses a substantial risk to smallholders, who are particularly vulnerable to market fluctuations and adverse

weather conditions. The combination of rising input costs and soil degradation traps farmers in a cycle of declining farm productivity and financial instability. To address these challenges, there is an urgent need for sustainable agricultural practices. AI-driven technologies, such as GenAI, combined with nutrient budgeting and precision agriculture, offer promising solutions. These tools can help farmers optimize fertilizer use, minimize waste, and safeguard soil health, thereby reducing production costs and enhancing resilience to climate change (Jha et al., 2023).

In this context, this paper investigates the potential impact of utilizing GenAI to provide site-specific fertilizer recommendations for small-scale Indian farmers. The study explores how AI-driven solutions can improve fertilizer use efficiency, lower input costs, and mitigate environmental degradation, particularly in light of the challenges posed by climate change and unpredictable weather patterns. The objective is to assess the benefits, methodologies, and challenges of integrating GenAI into rural farming systems while examining its potential to enhance agricultural sustainability and resilience for smallholders. Additionally, the study seeks to offer insights into the practical implementation of these technologies, with a focus on long-term soil health and crop productivity.

Review of Literature

Fertilizer Use in Indian Agriculture

The strategic application of agricultural inputs is fundamental to achieving sustainability within crop production systems (Zhang et al., 2015; Cui et al., 2018).. Use of fertilizers has contributed considerably to enhance crop yields. However, it has also led to several challenges, including soil nutrient imbalances and reduced agricultural sustainability. For balanced fertilisation, ideal $N:P_2O_5:K_2O$ use ratio is 4:2:1 but it was 10.9:4.4:1 in 2023-24. Deviations from this recommended ratio can limit productivity growth and undermine agricultural sustainability (Chand and Pandey, 2009; Sharma et al., 2020).

Research suggests that balanced fertilizer application can improve yield by 20-30% (Jat et al., 2018). However, intensive farming practices often involve continuous extraction of soil nutrients without adequate replenishment through external inputs, leading to soil degradation (Bora et al., 2022). As essential macro-nutrients are depleted, crop yields are adversely affected, resulting in significant reductions in agricultural productivity. Therefore,

it is imperative to find a delicate balance in the application of fertilizers, aligning the objectives of maximizing crop yields with the necessity of preserving environmental sustainability over the long-term. Recent studies underscore the importance of balanced nutrient management, emphasizing that both nutrient deficiencies and excesses can lead to reduced crop yields and negative environmental impacts (Jha et al., 2023). Evaluating the impacts of inappropriate fertilizer use frequently reveals alarming signs of environmental degradation, particularly in regions heavily reliant on chemical inputs (Zhen et al., 2005, 2006). Consequently, fostering a more scientifically grounded fertilizer policy that supports the optimal use of N, P, and K is essential for ensuring long-term agricultural productivity and sustainability (Velayudhan et al., 2024).

Fertilizers play a critical role in enhancing agricultural output amid increasing pressures on land and water resources. As the potential for raising farm production through the expansion of cultivable land is nearly exhausted, it is crucial to ascertain whether fertilizers are being used judiciously and optimally. Empirical evidence shows that growth in total agricultural output, as well as the output of various crops in India, has fluctuated depending on fertilizer usage (Chand et al., 2015). Therefore, implementing policies that promote the optimal application of plant nutrients is vital for meeting future food, feed, fuel and fiber requirements while ensuring sustainable agricultural practices.

The Role of Technology and GenerativeAI in Agriculture

The integration of GenAI is revolutionizing agricultural practices by transitioning them from traditional methods to more precise, data-driven approaches. Precision farming, enabled by technologies such as soil moisture sensors, weather stations, and drones, allows farmers to monitor their fields with unprecedented accuracy. This real-time data facilitates informed decision-making regarding irrigation, fertilization, pest control, and harvesting, ultimately leading to increased crop yields and more efficient resource utilization (Madrewar et al., 2024). In the context of Indian agriculture, where smallholder farmers constitute a significant portion of the farming community, the potential benefits of GenAI are particularly substantial. These technologies can help bridge the gap between conventional farming practices and modern agricultural methods, providing solutions to some of the sector's most pressing challenges. Notably, AI can analyze vast datasets to predict

crop performance, detect diseases early, optimize supply chains, and recommend the optimal times for planting and harvesting (Zhang et al., 2019). Despite these advancements, challenges related to data quality and algorithm transparency persist, which can hinder the widespread adoption of these technologies (Madrewar et al., 2024).

India has undertaken significant initiatives to embrace digital advancements in agriculture, as evidenced by the introduction of the 'India Digital Ecosystem of Agriculture' plan centered around 'AgriStack,' a collection of technology-based interventions designed to facilitate sector digitalization (Garg, 2020). However, prevalence of small farms presents challenges for implementing digitization initiatives effectively, as many smallholder farmers may not be familiar with new digital technologies (Beriya, 2022; Xie et al., 2021). Furthermore, absence of uniformity across platforms and fragmented initiatives hampers the development of cutting-edge farm management software systems, rendering data ineffective (Shams et al., 2021). The lack of public awareness and relevant studies also complicates efforts to assess the potential increases in revenue and yield associated with digitalization efforts (Chandra and Collis, 2021).

GenAI, a subset of artificial intelligence, enables the creation of personalized content and solutions based on extensive datasets. Studies have highlighted its effectiveness in various agricultural applications, including crop management and pest control (Huang et al., 2022). However, its application in providing tailored fertilizer recommendations remains underexplored, particularly in developing countries like India. This gap presents a significant opportunity for further research and development, particularly in enhancing agricultural practices of smallholder farmers. Advancements in GenAI, particularly with large language models (LLMs) like GPT-3 and GPT-4, are transforming agricultural knowledge accessibility, especially in low-resource settings. Projects such as Kisan.AI have utilized LLMs to provide real-time advice on crop management and pest control (Kissan, 2024). However, these systems face challenges in adapting to diverse agricultural ecosystems due to limited knowledge bases and difficulties in ingesting non-digital agricultural information. Additionally, lack of robust multilingual support and inability to process multimodal inputs, such as images and audio, further restricts their applicability in rural contexts (Raiaan et al., 2024). Most existing LLM-based agricultural chatbots tend to focus on a narrow range of crops and regions, which may

neglect the complex needs of smallholder farmers (Silva et al., 2023; Tzachor et al., 2023).

While the integration of AI in agriculture holds significant promise for enhancing crop productivity and sustainability, it is crucial to confront the challenges that impede effective implementation, particularly in developing regions like India. By prioritizing tailored solutions for smallholder farmers and enhancing access to agricultural knowledge, the sector can not only address pressing issues related to fertilizer recommendations but also pave the way for a more resilient and sustainable agricultural future. This approach will enable farmers to optimize resource use, improve crop yields, and ultimately contribute to food security in the face of growing environmental and economic pressures.

Methodology

Study Area and Sample Size

This pilot study was conducted in Khammam District, Telangana, India, focusing on small and marginal chilli farmers across three major blocks: Khammam Rural, Kusumanchi, and Thirumalahpalem. A total of 1,400 farmers participated in the study, selected from a larger pool of 5,000 beneficiaries under the *Saagu Baagu* project, a public-private partnership (PPP) initiative. Digital Green served as the implementing partner, collaborating with Krishitantra, a technology consortium partner, and the Government of Telangana, the project's official owner. Farmers received fertilizer recommendations generated by GenAI, customized for their specific plots. To ensure effective use, training sessions were conducted, where the farmers were taught to interpret and implement the AI-generated fertilizer guidance.

In 2022, soil samples were collected from 1,400 chilli farmers. The selection of participants followed a grid sampling method aimed at covering all soil types within the study area. In each village, 2–3 distinct soil types were identified. For a comprehensive assessment, pilot phase focused on representative soil samples across these varying conditions to evaluate the efficacy of the GenAI-based recommendations. A baseline survey was conducted with 708 farmers, and an end-line survey, after the cropping season, included 776 farmers of Khammam district of Telangana (**Figure 1**). This sample structure allowed for an in-depth comparison of soil testing adoption, fertilizer usage, and yield improvements between the two periods.

Community Resource Persons (CRPs), who are the frontline workers delivering project services, were

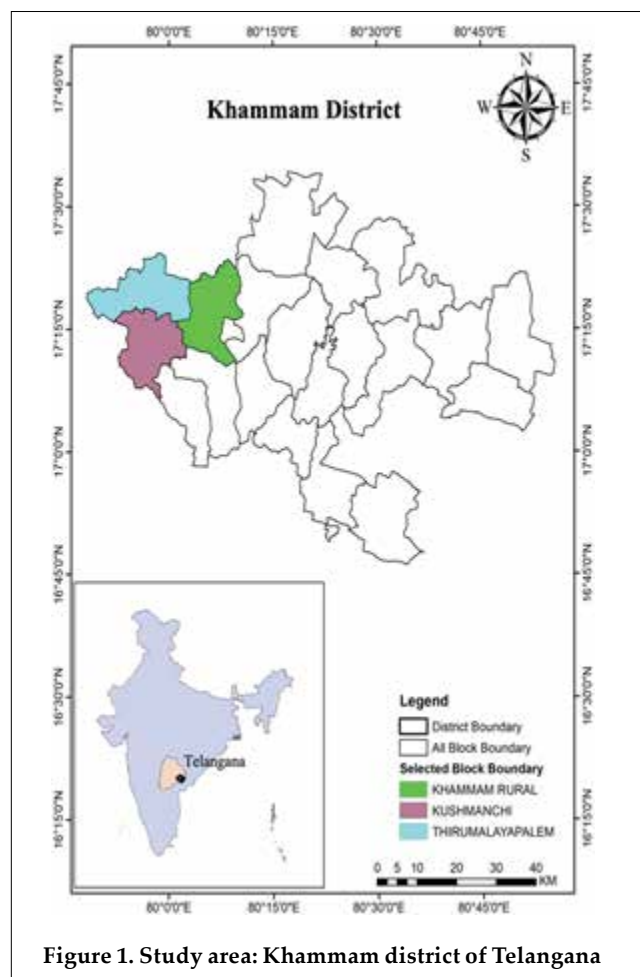


Figure 1. Study area: Khammam district of Telangana

trained on scientific soil sampling techniques. The training sessions were conducted collaboratively by Krishitantra, the Department of Horticulture, Telangana, and Digital Green. This ensured that the soil samples collected were of high quality and accurately represented the different soil types in the study area.

Soil Testing Procedure

Soil sampling for the study followed a systematic and scientific procedure designed to ensure the accuracy and representativeness of the samples. For each 0.5-hectare (5,000 square meter) plot, soil samples were collected using a zig-zag sampling method, which ensured a comprehensive representation of the entire plot. Care was taken to avoid areas that could introduce contamination or bias, such as recently fertilized plots, bunds, channels, marshy areas, near trees, wells, compost piles, and plot borders. For shallow-rooted vegetable crops like chilli, soil samples were collected from a depth of 0-15 cm using the V-shaped soil sampling technique. This process involved removing surface litter, grass, and debris from the

sampling point, followed by driving an auger into the soil to a plough depth of 15 cm to collect the soil. If the auger was unavailable, a 'V' shaped cut was made to a depth of 15 cm using a spade. From the exposed face of the cut, a 2.5-3 cm thick slice of soil was carefully removed.

At each sampling site, 10 to 15 soil samples were collected and placed into a bucket or tray. The samples were then mixed thoroughly by hand and spread evenly on a clean plastic sheet or paper. The composite soil sample was reduced to approximately 500 grams using the quartering method, where the soil was divided into four quarters, and two opposite quarters were removed. This process was repeated until the desired quantity was achieved. The soil sample was then air-dried in the shade, placed into a labelled plastic bag, and submitted to the laboratory for analysis. This standardized soil sampling protocol ensured that the samples accurately represented the soil conditions across various plots, allowing for reliable analysis and fertilizer recommendations tailored to each specific plot.

GenAI Model Development

In this study, the Krishi RAASTA, an IoT-based automated portable soil testing solution, was used to conduct rapid and reliable soil analysis for the participating farmers. Krishi RAASTA operates on the principle of spectrophotometry and offers a more efficient and environmentally friendly approach to soil testing. It uses only 1/8th of the chemicals typically required in traditional soil testing laboratories, and can test up to 100 soil samples per lot, with refillable chemical supplies. The device, which weighs less than 12 kilograms and has a compact design under 2.5 cubic feet, is capable of providing instant soil quality reports along with crop-specific fertilizer recommendations directly to the farmer's mobile phone. Krishi RAASTA is both electricity and battery-operated, making it highly versatile for field conditions, especially in remote areas. It can analyze 11 critical soil parameters N, P, K, pH, EC, organic carbon, sulphur, boron, zinc, iron, and copper—within 45 minutes, with a reported accuracy of 95% compared to traditional soil testing labs.

The soil sampling followed the standard procedure described earlier, with field workers from Krishitantra collaborating with Digital Green's field team to collect and test soil samples. The field team registered farmers' details, including personal information (name, mobile number, address), geographical data (latitude, longitude), and historical data such as previous crop cultivation

and fertilizer usage. The soil samples were collected following the V-shaped method and subjected to analysis for the 11 parameters mentioned. Once the analysis was complete, the soil test report was instantly generated and sent to the farmer via SMS or printed format, as per the farmer's preference. All data collected was automatically synchronized on Krishitantra's secure server hosted on Amazon Web Services (AWS), ensuring seamless data integration. The cloud platform, accessible via Krishitantra's API service, allowed for remote monitoring of test results. Farmers and project stakeholders were provided with unique login credentials to access the portal, where they could view and print the reports. Fertilizer recommendations, both for macro and micro environments, were customized based on specific crop and regional requirements, ensuring targeted nutrient management solutions for each farm. By integrating this advanced soil testing solution, the study aimed to enhance the efficiency of fertilizer recommendations and improve agricultural productivity, contributing to more sustainable farming practices.

Application Architecture

The application architecture (**Figure 2**) of this study integrates web-based interfaces, connected devices, and scalable server infrastructure to manage soil testing and fertilizer recommendation workflows.

The architecture is briefly described in the following section.

- i. *Web User Interface (UI)*: The web UI provides the front-end access for users to manage farmer profiles, soil test results, and fertilizer recommendations. It includes modules for:
 - ♦ **User Management**: Enables administrators to manage users, permissions, and roles within the system.
 - ♦ **Fertilizer Management**: Allows the user to input, view, and analyze fertilizer recommendations based on soil test results.
- ii. *Device Application Architecture*: The device application manages interactions between the soil testing devices and the server infrastructure. It consists of several features:
 - ♦ **Device Management**: For configuring and maintaining the portable soil testing devices.
 - ♦ **Farmer Management**: Allows the system to store and update information related to registered farmers, including their geolocation, soil types, and crop history.

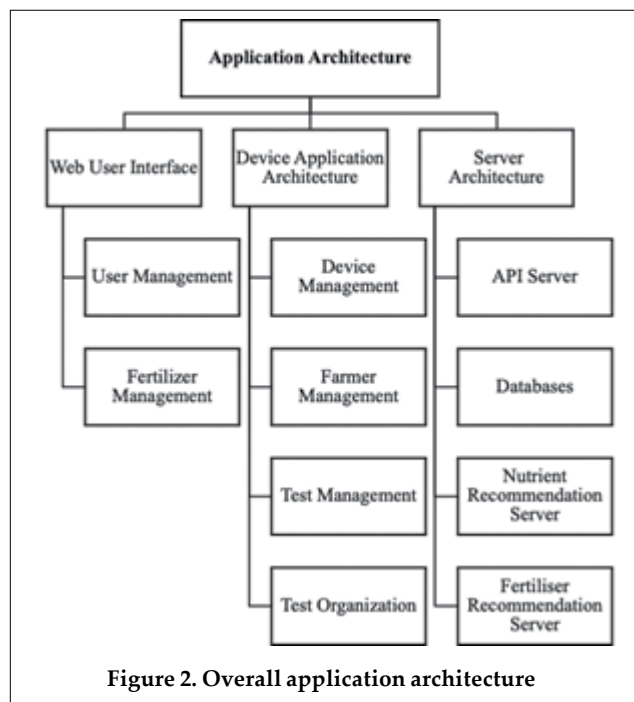


Figure 2. Overall application architecture

- ♦ **Test Management**: Oversees the collection, testing, and recording of soil samples.
 - ♦ **Test Organization**: Facilitates the systematic organization and categorization of soil test data for analysis.
- iii. *Server Architecture*: The server architecture is designed to be scalable and flexible, supporting various workloads through cloud services. It is divided into four key components:
 - ♦ **Fertilizer Management**: Allows the user to input, view, and analyze fertilizer recommendations based on soil test results.
 - ♦ **API Server**: The API server runs background code and provides API endpoints for communication between client devices and the system. It manages data flow between the device and database, nutrient recommendation, and fertilizer recommendation servers. Auto-scaling features are enabled through the use of elastic load balancer and electric container services to manage varying loads on the application.
 - ♦ **Databases**: All data, including soil test results, farmer profiles, and fertilizer recommendations, are securely hosted on a cloud-based database. The database is optimized for fast data retrieval and secure storage of large datasets.
 - ♦ **Nutrient Recommendation Server**: This server processes soil test data and generates

specific nutrient recommendations for each sample in kg ha^{-1} . The nutrient recommendation is aligned with guidelines provided by agricultural experts and tailored to the specific crop requirements of the farmer.

- ♦ **Fertilizer Recommendation Server:** Based on the nutrient recommendations, this server calculates the appropriate quantities and types of fertilizers required to meet the soil's nutrient needs. The recommendations are customized according to expert guidelines and are crop- and region-specific to ensure optimized fertilization.

This integrated application architecture ensures efficient management of soil testing operations and delivery of tailored fertilizer recommendations to farmers, improving agricultural productivity through data-driven decisions. Use of scalable cloud infrastructure supports the system's capacity to handle a large number of users and data points, ensuring reliability and performance even under varying loads.

Data Analysis

The end-line evaluation of the intervention was conducted by IMPACT following the 2022-23 cropping cycle, specifically during May-June 2023. This evaluation aimed to achieve several key objectives such as (i) assess the extent to which digital extension services are reaching farmers and their levels of adoption, (ii) analyze the patterns of adoption of promoted chilli farming practices among the farmer population, and (iii) evaluate the adoption and perceived utility of specific interventions, particularly soil testing using the Krishi Tantra technology. To rigorously evaluate the efficacy of the intervention and its impact on improving outputs and profit margins for farmers, a quasi-experimental design was employed. This approach is particularly valuable in agricultural research, as it allows for the assessment of the effects of interventions in real-world settings where randomization may be challenging or impractical

(Lahiff, 2021). In this study, the minimum sample size necessary to detect a difference in key outcomes of at least 10% was calculated to be 385, utilizing a 95% confidence interval and an 80% power level. To enhance the robustness of the findings and ensure representativeness across the three blocks of Khammam district, the sample size was increased to 450 farmers.

Furthermore, to capture a sufficient number of farmers who were engaged with specific interventions, such as soil testing, quality assaying, and Kalgudi, a booster sample of 100 farmers from each intervention was included. This methodological decision increased the total sample size to 776 farmers, allowing for a comprehensive examination of the intervention's impact on farming practices. In addition to the treatment group, a control group comprising 516 farmers from a non-intervention block in Khammam district was included in the analysis. This control group serves as a crucial comparison point, facilitating the evaluation of the intervention's effects by contrasting outcomes between those who received the interventions and those who did not.

Data collected from these farmers were analyzed to discern trends in adoption rates, perceived utility of the interventions, and overall impact on agricultural practices and profitability. Statistical methods, including regression analysis, were employed to assess the relationships between the intervention and various outcomes, allowing for a nuanced understanding of the factors influencing farmers' adoption of new technologies and practices.

Results and Discussion

Soil Testing Adoption

The results of the intervention reveal a notable increase in the adoption of soil testing among small and marginal farmers in Khammam district during the 2022-23 cropping season (**Figure 3**). Of the 776 farmers surveyed, 57% (N=441) indicated they had their soil tested before the start of the cropping

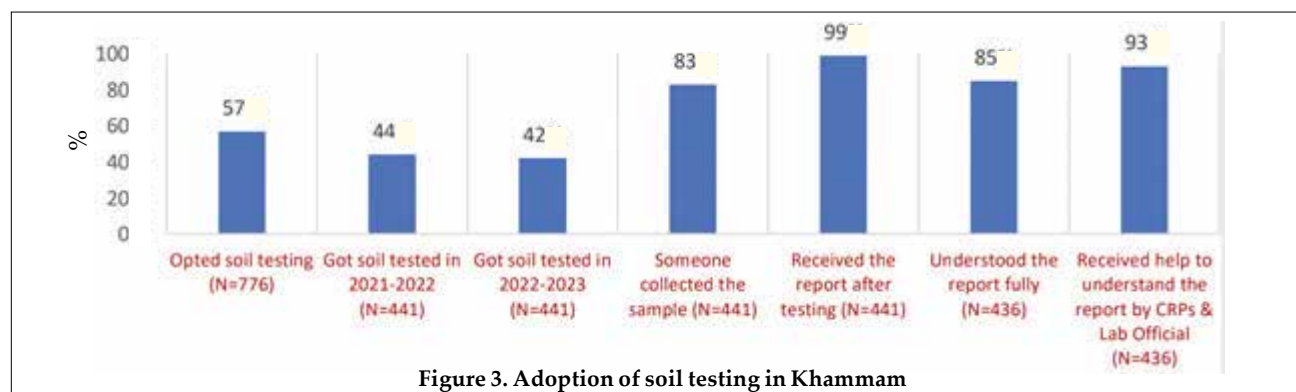


Figure 3. Adoption of soil testing in Khammam

season in April-June 2022, representing a substantial increase from the 44% adoption rate during the previous season (2021-22). This finding reflects a growing recognition of soil testing as an essential tool for optimizing fertilizer usage, particularly in the context of sustainable farming practices.

Interestingly, the data showed a gendered pattern in the adoption of soil testing. A significantly higher proportion of women farmers (63%) had their soil tested compared to men farmers (41%). This discrepancy may suggest that women farmers are more receptive to adopting new agricultural practices, or that they may have better access to extension services such as those offered by Digital Green's CRPs (Community Resource Persons). These CRPs were responsible for collecting soil samples for the vast majority (94%) of farmers who participated in the soil testing programme, while the Department of Agriculture and Krishi Tantra representatives played smaller roles, assisting 17% and 9% of farmers, respectively. Among the farmers who had their soil tested, 99% reported receiving a soil health card, which detailed the findings of the test. A large majority of these farmers (85%) were able to understand the report, although most of them (93%) acknowledged that they required assistance from CRPs or lab technicians to interpret the results (**Figure 3**). The support provided by these field staff highlights the critical role of agricultural extension services in ensuring that farmers can apply the insights from soil testing to their farming practices.

In terms of the practical application of the soil health report, 98% were informed about the precise quantity of fertilizers to be used on their land, and 74% were provided with specific recommendations

about the types of nutrient-specific fertilizers required. This level of guidance is crucial in helping farmers make informed-decisions about fertilizer application, which can improve both farm productivity and soil health over time.

Improved Yield and Chilli Production

The pilot study revealed substantial improvements in crop yields, particularly in chilli production, due to the adoption of GenAI-driven fertilizer recommendations. These site-specific recommendations were tailored to the unique nutrient requirements of each plot, ensuring efficient use of fertilizers and other inputs. The findings from the study demonstrated that farmers utilizing these AI-generated recommendations experienced an average yield increase of 18% across various crops. For example, wheat yields rose from 3,500 kg ha⁻¹ to 4,130 kg ha⁻¹, underscoring the benefits of precision agriculture enabled by AI technologies.

Focusing on chilli production, study used a difference-in-difference (DiD) approach to measure the intervention's impact. The DiD method compared the changes in outcomes over time between intervention and control groups, providing a clear picture of how the adoption of AI-driven fertilizer recommendations influenced agricultural output. The data indicated that production of chilli increased significantly in intervened areas compared to control areas as shown in **Table 1**. At the end line, average quantity of chilli produced kg acre⁻¹ in the intervened areas increased from 1,247 to 1,820 *i.e.* 46% rise while control areas saw a smaller increase from 1,339 to 1,678, *i.e.* 25% improvement. The DiD analysis calculated that this equated to an additional 234 kg acre⁻¹ of chilli produced in the intervened areas compared to what would have been expected without the intervention,

Table 1. Economic analysis of chilli cultivation in Telangana										
Parameters	Intervention				Control				DiD	DiD (%age points)
	Baseline (N=708)	End line (N=776)	Change from baseline		Baseline (N=405)	End line (N=516)	Change from baseline			
			Absolute	%			Absolute	%		
Average chilli harvested in kg acre ⁻¹	1,247	1,820	573	46	1,339	1,678	339	25	234	21
Average sale price of chilli in Rs. kg ⁻¹	165	210	45	27	171	204	33	19	12	8
Total revenue generated in Rs.	2,05,755	3,82,200	1,76,445	86	2,28,969	3,42,312	1,13,343	50	63,102	36
Total investment in Rs. acre ⁻¹	76,048	89,871	13,823	18	65,452	77,564	12,112	18	1,711	0
Profit	1,29,707	2,92,329	1,62,622	125	1,63,517	2,64,748	1,01,231	62	61,391	63

translating to a 21% higher yield. The difference in chilli production between the intervention and control areas can be attributed to several factors.

Primarily, AI-driven fertilizer recommendations ensured that the farmers applied the correct type and quantity of fertilizers based on the specific nutrient needs of their soil and crop. This optimization of inputs not only increased crop productivity but also reduced the overuse or misuse of fertilizers, contributing to both economic and environmental benefits. Additionally, use of non-pesticidal management (NPM) practices, integrated as part of the advisory system, further enhanced crop health and yield. These findings are further supported by farmer feedback on the perceived utility of soil testing and fertilizer recommendations as already enumerated.

In addition to yield increases, farmers in the intervened areas also reported an increase in the market rate of chilli, which was significantly higher than in control areas, further amplifying the economic benefits of adopting GenAI-driven advisory services.

Input Cost Analysis

The input cost analysis from the pilot study provided valuable insights into the impact of GenAI-driven advisories on farm expenses, particularly with respect to the rationalization of input use. While the total input costs remained stable in intervened areas, further analysis revealed significant shifts in the allocation of these expenses, particularly in key categories like pesticides and labour. The most notable finding was the significant reduction in pesticide use, which dropped considerably more in intervened areas compared to control areas. This reduction in pesticide use is a direct result of the precision recommendations provided through the GenAI advisories and soil testing, which enabled farmers to target pesticide

applications more efficiently.

In the control areas, reduction in pesticide cost in intervened areas was nearly double, showcasing the effectiveness of the intervention in helping farmers cut unnecessary pesticide expenditure as shown in **Table 2**.

Reduction in pesticide costs is substantial, as it directly impacts both environmental sustainability and farmers' profitability. By minimizing pesticide usage, farmers can reduce the environmental burden associated with chemical inputs, while also lowering their overall input costs. The decrease in pesticide-related expenditures also led to reductions in paid labour, particularly in tasks related to pesticide spraying, which suggests an added benefit in terms of labour cost efficiency.

The data further indicates that the savings achieved from reduced pesticide use were redirected into other areas, most notably the purchase of farm equipment. This reallocation suggests that farmers are not only cutting costs but are also investing in long-term productivity improvements. Equipment purchases may support enhanced mechanization, reducing labour dependency and further improving efficiency in the long-run. These findings underline the effectiveness of AI-driven advisories in promoting the optimal use of agricultural inputs, leading to cost savings and improved resource allocation for small scale farmers.

Conclusion

The findings from this study suggest that GenAI can be a game-changer for small-scale agriculture in India, providing precise, plot-specific fertilizer recommendations that improve crop yields and reduce input costs. Use of AI-generated advisories, tailored to the specific nutrient needs of individual plots, led to significant productivity gains, particularly in chilli production, where yields

Table 2. Difference in input cost (Rs.) incurred by farmers in different crop cycles

Inputs	Intervention			Control			DiD
	Baseline	End line	Difference	Baseline	End line	Difference	
Seeds and Nursery	8,236	7,782	-454	8,092	4,606	-3,486	3,032
Fertilizers	9,380	9,702	322	9,008	9,637	629	-307
Pesticides	17,429	9,818	-7611	13,900	8,955	-4,945	-2,666
Paid Labour	7,916	6,129	-1787	5,356	4,576	-780	-1007
Irrigation	442	1,958	1,516	493	1,457	964	552
Hiring machinery	2,676	321	-2355	1,580	520	-1,060	-1,295
Farm equipment purchase	498	3,482	2984	386	2,173	1,787	1,197
Harvesting	19,762	16,449	-3,313	17,111	20,220	3,109	6,422
Post-harvest management cost	29,432	41,414	13,982	26,639	38,203	11,564	2,418

increased by 46% in intervention areas compared to a 25% rise in control areas. By reducing over-application of fertilizers and pesticides, GenAI recommendations not only optimized input use but also contributed to better soil health and long-term environmental sustainability. Additionally, use of advanced IoT-based soil testing devices, such as Krishi RAASTA, further improved the accuracy and timeliness of fertilizer recommendations, enabling farmers to make data-driven decisions in real-time.

The successful implementation of such AI-driven interventions hinges on addressing several key challenges. Digital literacy among farmers, availability of supporting infrastructure, and reliable access to data remain significant barriers, especially in rural areas. The scalability of AI solutions will depend on closing these gaps and ensuring that smallholder farmers are equipped with the necessary tools and knowledge to fully utilize these technologies. Moreover, continued research is needed to evaluate the long-term impacts of AI interventions on agricultural sustainability, soil health, and farmers' livelihoods. In conclusion, integration of Generative AI in agriculture has the potential to reshape farming practices, particularly for smallholders in developing countries, by enabling more sustainable and resilient agricultural systems. As climate change and market pressures continue to challenge global food security, AI technologies could play a crucial role in safeguarding the future of small-scale farming, enhancing productivity, and improving the economic stability of rural communities.

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New Publications to be Made Available in December, 2024 for Sale

- ♦ **Fertiliser Statistics 2023-24**
- ♦ **Specialty Fertiliser and Micronutrient Statistics 2023-24**
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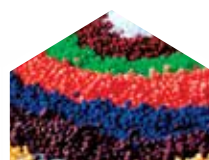
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ICLeaf - Leaf Scanning Technology with Crop Advisor for Enhancing Fertilizer and Nutrient Efficiency

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Abstract

ICLeaf is a pioneering leaf scanning technology designed to revolutionize crop nutrition management. Developed by Agriculture Research Organization (ARO), ICLeaf employs cutting-edge X-ray fluorescence and near-infrared spectroscopy to provide a rapid and non-destructive analysis of 11 essential nutrients in leaf samples. This technology delivers precise, actionable data in just 3 to 4 days by significantly reducing the analysis time from hours for chemical tests to just 5 minutes for physical tests, enabling farmers to make informed decisions that enhance productivity, optimize fertilizer use, and promote environmental sustainability. By integrating with Crop Advisor, ICLeaf addresses critical challenges in crop production, such as nutrient deficiencies, precision fertilization, and the differentiation between disease and nutrient-related issues. ICLeaf's advanced capabilities contribute to sustainable crop production, reducing nutrient waste, and improving fertilizer use efficiency, ultimately leading to increased yields and cost savings. Since its launch, ICLeaf has been showing a significant social impact, with many farmers reporting improved crop yields and reduced fertilizer costs. Through precise nutrient management, ICLeaf is transforming the agricultural landscape, helping farmers unlock their crops' full potential.

Key words: ICLeaf, crop advisor, leaf scanning technology, non-destructive, precision fertilization, nutrient management

Introduction

The health and productivity of crops are intimately tied to the condition of their leaves, making leaf analysis a crucial aspect of modern agriculture. As the primary site of photosynthesis and nutrient absorption, leaves offer vital insights into the overall well-being of plants. Traditional methods of leaf analysis have been evolved but the techniques categorized into destructive and nondestructive approaches. While destructive methods provide detailed information, they often compromise the integrity of the sample. In contrast, nondestructive methods are known for their precision, speed, and ability to repeatedly monitor plant health without damaging the tissue.

Recent advancements in information technology have further transformed agricultural research, introducing innovative solutions that enhance the accuracy and efficiency of leaf analysis. Among these breakthroughs is ICLeaf, a state-of-the-art technology developed by ARO that is setting new standards in crop nutrition management. ICLeaf offers rapid, non-destructive analysis of 11 essential nutrients in leaf samples, employing X-ray fluorescence (XRF) to measure phosphorus, potassium, calcium, magnesium, sulphur, zinc, iron, manganese, molybdenum, and copper, and near-infrared (NIR) spectroscopy to assess nitrogen content. This revolutionary technology provides actionable data within a few days, empowering farmers

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to make informed decisions that boost productivity, optimize fertilizer use, and promote sustainable practices.

In an era where precision agriculture is becoming increasingly important, ICLeaf represents a significant advancement in the field. ICLeaf addresses key challenges in agriculture, such as nutrient deficiencies and precision fertilization, while also distinguishing between disease symptoms and nutrient-related issues. By integrating with tools like Crop Advisor from Agmatix is a digital tool designed to optimize crop nutrition. It uses data and AI to create customized nutrient plans for specific crops and fields. This helps farmers apply the right nutrients at the right time, improving yield and sustainability.

ICLeaf - Innovative Solution Addressing Challenges in Crop Production

ICLeaf addresses several critical problems related to plant health and productivity. Here are some problems that ICLeaf and Crop Advisor helps to resolve:

Nutrient Deficiencies and Imbalances

Plants require a balanced intake of essential nutrients for proper growth and development. Crops often struggle with nutrient deficiencies or imbalances due to various factors like poor soil

quality and unfavourable pH, improper fertilization, or environmental conditions such as excess rainfall and drought. This can lead to stunted growth, poor yield, and overall reduced crop health. Nutrient-deficient plants are often weaker and more susceptible to pest infestations and diseases, further compounding the problem.

ICLeaf provides a precise snapshot of the nutrients present in plant tissues, allowing for early detection of the deficiencies and toxicities. By identifying specific nutrient imbalances, ICLeaf helps farmers adjust their fertilization strategies to ensure plants receive the right nutrients in optimal amounts, leading to healthier crops and improved yields.

Precision Fertilization & Monitoring Fertilizer Efficiency

Precision fertilization involves applying the right type and amount of fertilizer at the correct time and location to maximize crop productivity and minimize waste. Over-application of fertilizers can result in wastage, environmental damage, and decreased crop yields, leading to issues such as algal blooms and eutrophication. Conversely, insufficient application causes poor plant growth, nutrient deficiencies, and economic losses due to stunted development and reduced yields. Effective fertilizer use is complex, as factors like soil type and pH, moisture levels, and microbial activity influence nutrient absorption and utilization.

ICLeaf seamlessly integrates with Crop Advisor, providing real-time insights into crop health and nutrient status. ICLeaf provides a detailed analysis of plant nutrient content, enabling precise adjustments in fertilizer application. Crop Advisor promotes sustainable crop production by ensuring precise nutrient application throughout the season, promoting sustainable growth and minimizing waste. This helps farmers apply fertilizers more accurately and optimizes precision fertilization efforts. This allows for timely interventions to optimize nutrient availability, maximizing yield and quality.

Disease and Pest Differentiation

Symptoms of nutrient deficiencies can often mimic those caused by pests or diseases, such as yellowing leaves, leaf spots, and stunted growth. These symptoms can lead to misdiagnosis and incorrect treatments, potentially exacerbating the problem and wasting resources. For instance, treating a nutrient deficiency with pesticides or fungicides may not address the underlying nutrient issue, causing the problem to worsen. Additionally, applying the wrong treatment can lead to increased costs and environmental impact.

ICLeaf offers precise analysis of nutrient levels in plant tissue, enabling accurate differentiation between

nutrient deficiencies and other issues. This detailed insight helps identify whether symptoms such as yellowing leaves or stunted growth are due to a lack of essential nutrients or other factors. By pinpointing exact nutrient imbalances, ICLeaf and Crop Advisor facilitates targeted fertilization and nutrient management, avoiding unnecessary treatments for pests or diseases, enhancing crop management strategies, thereby enhancing farmers' productivity on sustainable basis.

Environmental Sustainability

Over-fertilization leads to excess nutrients washing away and entering water bodies. This can cause water pollution, eutrophication, and soil degradation. It also causes algal blooms in water bodies, depleting oxygen, harming aquatic life, and creating dead zones. Eutrophication promotes algae and aquatic plant growth, disrupting ecosystems and reducing biodiversity. Soil degradation also occurs due to over-fertilization, reducing its ability to support healthy plant growth.

ICLeaf enables precise nutrient management and reduces runoff risk and unnecessary costs, promoting sustainability. Crop advisors, using ICLeaf results, offer expert guidance to create customized nutrient plans, recommending appropriate fertilizers and application rates. They ensure that nutrient management is part of a holistic strategy that includes pest control and soil health, fostering long-term sustainability and optimal crop performance while educating farmers on best practices.

ICLeaf

ICLeaf is a groundbreaking technology-driven service that combines XRF and NIR analysis to offer unparalleled precision in nutrient diagnostics for high-value crops such as grapes, pomegranate, banana, and tomato. ICLeaf is setting new standards in leaf testing, offering an extensive and repetitive service scope that is both effective and in high demand.

ICLeaf Sampling Protocol and Calibration Standards

Avoid taking samples from border rows, diseased trees, trees near irrigation channels, water-stressed or waterlogged areas, and trees that have been recently sprayed. Protocols for crop-wise, stage-wise, leaf sample collections are given in **Table 1**.

Calibration and Standardization XRF and NIR

- Calibration is essential to ensure accurate and reliable results when using XRF and NIR spectroscopy for leaf testing. Regular updates and recalibrations are necessary to maintain precision as these technologies are applied to various crops and changing conditions.

Table 1. Protocols for leaf sample collection

Crop	Stage	Position	No. of leaves
Banana	Before bunching	Two strips 20 cm wide from each side of midrib to margin from the centre section of the third fully expanded leaf	25
Grapes	Bud differentiation stage	Recently matured leaf or 4 th to 5 th leaf from bottom	50
	Full bloom stage	Leaf opposite the first cluster or bunch	50
Pomegranate	Mid-season (Fruit development)	Leaf pair from the growing tip of non-fruiting secondary branches of tree node)	50
Tomato	Before flowering	Youngest mature leaf, 4 th or 5 th leaf from the top	50
	Maturing of first fruit		50
Cotton	Bloom stage	Youngest mature leaf, 4 th or 5 th leaf from the top	50

- For standardization, we tested 50 samples of each crop using wet chemistry methods. The same samples were also analyzed in Israel using XRF technology to establish a standard logarithmic correlation between the sample readings. This process ensures that the XRF results are accurately aligned with the wet chemistry data, allowing for consistent and reliable nutrient analysis.

A snapshot of procedure of sample analysis with XRF and NIR technologies from drying of sample to generation of report are given in **Photos from 1 to 4**.

Key Benefits of ICLeaf

- ♦ **Rapid Nutrient Diagnosis** - ICLeaf offers a faster and accurate method for nutrient diagnosis, enabling farmers to make timely fertilization decisions, thereby ensuring optimal crop health and maximizing yields, unlike conventional leaf analysis's time-consuming nature.
- ♦ **Non-Destructive Analysis** - ICLeaf's non-destructive XRF and NIR technologies enable repeated measurements of plant material without compromising its integrity. This allows for ongoing monitoring of nutrient status throughout the growing season, providing a comprehensive understanding of the plant's nutritional needs, unlike traditional methods that require sample destruction.
- ♦ **Comprehensive Nutrient Assessment** - ICLeaf combines the strengths of both XRF and NIR technologies to provide a more complete picture of leaf nutrient status. XRF is effective for analyzing various macro- and micro-nutrients, including trace elements, while NIR is particularly effective

for assessing key macronutrients like nitrogen, addressing the limitations of traditional methods.

- ♦ **Precision Agriculture Integration** - ICLeaf seamlessly integrates with Crop Advisor, enabling optimized nutrient management plans based on leaf analysis data. This supports precision agriculture practices by providing real-time insights into crop health and nutrient status, enabling targeted fertilizer application and resource use optimization, thereby improving nutrient efficiency and reducing environmental impact.
- ♦ **Sustainable Crop Production** - ICLeaf's periodic analysis ensures precise nutrient application throughout the season, promoting sustainable growth and minimizing waste and environmental harm, contrasting with single annual applications, thereby promoting optimal crop development and yield.

Crop Advisor

Crop Advisor is a cutting-edge tool that integrates precision agriculture technologies such as satellite imagery and soil sensors to enhance nutrient use efficiency (NUE) and fertilizer use efficiency (FUE) in agriculture. By providing real-time insights into crop health and nutrient status, Crop Advisor empowers farmers with data-driven recommendations, ensuring optimal crop health and maximizing yields. This technology enables farmers to make informed decisions that significantly improve both NUE and FUE.

Key Features of Crop Advisor

- **Data-Driven Recommendations** - Crop Advisor



Photo 1. Drying of sample

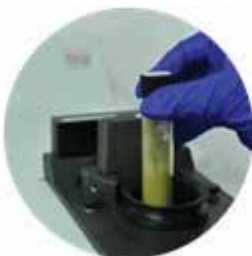


Photo 2. Analysis with NIR



Photo 3. Analysis of XRF



Photo 4. Report generation

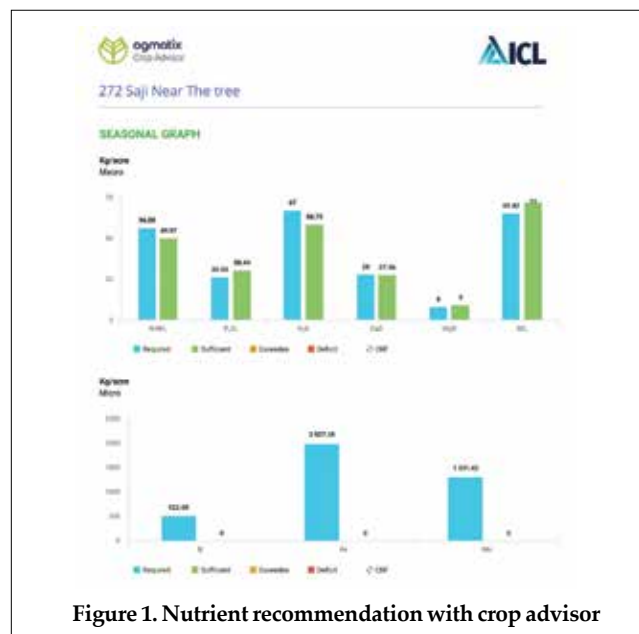


Figure 1. Nutrient recommendation with crop advisor

uses data-driven recommendations, analyzing soil characteristics, historical performance, and field conditions, to provide precise, tailored recommendations for specific crops, varieties, and expected yields.

- Integrated Nutrient Management - Crop Advisor seamlessly integrates with nutrient analysis tools like ICLeaf, offering detailed recommendations based on leaf analysis data, enhancing crop efficiency, waste reduction, and overall performance by tailoring nutrient management to specific crop needs.
- Customized Fertilization Plans - Crop Advisor creates customized fertilization plans (Figure 1) based on field data, considering soil health, crop type, growth stage, and environmental factors. They can also make dynamic adjustments based on soil and crop analysis, enhancing uptake and reducing wastage.
- Reduced Environmental Impact - Precision nutrient application minimizes over-fertilization risk, reducing waste and protecting the environment (Figure 2). Crop advisors offer targeted nutrient recommendations to minimize nutrient waste, costs, and environmental impact, such as water pollution.
- Improved Crop Yields - Optimizing nutrient

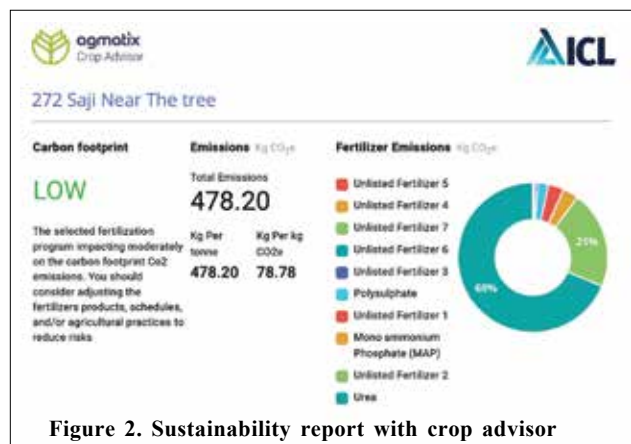


Figure 2. Sustainability report with crop advisor

applications can boost crop yields, increase productivity, and reduce fertilizer use, ultimately improving farm profitability by reducing the total amount of fertilizers used.

There has been considerable CO₂ emission and carbon footprint in kg per MT of yield and per hectare of the area from the fields of the growers from August 2022 to July 2024 as illustrated in Figure 3.

ICLeaf: Social Impact

- Since the launch in August 2022, 1600+ leaf samples have been tested on grapes, tomato & banana from the states of Maharashtra, Karnataka, Madhya Pradesh, Gujarat, Andhra Pradesh & Tamil Nadu.
- ICLeaf supports the sustainable useability of products with different environmental sensitivity. For each prescription, it is possible to see a calculated carbon footprint. Based on this view, it is possible to change the product used in the prescription and see the corresponding change in carbon footprint for the field.
- To date, on an average 125 to 140 kg of carbon have been saved per field through changes to product type leading to less runoff and other environmental impacts.
- Impact on yield improvement: About 47% of farmers who received the ICLeaf and Crop Advisor report experienced a 10 to 20% increase in yield.
- Impact on saving cost on fertilizer application: 75% of farmers experienced that by following the Crop Advisor report, there is decreased fertilizer cost.
- As a result, we've developed a strong connection with high-value horticulture and commercial crop

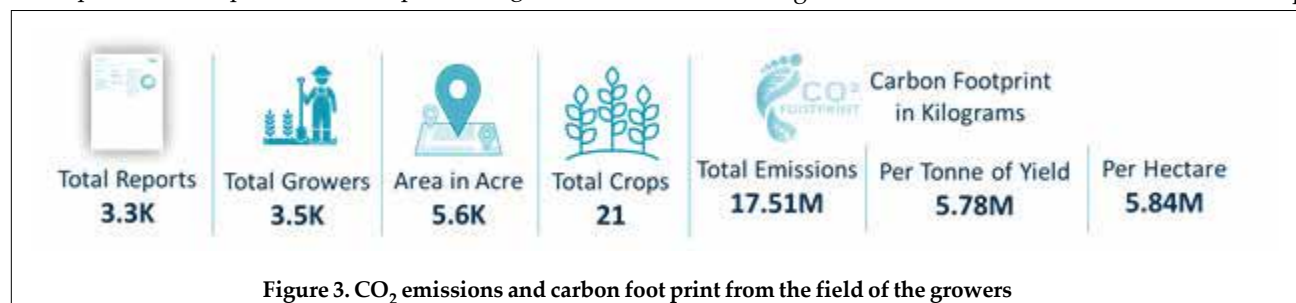


Figure 3. CO₂ emissions and carbon foot print from the field of the growers

growers, helping them plan optimal nutrient management by identifying deficiencies.

(Source – ICL internal survey done during Q2 2023 in the state of Maharashtra over teleconference in Marathi language. Samples were randomly selected.)

Farmers Success with ICLeaf

Farmer Name: Rajendra Fapale

Address: Savargav Tal, Sangamner, Ahmednagar

Crop: Tomato



Photo 5. Tomato crop in the field

With over 20 years of experience in tomato farming, we witnessed remarkable improvements in growth and production after learning about the leaf testing technology introduced by ICL as ICLeaf. We tested our tomato leaf samples for the first time with great excitement. The report provided us with detailed information on stagewise nutrient requirements, identifying nutrient deficits and excesses. By following the Crop Advisor report from planting to harvest, we achieved a significant increase in yield. Implementing the fertilizer management plan based on the ICLeaf and Crop Advisor reports, we were able to achieve 40-45 tonnes of yield per acre. Crop of tomato is shown in **Photo 5**.

Farmer name: Amit Bhor

Address: Bhorwadi, Junnar, Pune

Crop: Grapes

Managing a vineyard is tedious and labour-intensive, especially when aiming for export-quality grapes, which require precise nutrient and water management. In the past, we relied on soil and petiole testing, but the lengthy wait for results was a



Photo 6. Grapes in the field

challenge. Then we discovered ICLeaf. We decided to test it by sending a leaf sample from one plot. The ICLeaf report quickly identified the crop's nutritional

deficiencies, and we followed the recommended fertilizer management practices. The Crop

Advisor report made it easier and more timely to manage upcoming fertilizer applications, helping us achieve our targeted yield from the same plot. We are thrilled to see an increase in yield and quality while reducing extra costs on additional fertilizers. A crop of grapes is depicted in **Photo 6**.

Conclusion

ICLeaf stands out as a transformative technology in modern agriculture, offering a precise, rapid, and non-destructive approach to leaf nutrient analysis. By providing real-time assessments, ICLeaf enables farmers to fine-tune their fertilization strategies, ensuring crops receive the right nutrients at the right time. This precision mitigates the risks of nutrient imbalances, reducing the likelihood of over- or under-application of fertilizers, which can lead to economic losses and environmental harm. Additionally, ICLeaf's ability to differentiate between nutrient-related issues and disease symptoms optimizes crop management, preventing unnecessary treatments and enhancing overall crop health.

Since its launch, ICLeaf has made a significant social impact, with many farmers reporting substantial improvements in yield and cost savings. As a revolutionary technology, ICLeaf is transforming sustainable agriculture by addressing crop nutrition management challenges. It enables farmers to achieve higher yields, reduce costs, and minimize their environmental impact while ensuring crop health and productivity. This pioneering technology is essential for farmers meeting the demands of a growing global population.

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Short Note :

Fasal : Revolutionizing Agriculture through AI and IoT

Subhangi Ghosh

Fasal, Bengaluru, Karnataka

In the heart of India's agricultural landscape, a revolution is quietly unfolding. Founded in 2018 by visionaries Shailendra Tiwari and Ananda Verma, Fasal has emerged as a beacon of innovation in the agricultural sector. Born from a passion for transforming traditional farming practices, this pioneering company has quickly established itself as a leader in precision horticulture, bringing the power of technology to the fields of India and beyond. At its core, Fasal is driven by a simple yet powerful mission: to empower farmers by eliminating guesswork from farming. The company's mantra, grow more, grow better, and sell better, encapsulates its holistic approach to agricultural transformation. Fasal is not just about improving farming; it is about revolutionising the entire agricultural value chain.

Fasal has been using innovative use of cutting-edge technologies. By leveraging a potent combination of artificial intelligence, crop sciences, and the internet of things, Fasal provides farmers with unprecedented insights and support. The company's solutions offer farm-level intelligence, tailoring recommendations to each unique farm environment. This personalized approach extends to crop-specific solutions, recognizing that different crops have different needs. Moreover, Fasal's stage-specific guidance ensures that farmers receive precise recommendations based on the growth stages of their crops, optimizing care throughout the growing season. But Fasal's impact goes beyond the field. The company's full-stack offering transcends mere data analysis, providing actionable intelligence for optimal growing conditions. Taking it a step further, Fasal's B2B brand, Fasal Fresh, bridges the gap between farm and market. By procuring and marketing high-quality produce, Fasal ensures that farmers not only grow better crops but also secure attractive prices for their harvest.

Farmers using Fasal's solutions have seen reductions of up to 60% in water and up to 30% in pesticide usage, contributing to more sustainable farming practices. Crop yields have increased by up to 30% along with improvement in quality boosting farm productivity and profitability. Since its inception, Fasal has rapidly expanded its footprint across major agricultural regions in India. The company's solutions are not just empowering individual farmers but transforming horticultural practices on a broader scale, contributing to a more sustainable and profitable agricultural ecosystem. From the grape vines of Maharashtra to the pomegranate farms of Karnataka, Fasal's impact is being felt across diverse crops and regions. Some of the crops, where Fasal is creating an impact are chilli, tomato, banana,

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pomegranate, grapes, guava, rice and many more across varied geographical terrains of India and South East Asia. An overview of technology for smart-farming is depicted in **Photo 1**.



Photo 1. An overview of technology for smart farming

Looking to the future, Fasal's vision remains clear and ambitious: to be at the forefront of agricultural innovation, driving positive change in farming communities worldwide. The company continues to invest in research and development, exploring new ways to harness technology for agricultural advancement, Fasal is constantly pushing the boundaries of what's possible in Ag-tech.

As climate change and population growth pose increasing challenges to global food security, Fasal's work becomes ever more crucial. While revolutionising 80,000+ acres of land, Fasal has minimized 54,965 MT of GHG emissions, saved 82.8 Billion+ liters of water and prevented 1.27 lakhs kg of chemical usage while growing crops. We are ensuring a sustainable future for agriculture by promoting resource-efficient, high-yield farming practices. With Fasal, future of farming is not just sustainable – it's thriving, productive, and technologically empowered.

Farmers interested in joining the agricultural revolution can visit <https://fasal.co/> to learn more about how Fasal is shaping the future of agriculture. From detailed product information to success stories from partner farmers, website offers a window into the transformative potential of precision horticulture. As Fasal continues to grow and innovate, it remains committed to its founding vision: a world where every farmer has the tools and knowledge to cultivate success, sustainably and profitably. ■

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FAI Activities

Improving Professional and Personal Effectiveness

The Fertiliser Association of India - Northern Region (FAI-NR), New Delhi, organized a training programme on **Improving Professional and Personal Effectiveness** during September 25-28, 2024 at Jim Corbett National Park, District Almora, Uttarakhand. Sixty-one participants from twelve member companies attended the programme. The training programme was inaugurated by Mr. S.P. Mohanty, Managing Director, HURL, New Delhi and Keynote Address was delivered by Mr. Sanjiv Kanwar, Chairman, FAI-NRC and Managing Director, Yara Fertilisers India Private Limited, Gurugram.

In his keynote (on-line) address, Mr. Sanjiv Kanwar, dwelt upon regenerative agriculture in view of the challenges being encountered in agriculture. The challenges comprise of depletion of soil and water resources; decline in soil health due to non-replenishment of nutrients as per the crop requirement; changing pattern of climate change having adverse effect on productivity of crops and environment; adoption of same cropping system more so in Indo-Gangetic plains; etc. He cited the examples of adverse effect of rising temperature at the time of maturity on production of apple in Himachal Pradesh and wheat in the northern region. Further, average yield of paddy is about 1.7 times more in China than in India. Therefore, promoting regenerative agriculture is the need of the hour.

Mr. Kanwar then apprised the trainees that although there is no official definition of regenerative agriculture. In Yara terms, it is defined as a systematic, outcome-based approach to adopt the best sustainable farming practices that positively affect nature and climate, across five recurrent themes such as climate, soil health, resource use, biodiversity and prosperity. Yara has taken accountability and responsibility to do something about the same.



Mr. Sanjiv Kanwar

Giving the key drivers of climate change such as product carbon footprint at farm gate ($\text{CO}_2\text{eq MT}^{-1}$ of crop); absolute farm green house gas as emissions ($\text{CO}_2\text{eq ha}^{-1}$); and monitoring of increase or decrease in soil organic carbon stock; Mr. Sanjiv Kanwar remarked that mitigating in-field carbon emissions and improving crop resilience are of paramount importance. The key drivers for change in soil health include physical, chemical and biological composition



Mr. S.P. Mohanty lighting the lamp at the inaugural session. Others seen in the picture from left to right are Mr. Harinder Kaushik, Mr. Manish Goswami and Dr. D.S. Yadav

of soil; fields without cover crops (days in a year); percentage of fields with minimum tillage; and assessment score of soil health. Therefore, improvement in soil fertility/productivity & soil structure and prevention of soil degradation are vital areas. Further, the key drivers for use of resources comprise of crop yield in MT ha^{-1} ; ratio of N removal and added N; water use efficiency in MT of crop m^{-3} of water use; land use efficiency *i.e.* extra $\text{MT of crop ha}^{-1}$ vs. base line; and per cent recycled nutrients used on farm. Therefore, efficient use of all resources especially nutrient and water need be given more emphasis.

In case of biodiversity, the key drivers for change are numbers of crop species ha^{-1} rotation $^{-1}$ in a year; and land use efficiency. Every effort needs to be made to protect the natural habitat. The key drivers for change in prosperity is the return on investment made more so by small and marginal farmers. Therefore, ways and means need to be in place to improve livelihood of the farmers. He concluded his address by underlining that good farms are good for the future and for that integration of the best of the past and present will certainly create a resilient future for every farm.

In his inaugural address, Mr. S.P. Mohanty stated that lot of water has flown in fertilizer industry in view of ups and downs over the years. He complimented the efforts of the FAI, in taking up various issues of the industry with the Government of India, suggesting their amicable solutions. Fertilizer industry has been instrumental in overall development of agriculture in the country.

There has been lot of transformation in the product development, starting from products of SSP in 1906 to urea, NP/NPK complexes and now nano products. As the fertilizers are plant food, the fertilizer industry plays a key role in ensuring food security by making fertilizers available to the farming community for use in their crops across the country. The marvelous achievements have become possible due to concerted efforts of the personnel working in the sector. Population of the country reached a level of about 143 crore and it will continue to be on the path of increase. Therefore, increased foodgrain production from stagnant net cultivated area will have to be obtained. There is no room of complacency except to keep pace with the challenges by addressing the same. Towards this, use of fertilizers in balanced proportion will have to be given more impetus to improve soil health and enhance crop production on sustainable basis.

In view of deterioration of soil health, Mr. Mohanty stated that Government of India is concerned and have been notifying various programmes/schemes to improve soil health. One of the vital initiatives is PM-PRANAM. The objective is to restore fertility of the Mother Earth. It is to promote balanced and sustainable use of fertilizers along with organic manures, alternative fertilizers, nano fertilizers, bio-fertilizers, etc. Market development assistance of Rs. 1500 MT⁻¹ to support marketing of liquid/fermented organic manures, phosphate rich organic manures produced as byproduct from bio-gas plants/compost bio-gas plants set-up under the umbrella of GOBARdhan scheme will help in promotion of organic-based fertilizers for sustenance of soil health. The scheme will also address the on-going issue of management of crop residues, and *Paralli* burning on one hand and minimizing the environmental footprints on the other, besides providing additional income to the farmers.

He apprised the participants about the policy-related areas and challenges/issues of the fertilizer sector. The sector has been a conduit towards reimbursement of subsidy to the fertilizer industry by the Government of India on behalf of the farmers for administrative convenience for the last 47 years. India is greatly import dependent to meet its requirement of raw materials for production of fertilizers and also for finished products. Therefore, ways and means need to be in place towards self-reliance in production of fertilizers and in meeting the demand of the farmers from the indigenous sources. Commissioning of new urea plants in the recent years is resulting in reduction in import of urea. With commissioning of one more plant, import dependency on urea will further get reduced. The

Government needs to recognize the legitimate elements of cost of production of urea under the pricing and subsidy policy. The energy norms from 2025-26 should be realistic and there is a need for rationalization of policy for production of urea beyond reassessed capacity to make this production viable.

In case of phosphatic fertilizers, Mr. Mohanty pointed out that operating installed capacity of P₂O₅ is 7.38 million MT but the capacity utilization is less. We are more import dependent which can be minimized considerably, provided capacity utilization is improved. However, raw materials/intermediates such as rock phosphate, phosphoric acid, ammonia and sulphur are mainly procured through imports for production of phosphatic fertilizers. The prices of such commodities are controlled/manipulated by few dominant players in the world to the disadvantage of India. To tide over the problems, Indian companies have already set up joint ventures in phosphate rich countries such as Jordan, Senegal, South Africa, Tunisia and Morocco. The Government needs to support & facilitate more such ventures abroad for P&K fertilizers. Use of phosphate rich organic manure having 8% P₂O₅ should also be encouraged.

Regarding potash, he stated that the country does not have any commercial proven potash reserves. Entire demand of K has to be met by import. Similar joint ventures for sustainable supply of MOP at reasonable price as stated for raw materials in production of P&K fertilizers are needed. Government, under NBS policy, has promoted Potash derived from Molasses (PDM), which is getting generated during the processing of sugarcane.

Mr. Mohanty had also pointed out that introduction of 100% *neem* coated urea and development of sulphur coated urea have better nitrogen use efficiency compared to normal non coated urea. However, R&D in development of coating of products on urea can regulate N release matching plant demand and mitigate environmental and leaching losses. Towards this, knowledgeable and experienced people shall surely find solutions, as was done for *neem* and sulphur coated urea. The other transformation is establishment of compressed biodegradable gas plants for production of organic-based fertilizers. Indian Oil Corporation has taken lead to establish such plants. Recent transformation in the sector is production and use of Nano urea, Nano DAP, Nano phosphorus, Nano zinc and Nano copper having better use efficiency and minimum damage to the environment. Use of drone for their applications would be more effective.



Faculty, participants and FAI officials

In his concluding remarks, Mr. Mohanty cited the example of Sri Lanka regarding adoption of natural farming and the problems the country had faced. Therefore, organic farming should be promoted in areas which are suitable for such farming especially in hilly areas. Such practices, if adopted in traditional areas, cannot meet the requirement of food, fuel, fibre and feed of the growing population. Therefore, adoption of integrated use of fertilizers is the need of the hour.

He wished the programme a success.

Earlier in his welcome address, Dr. D.S. Yadav, Director (Publications & Public Relations), FAI, New Delhi briefed about course content and topics to be covered by the resource persons. He then gave an overview of FAI, its activities, training programmes and four monthly journals in addition to adhoc publications brought out by the Association. He requested the participants to become technical and professional members of the FAI to get the benefits of the journals.

Mr. Harinder Kaushik, Officer, FAI-NR, New Delhi, proposed a vote of thanks after the inaugural session.

The four-day training programme *inter alia* covered topics, such as Changing Pattern of Pricing and Subsidy Policies for the Sector by Mr. S. Shivakumar, Executive Director (Finance), Rashtriya Chemicals & Fertilizers Limited, Mumbai; An Overview of FCO 1985 and Recent Developments by Mr. Shyam Babu, Director, Central Fertilizer Quality Control & Training Institute, Faridabad; Salient Features of iFMS and DBT in Fertilizer Sector by Mr. Hemant B. Dabak, Chief Manager (Coordination), Hindustan Urvarak & Rasayan Limited, New Delhi; International Trade and Effective Ways for Port Operations by Mr. Rajesh Kumar Sahni, Head (Supply Chain), Yara Fertilisers India Private Limited, Gurugram; Precision Agriculture – Tech-based Solutions by Dr. Adarsha T.S., Joint General Manager (Agriculture Services and R&D), Zuari

FarmHub Limited, Bengaluru; Fertilizer Marketing Strategies in the Changing Environment by Mr. Dileep Singh, Chief Marketing Officer, Indorama India Private Limited, New Delhi and Improving Logistics Operations for Optimizing Cost by Mr. Dileep Singh on behalf of Mr. V.S. Chauhan, General Manager (Supply & Distribution), CFCL, Kota; Nano Fertilizers in Agriculture and Marketing Strategy by Dr. Tarunendu Singh, Head (Agricultural Services), IFFCO, New Delhi; Improving Productivity and Cost Optimization of Fertilizer Plants by Mr. Manish Goswami, Chief (Technical), FAI, New Delhi; Fertilizer and Raw Material Scenario, and Importance of Water Soluble Fertilizers and Micronutrients in Agriculture by Dr. D.S. Yadav; Role of Organic-based Fertilizers, Bio-fertilizers and Bio-stimulants in Indian Agriculture by Dr. V.K. Tiwari, Joint General Manager (Marketing), KRIBHCO, Noida; Giving Boost to Promotion of SSP in Indian Agriculture by Mr. Rajesh Kumar Pastiya, Senior Associate Vice President (SSP) & Head (Manufacturing), Coromandel International Limited, Secunderabad and Soft Skills for Success (Interpersonal Skills, Time Management & Effective Leadership, Team Building, Stress Management & Positivity for Success) by Dr. Mahipal Singh, Professor & Head, Department of Physics, Radhey Hari Government Post Graduate College, Kashipur, Uttarakhand.

Mr. Manish Kumar, Director (Finance), KRIBHCO, Noida was the Chief Guest at the valedictory session. In his address, he thanked FAI-NR for inviting him to address the participants of this vital training programme. The theme is very critical to the global agricultural sector and indeed for sustaining food security and soil health. It is beyond doubt that fertilizers have played and will continue to play vital role in improving farm productivity to meet the demand of growing population. He stated that fertilizer industry is highly complex, dealing with a variety of raw materials; production process; import of finished fertilizer products;



Mr. Manish Kumar giving certificate to a participant. Others seen in the picture from left to right are Dr. V.K. Tiwari, Dr. D.S. Yadav and Mr. Harinder Kaushik

movement of fertilizers through rail & road and handling of fertilizers at rake points and warehouses; distribution channel and the farmers. Effective management strategies at every level are being adopted to make fertilizers available to the farmers in time and comply with quality parameters in every respect as per FCO, 1985. The ultimate goal has always been to maximize agricultural output and minimizing environmental footprints.

Mr. Manish Kumar then enumerated the key areas of sustainable practices and innovation which are not an option but have become necessity in view of changing environment. Now more emphasis will have to be given on research and development to innovate fertilizer products which are more efficient and environment friendly. For achieving sustainable development goal, use of green technology is of vital importance. Planning for effective management of logistics and supply chain will also be necessary. Forecasting of fertilizer demand precisely, proper planning of production and import with inventory management, bridging the gap between demand and supply, and optimizing distribution networks, etc. will have to

be given more prominence. Optimization of cost from production to last mile delivery and reducing energy consumption in urea production will also be necessary.

Effective management also includes compliance with both national and international regulations to ensure that products meet safety standards and does not harm ecosystems.

In his concluding remarks, he mentioned that the future of food security will depend on how well the fertilizer industry adapts to the emerging challenges ahead, from environmental pressures to growing demand of food.

Mr. Manish Kumar covered the last point of management strategy that is embracing technology and data-driven decision making. By utilizing data analytics, managers can make informed-decision regarding production schedules, inventory management, and even product formulations.

Building strong relation with the end users of fertilizers *i.e.* farmers help in creating brand equity. Companies that invest in farmers' education by providing guidance on proper use of fertilizers to build-up soil health and enhance farm income succeed in their endeavour. Then, he stated that knowledge and skills of the personnel can be improved by participating in such programmes and understanding SWOT analysis is necessary.

Mr. Manish Kumar distributed certificates to the participants. On behalf of participants, Mr. Dattatray Gaikwad, Deputy General Manager (ETP), RCF, Thal, Mr. Ravichandran A., Assistant Manager (HR), KRIBHCO, Hazira, Ms. Priya Yadav, Agriculture Graduate Trainee, IFFCO, New Delhi and Mr. Mashoq Ahmad Rah, Junior Field Representative, IFFCO, Una, Himachal Pradesh shared their views and appreciated the course content and faculty of the programme. Mr. Harinder Kaushik proposed a formal vote of thanks at the end of programme.

Fertilizer Business Management

The Fertiliser Association of India (FAI), New Delhi organized a programme on **Fertilizer Business Management** during September 12-14, 2024 at Udaipur, Rajasthan. Fifty-five participants from eighteen organizations attended the programme. Dr. Naresh Prasad, Director (Marketing), FAI, New Delhi inaugurated the programme by lighting the lamp.

In his address, Dr. Naresh Prasad welcomed the participants and informed that this programme is

being organized keeping in mind the current challenges and changing environment under which the fertilizer industry has to operate in India, and how best to tackle and resolve these challenges in order to deliver business in the most economical, efficient and best possible way. He informed that there was a time in India's history when the agricultural production and yield was very low. In spite of the fact that our population was not that big compared to today's scenario, we were begging bowl and witnessed the



Dr. Naresh Prasad lighting the lamp at the inaugural session. Others seen in the picture are FAI officials and participants

Bengal Famine in 1943 and a large number of people lost their lives due to hunger. This prompted the Government of India after Independence to take bold steps in order to ensure food security to its population. As a result, introduction of high yielding crop variety seeds led to Green Revolution in India and we became self-sufficient in food grain production in the year 1968. As a result, this transition from tall variety to dwarf variety crop seeds led to agricultural transformation from food scarcity to food sufficient nation.

Given the crucial role of fertilizer in agricultural production and sustainability, Dr. Prasad began his address by giving a historical overview of agricultural development in the country. He informed that agriculture is the backbone of Indian economy. Nearly 55% of the total workforce is engaged in agriculture and allied sector and accounts for 18% of India's GVA at current prices during 2022-23. India is also the net exporter of agricultural products. However, the most important contribution of agriculture will be to ensure food security to the nation on sustainable basis.

Dr. Prasad mentioned that since the demand for plant nutrients was quite high in case of HYV of crops, fertilizer use assumed prime importance in increasing agricultural production and yield. This led to increased use of fertilizers in agriculture. During 1950-51, our food grain production was 50.8 million MT while our nutrient consumption was 69.8 thousand MT only. However, during 2023-24, our food grain production has multiplied by 6.5 times to the tune of 332.3 million MT while our nutrient consumption has multiplied by 439 times to the tune 30.6 million tonnes. Thus, agricultural transformation through the use of HYV crop seeds and fertilizer use allowed India to become food surplus nation, and thereby ensuring food security to its population.

To meet the increasing demand of fertilizers, Dr. Prasad informed that fresh investment in the form of setting up new plants came in which were supported

by the policy of the Government. He gave an overview of product-wise number of plants; commissioning of 6 urea plants recently and more to be commissioned in 2025; product-wise capacity, production, import of finished fertilizers; import of different raw materials/feedstock/intermediates to manufacture Urea, NP/NPK complex and SSP in 2023-24. Country is import dependent to a great extent for finished fertilizers or raw materials. He suggested that any geopolitical or international crises be it war, global health hazard or diplomatic tensions in the resource rich nations creates disruption in timely supply and availability. In the past, it has led to sharp rise in prices due to limited availability. However, in order to ensure food security to its population, insulate farmers from the international market, and keep the fertilizer MRP affordable, Government of India has been bearing the impact of unprecedented price rise in the international market, which has led to significant increase in fertilizer subsidy bills in the last few years.

Further, Dr. Prasad reminded the participants that unlike other sectors which follow free-market policy, fertilizer business in India operates strictly under the controlled environment, whether it is production, supply, movement, marketing, quality or price. He briefly touched upon several issues currently being faced by the industry such as issue of inadequate compensation based on import parity price in the case of urea production beyond reassessed capacity, under recovery on account of primary and secondary freight, unrevised fixed cost, viability of urea plants with tightening of energy norms, and no respite under customs duty and GST. He also discussed the challenges that have emerged as a result of single brand promotion under One Nation One Fertilizer (ONOF) policy, keeping urea outside the NBS policy, logistic challenges, and opportunities under Pradhan Mantri Kisan Samridhi Kendra (PMKSK), the need for expansion of product basket and exclusive retail outlets, technological intervention such as the application of AI in fertilizer and agriculture sector, and the role of efficient/innovative fertilizer products. Further, he also mentioned about the fallout of Green Revolution in terms of deteriorating soil health, organic carbon, biological activities, environmental concern and climate change. There is a need for adoption of climate resilient agriculture. Further, he also emphasized the importance of understanding policy regulation properly whether it be Fertiliser Control Order (FCO), movement order, urea policy, nutrient based subsidy (NBS) policy, freight policy, gas pooling policy in order to execute fertilizer business effectively and efficiently.

He concluded his address by hoping that the programme will meet the expectation of the participants, and wished them a fruitful and



Participants with faculties and FAI officials

meaningful learning in order to excel and help in their respective organization.

Earlier, Mr. Parag Saxena, Chief (Marketing), FAI informed the participants that FAI has been conducting various training programs for the fertilizer industry personnel on the subjects of topical importance. The response in all these programmes from the Industry as well as the feedback received from the participants has been quite encouraging. Earlier also, FAI organized similar programme at Goa in 2022 and there were requests from the industry to organize such programme again. He gave an account of the presentations to be made by the learned speakers during the next 3 days and also highlighted the role and activities of FAI. At the conclusion of the inaugural session, Mr. Mustafiz UI Hasan, Marketing Executive, FAI proposed a formal vote of thanks.

During the programme, twelve presentations were made by the faculties from FAI, fertilizer industry and subject matter specialists. The inaugural session was followed by a virtual presentation on Fertilizer Policy – Key Initiatives and Desired Interventions by Mr. R.M. Deshpande, Senior Executive Director, NFCL, Hyderabad. He detailed about the evolution of urea policies from Retention Price Scheme (RPS) to New Pricing Scheme (NPS) I, II, III followed by New Urea Policy 2015 (NUP 2015); policy for production beyond reassessed capacity etc. Urea policies are fully integrated and overlapping with continuation of earlier policies and a sound historical understanding of the development of urea policies is crucial for effective fertilizer business management. He also discussed the change in urea pricing in Modified NPS-III such as Additional Fixed Cost (AFC), and in the current NUP 2015 changes such as the revised energy norms, regrouping of urea units into three categories, and compensation beyond RAC. Further, he also briefed about the *neem* coated urea policy, New

Investment Policy 2012, subsidy budget for fertilizer industry, and gas pooling policy of 2015.

On the policy of P&K fertilizers, he enumerated about RPS implemented in 1979 and then decontrol of price, movement and distribution effective from 25th August 1992 on the basis of report of the Joint Parliament Committee constituted by the Government of India in 1991. However, due to considerable increase in retail prices, an adhoc concession (later termed as concession) scheme/policy was announced for DAP, MOP, and NP/NPK fertilizer w.e.f. rabi 1992-93. Such concessions were revised from time to time in the later years. However, implementation of concession scheme did not really bring about any investment, rather subsidy outgo increased exponentially. To bring reform in the sector, the Government introduced the NBS policy for decontrolled P&K fertilizers w.e.f. 1st April, 2010 and for SSP from 1st May, 2010. He briefed about the policy and stated that at present, 28 fertilizer grades are eligible under NBS policy. He also pointed out that although SSP was included in NBS policy, it's treatment vis-à-vis other P&K fertilizers varied in case of balance subsidy claim procedures in pre-DBT period, freight policy and special adhoc subsidy. Mr. Deshpande also discussed key policy initiatives such as single brand ONOF policy, objectives of PMKSK, PM-PRANAM and retail price of Sulphur Coated Urea (Urea Gold).

However, on desired interventions in policy, he suggested realistic energy norms for urea units; updation of fixed costs to current levels and linking to suitable index; updation of normative working capital; reasonable minimum returns to the industry should be ensured till formulation of new policy; bringing urea under NBS scheme to ensure balanced fertilization; direct transfer of subsidy in the bank account of the farmers; decontrol on MRP of urea, bringing gas under GST; implementation of Integrated

Plant Nutrient Management Bill 2022; launching of new innovative products through R&D and viable transition to green technology in the fertilizer sector.

The second presentation was made by Dr. Naresh Prasad on Indian and Global Fertilizer Scenario and Future Outlook. He mentioned that India is the second largest consumer and producer of fertilizers in the world. With regard to import, India is one of the largest importer of fertilizers in the world and large requirement of fertilizers by India tend to increase the international prices. Due to volatile international market during 2022-23, the subsidy on fertilizers touched a figure of Rs.2,51,340/- crore mark. The International prices of fertilizers depend upon supply demand balance, crude oil prices, ocean freight, exchange rate variation, crop prices, competing demand from other usage, disrupted supply chains, domestic policies, geopolitical risk *i.e.* Russia Ukraine war, etc. As per the budget estimates for 2024-25, the subsidy on fertilizer is kept at Rs.1,64,103/- crore. He informed that Indian fertilizer sector is playing an important role of routing government subsidy on fertilizers to about 146 million farming families across the country for four and half decades. He detailed about the number of fertilizer plants, capacity and production in the country. With the commissioning of new urea units, production increased significantly. However, there is scope to increase production of P&K fertilizers. He also pointed out some of the issues of the agriculture sector viz. distortion in use ratio of major nutrients, deficiency of secondary and micronutrients, declining crop response ratio to fertilizer use, low fertilizer use efficiency and other environmental concerns.

On the second day, the first presentation was made by Mr. Rajesh Ruhela, Joint General Manager, IFFCO, Kandla on Fertilizers and Manufacturing Technology of Nitrogenous and Phosphatic Fertilizers. For production of ammonia, he discussed Haber-Bosch process, feedstock and complexities involved, and the latest technological developments. It was followed by discussion on production technologies for urea plants which covered production process, complexities involved, technological developments, leading technology suppliers, technology-wise operating urea plants, and key features of new ammonia-urea plants. Production of ammonia and urea is highly sophisticated and energy intensive process. He also remarked that the process licensors are few and same as for other parts of the world. For production of phosphatic and complex fertilizers, Mr. Ruhela discussed the raw materials involved, production process of sulphuric and phosphoric acid, NP/NPK complexes, granulation and drying process. In addition, he also shared the production process of urea phosphate (17:44:0) – a water soluble fertilizer and zinc sulphate monohydrate (33% Zn).

Mr. V.S. Chauhan, General Manager – Supply Chain & Distribution, CFCL, Kota made the second presentation on Ways and Means to Economize the Fertilizer Marketing Cost. He discussed the fertilizer supply chain; National Logistics Policy; elements of fertilizer logistics and cost such as transportation by rail and road handling; challenges involved in handling and ways of cost optimization; warehousing, and inter-state & intra-state movements. Further, he also explained monitoring of movement of fertilizers by DoF and freight reimbursement policies for urea and P&K fertilizers. He stated that the fertilizer industry is efficiently managing its logistics system, but the future will depend on integrating cutting-edge technologies, sustainable practices, and responsive policies. Bulk and container movement, multimodal movement, demand sensing & forecasting and infrastructure push are poised to enhance visibility and efficiency across the entire supply chain. Regulatory frameworks that incentivize multimodal movement, bulk transfer, fertilizer logistics park and cross-sector collaboration are imperative for driving positive transformation.

Third presentation was made by Dr. Amit Rastogi, Executive Vice President (Technology), Coromandel International Limited, Secunderabad on Status and Strategy for Promotion of Innovative/More Efficient Fertilizers. He supported the need to have more innovative fertilizers for increasing the food productivity in order to feed the growing population. Apart from making food available to all, there is a need for nutritional security also. The Government is also making its efforts for exploring indigenous sources of potash fertilizers, alternatives to chemical fertilizers, increasing use of micronutrients for balanced fertilization for sustainable agriculture. The Government is also promoting PM-PRANAM scheme to promote the use of organic fertilizers such as fermented organic manure and phosphate rich organic manure. The scheme will address many objectives such as reduction in the use of subsidized fertilizers through promotion of alternative fertilizers and their supply to farmers at affordable prices, utilization of biomass from various sources for production of alternative fertilizers thereby preventing harm to environment due to improper disposal and additional income to farmers through conversion of surplus biomass into alternative fertilizers. There is a need to develop strategy to promote innovative fertilizers by the experts in the field of R&D, agronomy, manufacturing, marketing and sale departments of the industry. Dr. Rastogi shared examples of innovative fertilizers already available in the Indian market such as *neem* coated urea, sulphur coated urea, nano urea, nano DAP, crop specific grades, urea-SSP, liquid fertilizers, potash derived from molasses, etc. and explained the key features.

Dr. Devraj Arya, Vice President (FS & RA), Agrostar, Pune made the fourth presentation on E-commerce in



Some of the participants with certificates after receiving from the executives

Agri Input – The Way Forward. Dr. Arya discussed the current issues being faced by the agri-input business such as low yield/productivity, quality issue, knowledge gap and poor market access & price realization. He informed that the need of the farmers have changed in the past few years as they are now looking for immediate information on crops; pest/disease; soil; fertigation; credible source for solving issues; timely supply of products at right prices; doorstep delivery of input products and services; & access to market information and market linkages. He suggested that these changes as well as the internet penetration in rural India have resulted in the emergence of e-commerce business. He then discussed the market size of agri-input industry in India; typical value chain; types of e-commerce business; and its difference with the traditional agri-input business. Further, he apprised the trainees about way in which AgroStar is leveraging innovative technologies and market outreach to lead e-commerce business in India. He concluded his presentation with a brief discussion on the scope of e-commerce in India, and the way forward for a better transition.

The fifth presentation was made by Dr. Naresh Prasad on Fertilizer Use – Myth and Reality. He discussed the reality behind the popular myths related to the use of fertilizers in India such as high consumption; harmful to people, wildlife and environment; why to add more when nutrients already available in the land and air; plant nutrients are different from organic fertilizers; subsidy is given to the industry and not to the farmers; pollute the soil; deplete the soil organic matter, not different from pesticides; and world can be fed without their use. Realities of such myths were listed by him. He also acquainted the trainees about the reality behind the myths surrounding the use of organic fertilizers and organically grown food.

Dr. K.K. Singh, Group Head - Agri Services and R&D, Zuari Farmhub Limited, Bengaluru made the sixth presentation on Marketing Challenges in Organic Fertilizers, Bio-fertilizers and Bio-stimulants. He gave

a brief overview on the sustainability of chemical fertilizer use in India and the potential of non-chemical fertilizer use and integration with conventional fertilizers. He discussed at length about such non-chemical fertilizers, their relevance and current market status. He then covered the challenges involved in the marketing of non-chemical fertilizers due to their perception, price, quality, and benefit to crops. Further, he proposed intervention at both production process and sales/marketing level to promote the use of non-chemical fertilizers. He suggested that developing a strong concept selling /farm consultative approach by marketers is the way forward to overcome the marketing challenges along with other infrastructural and extension support.

Seventh presentation of the day was made by Mr. Pankaj Singhi, Head Coastal Services, Avana Logistek, Ahmedabad on Coastal Shipping for Movement of Fertilizers – A Case Study. He explained the 7-R rules of logistics such as getting the right product, in the right quantity, in the right condition, at the right place, at the right time, to the right customer, and at the right price. He briefed about the present logistics infrastructure available in the country; available options for movement of fertilizers due to heavy dependence on rail network, encouragement of coastal shipping by the Government; promotion of multimodal options by utilizing coastal or inland waterways to help in reducing freight cost etc. He also presented a case study consisting of 7 coastal based plants located in 5 coastal states supplying fertilizers to 38 districts up to dealers / retailers / warehouse level. From the case study, he concluded that coastal shipping offers a distinct advantage over overburdened rail and road transport and provides cost effective, efficient handling, and environmental friendly option.

On the last day of the programme, a total of four presentations were made. The first presentation was on AI Application in the Fertilizer Sector and Need for Policy Initiatives by Mr. D.K. Tyagi, CEO, Farmgate

Technologies Private Limited, Hyderabad. He elaborated on the challenges, potential for transforming industries, and the role and benefits of AI in the fertilizer and agriculture sectors. He shared a case study in which an AI-based platform uses satellite imagery and AI algorithms to analyze crop needs and recommend precise fertilizer requirements. By adopting AI, improvements in crop yield were observed, along with a reduction in fertilizer use that resulted in cost savings. In another case study, the technology enhanced the ability of fertilizer to interact with plant roots and improve nutrient uptake, making it a more efficient option. He further emphasized the need for policy initiatives such as incentives for AI adoption, public-private partnerships for R&D, establishing standards and guidelines for AI use, and creating digital infrastructure.

Second presentation was made by Mr. Kevin Benny, Assistant Manager (PMT - Energy), MCX, Mumbai on Energy Price Risk Management. He emphasized that fertilizer production, particularly urea, is vital for food security, with urea alone making up 60% of domestic fertilizer production. Natural gas is the primary feedstock, representing over 80% of production costs. Industry's increasing reliance on liquefied natural gas has heightened volatility in fuel prices, complicating cost management. To mitigate price volatility, he informed that companies are encouraged to use commodity derivatives for hedging. Successful global examples highlight how firms like CF Industries and Nutrien employ financial instruments to stabilize costs and enhance profitability. Therefore, effective management of energy price risk through regulated exchanges like the Multi Commodity Exchange of India Limited (MCX) is essential for maintaining competitive performance and ensuring sustainability in the fertilizer sector.

Dr. A.P. Singh, Senior Manager (Agriculture Services), IFFCO, Jaipur, shared insights on Nano Fertilizers in Crop Nutrition. He explained that nano urea (liquid) has a use efficiency of more than 90% under optimal field conditions. The precision and targeted application of nano urea (liquid) as a foliar treatment can reduce the requirement for granular urea by up to 50% for different crops. For precision application, nano DAP (liquid) can reduce the requirement for granular DAP by 50-75% for crops. The main characteristics of nano fertilizers include a reduction in size, an increase in surface area-to-volume ratio, ability to cover more surface area than conventional fertilizers, a higher number of molecules available for reaction on the leaf surface, ease of entry into plants through stomata and other openings, and effective provision of nutritional requirements to the plants. The objectives behind the development of innovative nano fertilizers are to enhance nutrient use efficiency, increase crop productivity and quality at low input costs for

farmers, reduce imbalanced and indiscriminate application of conventional fertilizers to soil, and address soil-air-water pollution with precision. Dr. Singh discussed the potential benefits of nano fertilizers, such as crop improvement, crop protection, crop yield growth, precision farming, stress tolerance, and soil enhancement. He also shared the results of scientific trials on various crops, including wheat, mustard, maize, gram, groundnut, *bajra*, *moong*, cumin, fenugreek, and isabgol.

The virtual presentation on Amendments in FCO and Regulations was made by Mr. Shyam Babu, Director, Central Fertilizer Quality Control and Training Institute, Faridabad. He explained that the Government of India has notified fertilizers as essential commodities to regulate quality, production, supply, distribution, and trade, ensuring their availability to farmers. He detailed about 39 clauses and 7 schedules of the FCO, along with the enforcement authorities and their roles and responsibilities. There are various provisions for packing and marking that manufacturers, importers, and pool handling agencies must follow under the FCO. He informed that if fertilizer bags are cut, torn, or damaged during transportation or mishandling, the manufacturer or importer must, under intimation to the State Government and Central Government, repack the fertilizer in new bags or re-standardize the quantity in terms of declared weight. Provisions for the disposal of non-standard fertilizers and the procedure for fixing the price of such fertilizers were also outlined. He explained the sampling procedure, provisions for laboratory analysis, time limits for analysis, communication of results, and legal action if samples are found to be non-standard.

Dr. D.P. Singh, Assistant Director, Government of Rajasthan, Udaipur, interacted with the participants and explained the sampling procedure, particularly in Rajasthan. He stated that, according to the provisions of the FCO, only quality fertilizers, as specified in the FCO, should be supplied to the farming community. The Central Government and all State Governments are very strict regarding fertilizer quality. Dr. Singh then outlined the procedure of taking sample by the inspector under clause 28 and despatch of the samples and related areas of analysis in state laboratory, National Test House laboratories, or Central Fertilizer Quality Control and Training Institute given in sub clause 1 to 6 under Clause 28B.

At the conclusion, Dr. Naresh Prasad summarized the deliberations and requested the participants to clear their doubts, if any or ask the questions which they feel were un-answered. The queries raised by the participants were suitably addressed. At the end of the programme, Dr. Prasad, Dr. D.P. Singh and Dr. A.P. Singh distributed certificates to the participants. ■



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Proposed FAI Training Programmes / Seminars / Workshops – 2024-25 (Tentative)						
S. No.	Month	Name of the Programme	No. of Days	Residential (R)/ Non-residential (NR)	Name of City	Department/ Region
1	November 19, 2024	Fertilizer Dealer Training Programme	1	NR	Karimnagar, Telangana	Southern Region
2	November 20, 2024	Fertilizer Dealer Training Programme	1	NR	Gwalior, M. P.	Western Region
3	November, 2024	Balanced Crop Nutrition for Human and Animal Health	1	NR	Ranchi, Jharkhand	Eastern Region
4	November, 2024	National Seminar on Fertigation and Organic Fertilizers	1	NR	Krishnagiri, T.N.	Southern Region
5	December 4-6, 2024	FAI Annual Seminar	3	NR	New Delhi	FAI
6	December 17-20, 2024	Fertilizer Management Development Programme	4	NR	Hyderabad, Telangana	Southern Region
7	December 23, 2024	Fertilizer Dealer Training Programme	1	NR	Navsari Gujarat	Western Region
8	December, 2024	Marketing Research and Business Intelligence	1	NR	Thiruvananthapuram, Kerala	Southern Region
9	January 22, 2025	Fertilizer Dealer Training Programme	1	NR	Raigarh, Chhattisgarh	Western Region
10	January, 2025	Fertilizer Orientation Programme for Industry Personnel	4	R	Jaipur Rajasthan	Marketing
11	February, 2025	Fertilizer Management Development Programme	3	R	Goa	Western Region
12	January, 2025	Seminar on Use of Drone Technology in Agriculture	1	NR	Bhubaneswar, Odisha	Eastern Region
13	January, 2025	Fertilizer Management Development Programme	4	NR	Portblair, A&N Island	Southern Region
14	February, 2025	B2B Exhibition and Conference on Sustainable Agriculture and Technological Innovations in the Fertilizer Industry	2	NR	New Delhi	Marketing
15	February, 2025	Fertilizer Management Development Programme	3	R	Paradeep, Odisha	Eastern Region
16	February, 2025	Training Programme on Improving Professional and Personal Effectiveness	4	R	Jaisalmer, Rajasthan	Northern Region
17	February, 2025	Group Discussion on Operation and Maintenance Problems of Urea Plant	3	R	Chennai, T.N./Mumbai, Maharashtra	Technical
18	February, 2025	Fertilizer Dealer Training Programme	1	NR	Raichur, Karnataka	Southern Region
19	March, 2025	Fertilizer Orientation Programme for Agriculture Graduates	1	NR	Punjab	Northern Region
20	March, 2025	Workshop on Specialty Plant Nutrition	1	NR	Vadodara Gujarat	Western Region
21	March, 2025	Fertilizer Dealer Training Programme	1	NR	Punjab	Northern Region
22	March, 2025	Fertilizer Orientation Programme for Agriculture Graduates	1	NR	Wayanad, Kerala	Southern Region
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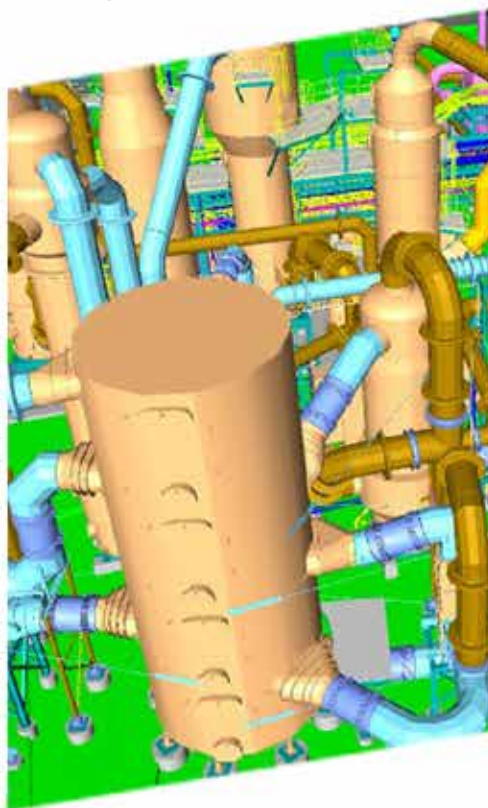


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FAI ANNUAL SEMINAR 2024
SUSTAINABLE FERTILIZER AND AGRICULTURE

4 – 6 December, 2024
Hotel Andaz Delhi, Aerocity, New Delhi, India

TENTATIVE PROGRAMME

Wednesday, December 4, 2024

0930-1700 hrs. : Registration
1100-1700 hrs. : Exhibition
1430-1600 hrs. : Inauguration, Distribution of Awards and Release of FAI Publications
1600 hrs. : High Tea
1900-2200 hrs. : Cultural Programme, Cocktails and Dinner

Thursday, December 5, 2024

0900-1700 hrs. : Registration
0900-1700 hrs. : Exhibition

SESSION I : SECTOR OUTLOOK

0915-1300 hrs.

- ◆ Reforms in Indian Fertilizer Sector
- ◆ Global Fertilizer Market and Future Prospects
- ◆ Global Fertilizer Prices and Outlook

SESSION II : DIGITAL AGRICULTURE

1400-1700 hrs.

- ◆ Innovations in Fertilizers
- ◆ Harnessing Data & Agtech for Integrated Crop Nutrition
- ◆ Digitization of Indian Agriculture
- ◆ Biofertilizers & Organic Fertilizers for Sustainable Farming

Friday, December 6, 2024

0900-1200 hrs. : Registration
0900-1700 hrs. : Exhibition

SESSION III : SUSTAINABILITY IN FERTILIZER PRODUCTION

0900-1300 hrs.

- ◆ Green Ammonia: Opportunities and Challenges
- ◆ Commissioning & Operating Experience of New Ammonia-Urea Plants
- ◆ Energy Improvement Project and Capacity Enhancement of Ammonia Plant
- ◆ Hyper-U: a Novel High-Efficiency Hybrid-Stripping Process
- ◆ Efficient Production of Phosphoric Acid Using Low-Grade Phosphate Rock
- ◆ Sustainable Solutions for Acid and Complex Fertilizer Plants

SESSION IV : INNOVATIVE MARKETING STRATEGY

1400-1600 hrs.

- ◆ Fertilizer Marketing Strategy under Changing Environment
- ◆ Nano Fertilizer – The Way Forward : Research Perspective
- ◆ Nano Fertilizer – The Way Forward : Industry Perspective
- ◆ Agri-input Digital Marketing – Prospects and Challenges

1600 hrs.

- ◆ Valedictory Session

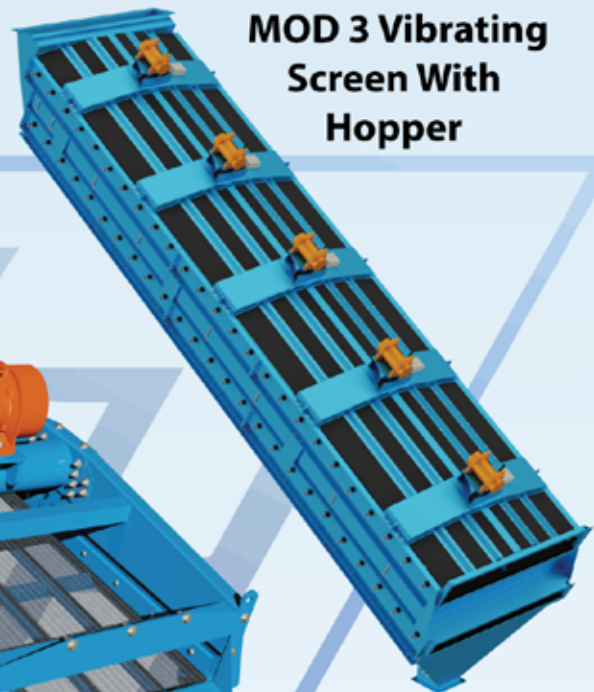


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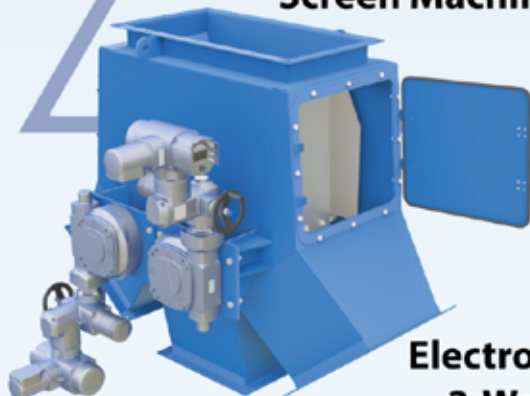
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Fertilizer Scene

Production of N at 1.394 million metric tonnes (million MT) registered a decline of 3.0% during September 2024 over September 2023. However, production of P_2O_5 at 0.462 million MT recorded an increase of 8.4% during the period. Production of urea and DAP registered a decline of 6.6% and 5.9%, respectively, during September 2024 over September 2023. However, production of NP/NPK complex fertilizers and SSP recorded sharp increase of 23.5% and 18.7%, respectively, during the period. Production of most of the NP/NPK complex fertilizer grades increased except 14-28-0, 15-15-15, 9-24-24, 12-32-16 and 10-26-26, which showed negative growth during the period. Capacity utilization of N declined from 99.4% during September 2023 to 95.8% during September 2024. In case of P_2O_5 , it increased from 70.3% to 74.2%, during the same period.

Production of N and P_2O_5 fell short from the target by 14.9 and 15.8 thousand MT, respectively, during September 2024.

As compared to the previous month, *i.e.*, August 2024, production of N declined by 5.1% during September 2024, while production of P_2O_5 increased by 0.1% during the period.

Production of total fertilizer nutrients (N+ P_2O_5) at 11.108 million MT during April-September 2024 increased by 1.0% over the corresponding period in the previous year.

Production of N at 8.476 million MT and P_2O_5 at 2.632 million MT during April-September 2024 registered increase of 0.9% and 1.1%, respectively, over April-September 2023. Among the major fertilizers, production of urea, NP/NPK complex fertilizers and SSP increased by 0.2%, 10.1% and 3.0%, respectively, during April-September 2024 over April-September 2023. However, production of DAP registered a decline of 7.6% during the period. Production of most of the NP/NPK complex fertilizer grades increased except 20-20-0 (ANP), 24-24-0-8, 28-28-0, 9-24-24 and 10-26-26, which showed negative growth during the period. Capacity utilization of N increased from 97.7% during April-September 2023 to 98.0% during April-September 2024. In case of P_2O_5 , it declined from 71.6% to 70.4% during the same period.

Cumulative production of N and P_2O_5 fell short by 302.6 and 170.4 thousand MT, respectively, during April-September 2024. Table given below shows production of N and P_2O_5 during September 2024 and April-September 2024 compared to the corresponding period in the previous year.

All India Production Target, Production and Capacity Utilization of N and P ₂ O ₅ September and April-September 2024 & 2023							
Item	Aug. 2024 ^P	Sept. 2024 ^P	Sept. 2023	+ % variation in Sept. 2024 over Sept. 2023	Cumulative (April/Sept.)		+ % variation in April/Sept. 2024 over April/Sept. 2023
					2024 ^P	2023	
◀ ('000 tonnes) ▶				◀ ('000 tonnes) ▶			
I. NITROGEN (N)							
A. Target of Production	1562.0	1409.1	1358.8	3.7	8778.3	8509.5	3.2
B. Production	1468.6	1394.2	1437.5	-3.0	8475.7	8396.4	0.9
a) Straight fertilizers	1220.8	1156.8	1234.2	-6.3	7128.7	7109.2	0.3
b) Complex fertilizers*	247.8	237.4	203.3	16.8	1346.9	1287.2	4.6
C. Capacity Utilization (%)	100.9	95.8	99.4		98.0	97.7	
II. PHOSPHATE (P ₂ O ₅)							
A. Target of Production	477.6	478.0	460.8	3.7	2802.7	2720.4	3.0
B. Production	461.7	462.2	426.3	8.4	2632.3	2603.7	1.1
a) Straight fertilizer (through SSP & TSP)	65.2	79.7	67.2	18.6	421.9	410.4	2.8
b) Complex fertilizers*	396.4	382.5	359.1	6.5	2210.3	2193.3	0.8
C. Capacity Utilization (%)	74.1	74.2	70.3		70.4	71.6	
P = Provisional	Note: Totals may not exactly tally due to rounding of figures				* = DAP+ NP/NPKs		



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