

Digital Soil Health Services for Long-term Sustainability of Agriculture

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Background

Since the beginning of the Green Revolution in 1965-66, the consumption of fertilizers in India has increased exponentially, from a mere 5 kg to 140 kg per hectare of the total cropped area by 2023-24¹. The increased use of fertilizers, combined with the expansion of irrigation, unlocked the potential of high-yielding seeds, significantly boosting agricultural production and addressing concerns of food and nutrition security. Nevertheless, the pattern of fertilizer consumption has remained notably skewed towards nitrogenous fertilizers, particularly in the states of Punjab, Haryana, and Uttar Pradesh, where the resource-intensive rice-wheat cropping system predominates (Figure 1a and 1b). This has resulted in the deterioration of soil health, water quality, biodiversity, and the environment. Moreover, the crop response to additional fertilizer application has started to diminish².

The main reason for the imbalanced use of fertilizers³ is the significant disparity in subsidy rates. Nitrogenous fertilizers receive a much higher subsidy, making them at least five times cheaper than phosphatic and potassic fertilizers⁴. When fertilizer-use efficiency is low, farmers tend to use more of the cheaper fertilizers, expecting higher crop yields. Notably, the expenditure on fertilizer subsidies in India increased from Rs. 40 billion in 1980-81 to Rs. 1291 billion in 2023-24 at 2011-12 prices.

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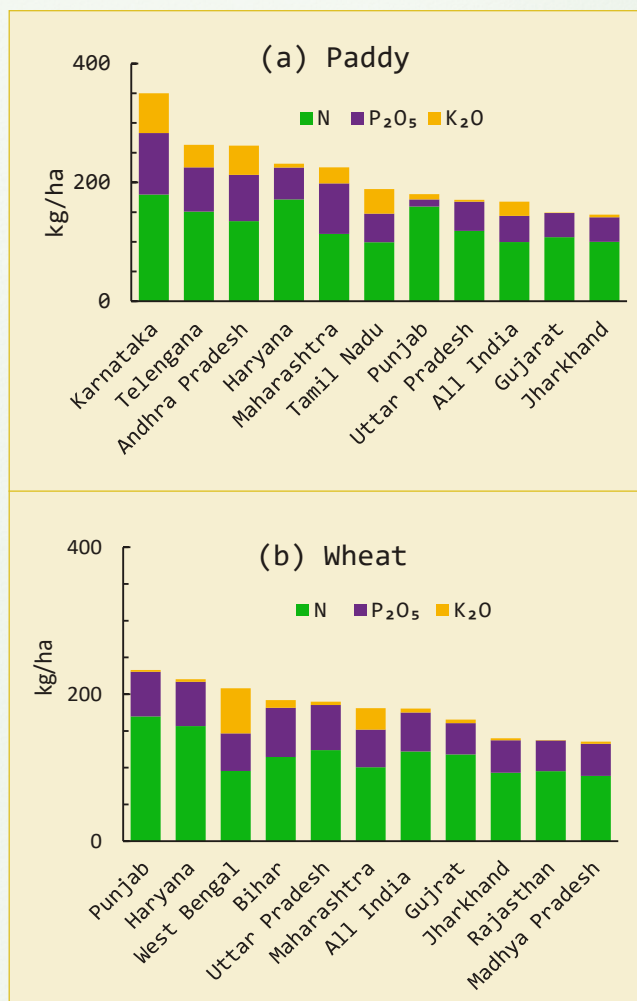
¹ Annual review of fertilizer production and consumption 2023-24, Indian Journal of Fertilisers, Fertilizer association of India.

² Vijayakumar, S., Gobinath, R., Kannan, P., & Murugaiyan, V. (2024). Optimizing potassium mining in rice-wheat system: Strategies for promoting sustainable soil health-A review. *Farming System*, 2(3), 100099.

³ Ideal ratio of NPK- 4:2:1, Current imbalanced ratio- 10.9:4.4:1; Annual review of fertilizer production and consumption 2023-24, Indian Journal of Fertilisers, Fertilizer association of India.

⁴ Birthal, P. S., Srivastava, S. K., Saxena, R., Godara, S., Chand, P., Kishore, P., Jumrani, J., Kandpal, A., Sharma, P. & Pant, D. K. (2025). *Indian Agriculture to 2047: Reshaping Policies for Sustainable Development*. Policy Paper 50. ICAR-National Institute of Agricultural Economics and Policy Research, New Delhi.

Figure 1. NPK use in paddy and wheat, 2021-22⁵



The Government of India has implemented several initiatives to reduce fertilizer consumption and address declining soil health. A significant measure is the introduction of the Soil Health Card (SHC) scheme in 2015, which offers farmers detailed information about the nutrient status of their soil, enabling them to make informed decisions regarding the types and quantities

⁵ Estimated using data from the Cost of Cultivation Scheme, Directorate of Economics and Statistics, Ministry of Agriculture and Farmer Welfare, Government of India

of fertilizers to use. Complementing this effort, the PM-PRANAM (Programme for Restoration, Awareness, Nourishment, and Amelioration of Mother Earth) scheme was launched in 2023 to incentivize states to decrease their reliance on chemical fertilizers. Moreover, a National Mission on Natural Farming has been launched in November, 2024 to encourage the use of natural bio-resources in crop production.

Despite the widespread distribution of SHCs, the translation of soil health information into effective farming practices remains limited, primarily because of policy and operational challenges. A notable gap is the lack of integration between fertilizer distribution and SHCs. Rather, their distribution is tied to the farmer's identification (Aadhaar Card). This disconnect between fertilizer distribution and soil health reduces the incentive to adopt soil test recommendations. Moreover, the lack of adequate soil testing facilities, long turnaround period for test results, inefficient information dissemination systems, and perceived risk of yield loss are additional factors deterring farmers from adopting soil health recommendations.

Digital soil testing, which integrates advanced sensors, machine learning algorithms, and data analytics, can address the limitations of traditional soil testing methods⁶. Such an innovation enables a more efficient, accurate, and timely evaluation of soil health and provides tailored recommendations regarding the appropriate type and quantity of fertilizer to be used for different crops. This approach consequently results in the optimal application of fertilizers, thereby reducing environmental footprints and the production costs.

Digital soil health assessment

Digital soil testing is a significant advancement in soil-testing methods. This allows rapid, on-site assessment of soil health and delivers real-time information on the status of soil health directly to farmers' smartphones. Moreover, this method can aggregate and store longitudinal data, providing a robust framework for monitoring soil health and policy decisions regarding the production and trade of fertilizers. Table 1 outlines the key differences between AI-based and traditional soil health assessments.

This study provides evidence on how utilizing soil health data gathered from farmers' fields with the help of an AI-driven portable soil-testing device influences fertilizer use, crop yields, and farm profits. The device, named 'Bhu Parikshak', was developed by the Indian Institute of Technology, Kanpur, and has been exclusively licensed to ScaNxt Scientific Technologies for commercial application.

⁶ Rahman, R., & Das, K. N. (2025). Artificial Intelligence and Machine Learning in Soil Analysis for Precision Agriculture: A Review. *Journal of Experimental Agriculture International*, 47 (5): 511-524.

Data were gathered from both adopters and non-adopters of soil health recommendations in the Lucknow and Hardoi districts of Uttar Pradesh. This effort was supported by the HCL Foundation in Hardoi and the People's Action for National Integration - PANI in Lucknow, both of which had acquired this device to generate and provide on-site information on soil health parameters to farmers in these districts under their Corporate Social Responsibility initiatives.

Table 1. Digital vs traditional soil testing systems

	AI-based	Laboratory based
Test parameters	N, P, K, Organic Carbon (OC), Cation Exchange Capacity (CEC), clay content	N, P, K, OC, EC, pH, S, Zn, Fe, Cu, Mn, B
Testing time (minutes)	2	180
Turnaround time	30 minutes	5 - 30 days
Soil quantity for test (gm)	5	500
Average cost to the implementer (Rs./test)	50 ⁷	200-300
Maximum capacity (samples/day)	250	25
Accuracy (%)	80-92	80-90
Testing site	Village /Farm	Lab

Source: <https://scanxt.com/bhu-parikshak/>

Impact of digital soil health services

Fertilizer use and crop yields

Fertilizer recommendation for the study area per ha varies from 60-150 kg for N, 30-60 kg for P₂O₅ and K₂O depending on rice variety, In rabi season, fertilizer recommendation for the study area per ha varies from 120 kg for N, 60 kg for P₂O₅ and 40 kg for K₂O for wheat crop⁸. The recommendation varies depending on location and soil test. Table 2 presents a comparison of the average use of different fertilizers as well as the yields of paddy and wheat between farmers who followed the digital soil test recommendations and those who did not and applied fertilizers based on their experience. Farmers following the soil test recommendations used significantly less nitrogen and phosphorus but more potash in both crops. Notably, this reduction and rebalancing of fertilizer use did not adversely affect crop yields; instead, it resulted in an increase in their yields. This has also led to a reduction in fertilizer costs and, eventually, if adopted widely, it could lead to a decline in the government's fertilizer subsidy burden.

However, a straight forward comparison of the averages of different indicators between users and non-users of digital soil health services may result in biased conclusions,

⁷ Average cost of the machine Rs 84,500.0

⁸ <https://upagriparadarshi.gov.in/MediaGallery/KrishiGyanM2021.pdf>

as it fails to account for differences in factors such as access to resources, education levels, and external environmental conditions that influence the decision to adopt. Ignoring these differences implies that the observed differences in averages could be confounded by these factors rather than representing a true causal effect of adoption itself.

To account for the effects of such confounding factors, the impact was evaluated using the propensity score matching (PSM) technique, which creates a balanced comparison between groups by matching households that adopted the recommendations with similar households that did not, based on a set of observed covariates. The sample size taken for the kernel-based study was 560 but effective sample size after matching in PSM was 552. The PSM provides the ATT (average treatment effect on the treated), which measures the difference in outcomes for adopters in the counterfactual absence of the intervention.

The ATTs indicate a substantially lower use of nitrogen by one-fourth in paddy and one-fifth in wheat cultivation following the soil test recommendations (Table 3).

Similarly, phosphorus use was reduced by 10% and 16% in paddy and wheat crops, respectively. On the other hand, the application of potash has more than doubled in paddy and 84% increase in wheat. These adjustments in nutrient application translated into a modest decline in fertilizer costs in paddy (3%), while wheat farmers realized a significant reduction of about 9% in fertilizer expenditure.

The adoption of digital soil health services has also led to a 13% increase in the yields of both paddy and wheat. However, the profit realization from paddy is significantly higher at 81% compared to wheat's 31%. This is mainly attributed to a greater reduction in the use of nitrogen and phosphorus in paddy than in wheat.

These findings imply that reducing fertilizer application does not necessarily lead to a decrease in crop yields, addressing the perceived risk of yield loss often associated with sustainable agricultural practices. From a policy perspective, this evidence supports the restructuring of subsidies and other incentives to reduce fertilizer usage and foster innovation for the sustainable development of agriculture.

Table 2. Comparison of nutrient use, yield, and net returns

Variable	Paddy			Wheat		
	Adopters (n= 275)	Non-adopters (n= 285)	Difference	Adopters (n= 275)	Non-adopters (n= 285)	Difference ⁹
N (kg/ha)	148	227	-79**	135	172	-37***
P ₂ O ₅ (kg/ha)	91	109	-18*	85	99	-14***
K ₂ O (kg/ha)	17	5	12***	18	10	8***
Fertilizer cost (Rs./ha)	7834	8170	-336	7521	8230	-708**
Subsidy benefits (Rs./ha)	15,325	21,942	-6616**	8170	10,181	-2011***
Total cost (Rs/ha) ¹⁰	79,773	78,460	1313	71,596	64,086	7510***
Yield (kg/ha)	4821	4280	541***	4292	3770	522***
Net returns (Rs./ha)	21,812	12,855	8957*	27,501	21,243	6258*

***, **, and * denote significance level at 1, 5 and 10% respectively.

Table 3. Change in fertilizer use on adoption of soil test recommendations

Variable	Paddy		Wheat	
	Absolute change	% change	Absolute change	% change
N (kg/ha)	-58.5*** (20.0)	-25.8	-37.6*** (7.4)	-21.8
P ₂ O ₅ (kg/ha)	-10.6** (6.4)	-9.7	-16.2*** (4.2)	-16.4
K ₂ O (kg/ha)	11.3*** (1.9)	218.9	8.3*** (1.7)	84.2
Fertilizer cost (Rs./ha)	-243 (446)	-2.9	-724*** (294)	-8.8
Yield (kg/ha)	760*** (75)	12.7	685*** (95)	13.7
Net returns (Rs./ha)	16,137*** (1748)	81.2	10,234*** (1379)	31.2

***, **, and * denote significance at the 1%, 5%, and 10% levels based on t-test, respectively.

Figures in parenthesis are standard error.

⁹ Based on t-test

¹⁰ Paid out cost + Family labour

Potential fertilizer subsidy savings

The observed decrease in fertilizer consumption resulting from the adoption of digital soil health services indicates a significant opportunity to reduce fertilizer subsidies, particularly for nitrogenous fertilizers. In 2023-24, approximately 30.64 million tons of NPK was consumed, with N accounting for two-thirds. The Government of India provided a subsidy of Rs. 61,755 per ton for N, which is significantly higher than Rs. 30,925 per ton for P_2O_5 and Rs. 9,145 per ton for K_2O .

In Uttar Pradesh, in 2023-24 approximately 3.1 million tons of NPK, backed by an estimated subsidy of Rs. 151 billion, was applied to paddy and wheat crops. As expected, nitrogenous fertilizers accounted for two-thirds of the total fertilizer consumption and 82% of the subsidy. By extrapolating the observed effects of soil health recommendations on fertilizer consumption, bringing 25% paddy and wheat cultivation under digital soil health services could potentially result in a saving of Rs. 8 billion in subsidy expenditure in the state.

Strategies for scaling up digital soil health services

The excessive and disproportionate use of chemical fertilizers not only affects soil health and the environment but also places a significant financial burden in the form of fertilizer subsidies. The political economy of agricultural incentives is complex, making policy shifts challenging once incentives are in place. Policymakers should consider scaling up digital soil health services as a strategic approach that aligns with the goals of long-term agricultural sustainability and food security and reduces the fiscal burden.

Linking fertilizer distribution to soil health: Linking the distribution of fertilizers to the status of soil nutrients can significantly reduce fertilizer use, maximize fertilizer-use efficiency, and improve soil health. Furthermore, it can significantly lower production costs for farmers and decrease the fertilizer subsidy burden. In India, approximately 250 million Soil Health Cards have been issued; however, the translation of soil health information in practice remains extremely limited

because of the long turnaround time. Digital soil health services provide valuable insights into soil nutrient trends, which can facilitate the dynamic adjustment of fertilizer production, trade, distribution, and subsidy policies.

Promote public-private partnerships: The current infrastructure for soil testing is inadequate, with 8,272 laboratories unevenly distributed across states to serve the needs of 146 million landholdings. This uneven distribution limits the ability to conduct timely and accurate soil analysis. Addressing this gap requires the strategic expansion of soil testing capabilities by fostering collaboration between public institutions and private enterprises.

Ensure inclusivity: The high initial investment in digital soil testing equipment is a barrier to entry, limiting the ability of individual farmers to benefit from precise soil diagnostics. To address this challenge and expand the reach of soil digital services, it is crucial to promote them through collectives, such as Farmer Producer Organizations (FPOs) and cooperatives. This will help distribute fixed costs, thereby enabling wider access to such technologies in the future.

Incentivizing farmers: To promote the adoption of digital soil health services, creating tangible incentives that align with broader environmental and economic goals is crucial. Integrating these services with eco-friendly farming practices, such as carbon credit programs and climate-smart agriculture initiatives, can offer significant benefits to farmers. Developing a payment system for soil ecosystem services is essential for ensuring timely and transparent compensation. Additionally, enhancing capacity through targeted demonstrations, awareness campaigns, and advisory services will empower farmers and entrepreneurs to understand nutrient dynamics and effectively interpret soil health recommendations.

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