American Journal of Agricultural Science, Engineering, and Technology (AJASET)

ISSN: 2158-8104 (ONLINE), 2164-0920 (PRINT)

VOLUME 10 ISSUE 1 (2026)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Agricultural Science, Engineering, and Technology (AJASET)
Volume 10 Issue 1, Year 2026
ISSN: 2158-8104 (Online), 2164-0920 (Print)
DOI: https://doi.org/10.54536/ajaset.v10i1.6642
https://journals.e-palli.com/home/index.php/ajaset

Effectiveness of the Khamari Mobile App in Enhancing Fertilizer Efficiency, Crop Yield and Economic Returns in Bangladesh

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Article Information

Received: October 14, 2025
Accepted: January 06, 2026
Published: April 27, 2026

Keywords

Balanced Fertilizer, Crop Zoning, Economic Benefit, Smart Agriculture, Sustainable Land Use

ABSTRACT

This study evaluates the effectiveness of the Khamari Mobile App, a geospatially enabled crop production advisory tool aimed to improve productivity and profitability in Bangladesh's agricultural sector. Field-level demonstration trials were conducted for 14 major non-rice crops during the Rabi and Kharif-I seasons of 2022–23 and 2024–25 across diverse Agro-Ecological Zones (AEZs). Fertilizer recommendations generated by the Khamari app were evaluated in terms of fertilizer-use efficiency, crop yield, and economic returns, and compared with farmers' conventional practices. The results indicate that app-based recommendations significantly reduced fertilizer use by 10–78% while increasing crop yields by 0.84–26.33%, resulting in higher net economic returns. Statistical analysis using a t-test at the 5% significance level confirmed that differences in fertilizer costs and yields between the two practices were statistically significant. These findings demonstrate the potential of Khamari app, as a geospatial decision-support tools, to enhance resource-use efficiency, farm profitability, and sustainability in Bangladesh's agricultural systems, while also providing policy-relevant insights for reducing excessive fertilizer use and associated subsidy burdens.

INTRODUCTION

Agriculture remains a cornerstone of Bangladesh's economy, supporting livelihoods, food security, and rural employment. However, the sector faces increasing challenges, including declining arable land, soil fertility degradation, rapid population growth and climate-induced stresses such as floods, droughts and salinity, etc. Addressing these constraints requires the adoption of modern, climate-resilient technologies that support sustainable agricultural intensification.

Therefore, it is essential to scale up climate-resilient innovations, promote balanced fertilizer use, cultivate crops suited to specific land and soil conditions, adopt improved crop and resource management practices, strengthen farmer capacity through training and technology dissemination and enhance market efficiency through strategic investments and policy support. Collectively, these measures can make Bangladesh's agriculture more sustainable, profitable and resilient to emerging risks.

In this context, the Bangladesh Agricultural Research Council (BARC) has been implementing Crop Zoning activities since 2017 to support evidence-based production planning and address key challenges in the agriculture sector. The overarching goal of this initiative is to guide crop production according to land suitability, thereby enhancing national food self-sufficiency and strengthening food security for the growing population.

Crop zoning has been carried out using upazila-level datasets on soil characteristics, land resources and agro-climatic conditions. To support this process, a geospatial technology-based Crop Zoning System-integrating GIS, remote sensing and GPS has been developed to determine crop suitability, provide fertilizer recommendations, guide crop production techniques, supply varietal information and estimate production costs and profitability. The system comprises four major components: the Crop Zoning Information System, the Crop Zoning Dashboard, the Agricultural Advisory Portal and the Khamari Mobile App.

The Khamari Mobile App is a geospatial, technology-enabled decision-support tool that delivers location-specific suitable crops, fertilizer recommendations, production techniques and profitability estimates. As part of the validation and promotion of the Khamari App, field-level demonstration trials have been conducted for rice (Chowdhury *et al.*, 2025) as well as for several other major crops to evaluate the effectiveness of its fertilizer recommendations. The results clearly indicate that adopting Khamari's fertilizer guidance leads to substantial

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fertilizer savings and notable yield increases across crops. Rice is the staple food crop of Bangladesh and is cultivated almost everywhere in the country. Alongside rice, wheat, maize, jute, tea, potato, vegetables, fruits, spices and oilseed crops are also widely grown. Although the area under cultivation for these crops remains relatively stable, their production has been steadily increasing (Table 1).

Crop diversification is crucial to ensuring food and nutritional security. Sequential cultivation of different crops on the same land through crop rotation helps maintain soil fertility, improves soil structure, reduces pest and disease infestation and ultimately increases overall crop production.

Table 1: Information on Cultivated Area and Production of Various Crops.

Year	**2021–22**		**2022–23**		**2023–24**	
Crop	**Cultivated Area (lakh hectares)**	**Production (lakh metric tons)**	**Cultivated Area (lakh hectares)**	**Production (lakh metric tons)**	**Cultivated Area (lakh hectares)**	**Production (lakh metric tons)**
Potato	4.64	101.45	4.55	104.32	4.57	106.01
Vegetables	4.55	50.1	4.63	53.64	5.05	55.39
Oilseeds	5.01	10.34	5.51	11.72	6.22	12.58
Pulses	3.75	4.32	3.56	4.4	3.47	4.29
Onion	2.05	25.17	2.04	25.47	2.08	29.17
Jute (bale)	7.21	84.32	7.29	84.58	7.23	95.81
Wheat	3.15	10.86	3.17	11.7	3.12	11.72
Maize	4.78	42.62	4.96	45.63	5.14	48.76

Source: Agricultural Yearbook 2024, BBS

To validate the accuracy and effectiveness of the Khamari Mobile App, field-level demonstration trials were conducted for 14 different crops across multiple Agro-Ecological Zones (AEZs). This scientific article synthesizes the findings from those trials to evaluate the agronomic, environmental, and economic benefits of Khamari-guided fertilizer management.

Fertilization is one of the most critical components of agriculture for achieving optimal crop yields. However, in many contexts, fertilizer application is still guided by farmers' experience and intuition rather than by scientifically derived nutrient requirements (Andrianto & Faizal, 2017). Such practice not only reduces resource-use efficiency but also leads to higher production costs and increases the risk of environmental degradation from excessive fertilizer use. Therefore, a scientifically informed, technology-enabled decision-support system is essential to provide accurate fertilizer recommendations that can help farmers improve yields, reduce input costs, and minimize the negative environmental impacts associated with improper fertilization.

Objectives

General Objective

1 To evaluate the effectiveness of the Khamari Mobile App in improving fertilizer-use efficiency, crop productivity and economic profitability across different crops in Bangladesh.

Specific Objectives

1 To compare fertilizer application rates under Khamari-recommended practices with those of farmers' conventional practices.

2 To assess yield variations resulting from the adoption of app-based fertilizer management.

3 To determine the economic impacts associated with Khamari-guided fertilizer recommendations.

4 To evaluate the app's potential contribution to sustainable and resource-efficient agricultural development.

LITERATURE REVIEW

Digital agriculture tools have significantly transformed crop management globally by delivering real-time, location-specific recommendations to farmers. Numerous studies have demonstrated that decision-support systems enhance agricultural productivity by enabling site-specific crop selection, improving fertilizer-use efficiency, reducing production costs and promoting environmentally sustainable farming practices.

Digital and Smart Agriculture Platforms

Smart farming applications are redefining the agricultural landscape by offering real-time, site-specific recommendations to farmers. According to Wolfert, *et al.* (2017), digital platforms that integrate information and communication technologies (ICT), including mobile apps, can significantly enhance productivity and farm management efficiency.

In Bangladesh, the increasing demand for food driven by population growth can be effectively addressed through the adoption of smart agriculture technologies. There remain some challenges on the ground as well and these need to be addressed efficiently through a consolidated effort by all the concerned bodies to promote smart agriculture effectively (Shawan, *et al.*, 2024). Ali, *et al.* (2025) indicated that only 30% of farmers of Bangladesh use e-technology, primarily due to poor mobile network coverage, lack of awareness and affordability issues. Real-time tracking and predictive analytics make it possible for farmers to find and fix potential problems quickly, which protects crops and increases production (Arun & Mishra, 2024).

A smartphone app is one platform where a farmer can *get all* the information and answers they require with just one swipe. Farmers' connectivity has shifted as a result of receiving agri-information via smartphone apps. Two billion people used smartphones worldwide in 2016, according to statistics (EMarketer, 2016).

Smart farming (Griffith *et al.*, 2013) using ICT components has been promoted by many national and international initiatives for inclusion in development initiatives (ARD, 2011). For scientists and agricultural practitioners, digital skills, including data collection methods, analytical techniques and communication technologies, offer opportunities to understand complex farming ecosystems and to tackle the challenges of agriculture (Kamilaris *et al.*, 2017). Haque, *et al.* (2025) demonstrates how technology-based methods are essential for climate-smart agriculture through insights that create a direction for Bangladesh officials and practitioners to improve food security and climate resilience. ICTs can provide farmers with better access to information and improve their ability to share knowledge amongst themselves and with others.

Geospatial Technologies in Agriculture

Global Positioning System (GPS), Geographic Information System (GIS) and Remote Sensing (RS) are widely used in agriculture for site selection, data management and the generation of data-driven outputs to support planning and decision-making processes.

GPS collects some farmland information and provides real-time location information for agricultural machines and tools to guide accurate property management (He *et al.*, 2011; Liu *et al.*, 2015). GPS positioning is continuously monitored to ensure accuracy and efficiency in farm operations.

Sampling points are identified using GPS and integrated into GIS, enabling spatial vectorization, interpolation, and visualization of entire farmland plots. This approach provides critical support for the scientific management of farmland information and the formulation of precise farming plans. At present, relatively mature technologies are found in this regard (Song *et al.*, 2021; Zhu *et al.*, 2007).

Remote sensing technology refers to detecting and identifying electromagnetic energy and accurately obtaining various field information without direct contact between the sensor and the object (Jia & Li, 2020).

Traditionally, surveying and recording agricultural land information relied on paper-based systems, which made data retrieval, storage, and analysis cumbersome and inefficient. Agricultural production information and geographic information can be organically combined by using GIS technology to provide unprecedented spatial and temporal characteristics for all types of agricultural information (Song, 2020). Existing soil and crop information data are sorted and analyzed by the GIS as attribute data; an efficient and operational field management system can be created by combining them with the vectorized base map data (He, *et al.*, 2011).

The integration of geospatial tools such as GIS, GPS, and RS has enhanced the capacity of farmers and policymakers to assess land quality, crop suitability, and nutrient needs. De Wrachien (2003) emphasized that such technologies are essential for land-use planning and achieving sustainable agricultural intensification. The applications of RS technology consider ecological and environmental parameters, soil factors, crop conditions and plant-soil diversity to optimize yields and agricultural productivity (Pandey & Pandey, 2023).

Balance Fertilizer use

Recent analyses reveal that over 60% of global agricultural soils now exhibit declining fertility indices, with 35% suffering from severe compaction (Wang *et al.*, 2018). Nitrogen use efficiency (NUE) in major cereal systems remains trapped at 30-50%, meaning that 50-70% of applied nutrients either volatilize into atmospheric NOx compounds or leach into aquatic systems (Congreves *et al.*, 2021). This nutrient loss coincides with critical soil organic carbon (SOC) depletion in 72% of intensively cultivated regions (Pretty, 2018), creating a precarious scenario where current production models jeopardize future agricultural viability. Fertilizers with low efficiency are used heavily in many areas to increase crop yields (Zhao, *et al.*, 2019). Although yields are relatively high, crop quality and income are low in some cases, and excessive fertilization causes a large amount of wastewater and pollution (Chen *et al.*, 2015). Fertilization is one of the key factors influencing soil fertility. Different fertilization methods and application rates can have varying impacts on the physicochemical properties of the soil (Wang *et al.*, 2023). Chen *et al.*, 2004 stated that balanced NPK fertilizer use and maintenance of soil quality are important for the development of sustainable vegetable production systems.

Environmental risk assessment of excess fertilization

The widespread use of fertilizers has significantly boosted agricultural productivity, but it has also led to a variety of adverse environmental impacts. Excessive application of fertilizers leads to increased greenhouse gas emissions from farmlands, such as the positive correlation between nitrous oxide emissions and nitrogen input (Menegat *et al.*, 2022). Furthermore, heavy metals and toxic residues in fertilizers can enter surface water bodies through runoff, causing eutrophication and pollution (Craswell, 2021). Studies have shown that the nitrogen and phosphorus nutrients in fertilizers, through leaching and runoff, are one of the primary causes of surface water pollution (Liu *et al.*, 2021). The unreasonable use of fertilizers also damages the ecosystem services of the farmland. Excessive application of fertilizers can alter the physicochemical properties of the soil, destroy soil structure, reduce soil biodiversity, and thus affect soil fertility and sustainable productivity (Zhang *et al.*, 2021). Meanwhile, the production and transportation of fertilizers also consume a large amount of energy, increasing carbon emissions (Kyttä *et al.*, 2021). Therefore, the use of fertilizers needs to consider both ensuring agricultural production and protecting the ecological environment and sustainable utilization of resources. Excessive application of chemical fertilizers can lead to nutrient imbalance, soil compaction, increased pH and degradation of soil structure, thereby reducing soil quality (Hartmann & Six, 2023). To reduce the environmental risks of fertilizers, it is necessary to optimize the application methods and quantities.

Site-Specific Nutrient Management and Fertilizer Recommendation Systems

Conventional blanket fertilizer application often results in either overuse or underuse of nutrients, which can negatively impact both crop yields and soil health. Site-specific nutrient management (SSNM) overcomes this issue by providing fertilizer recommendations tailored to the local soil fertility and specific crop requirements. Pampolino *et al.* (2012) demonstrated that SSNM can improve crop yields while reducing unnecessary input use. In Bangladesh, the BARC Fertilizer Recommendation Guide (Ahmmed *et al.*, 2018) offers science-based guidance and serves as the foundation for apps like Khamari to develop and provide localized fertilizer schedules.

Site specific nutrient management (SSNM) aims to empower farmers to adjust fertilizer application dynamically to meet the nutrient requirements of high-yielding crops, bridging the gap between natural nutrient sources like soil, crop residues, manure and irrigation water. It is based on the principles of 4Rs: right product, right dose, right time and right place (Sarma *et al.*, 2024).

Field Demonstrations, Adoption and extension

Field demonstrations play a crucial role in technology transfer by validating the effectiveness of recommendations under real-world conditions. Farmers' participation in extension training and demonstration programs can unlock their potential, enabling the adoption of improved production techniques and promoting sustainable farm productivity. Since its launch, Khamari has been promoted through field demonstrations, trainings, stakeholder workshops, and online tutorials. The Crop Zoning portal hosts the app, tutorial materials and production tech sheets, encouraging practical, field-level use. Current coverage indicates growing awareness and pilot adoption among extension agents and select farmer groups.

Sharing experiences and information is crucial as farmers prefer to make their decisions based on discussions and their own experiences, rather than accept top-down generalized recommendations (Ingram, 2008; Wellard, *et al.*, 2013). This participatory approach also reshapes the role of extension agents, transforming them into catalysts, facilitators and promoters of knowledge generation and exchange.

Khamari Mobile App

In agriculture, a wide range of activities is now supported by mobile apps available in app stores, including seed-to-seed cultivation, weather forecasting (Romani *et al.*, 2015), land preparation, nursery management, fertilizer calculation, pest and disease diagnostics, dairy farming (Gichamba & Lukandu, 2012), harvesting techniques, and crop sensor management (Lomotey & Deters, 2014). Khamari is a geospatial technology that enables farmers to make precise decisions on crop selection and fertilizer use directly on their lands (Chowdhury *et al.*, 2025).

Field trials on rice crops have demonstrated that Khamari's recommendations result in substantial fertilizer savings and improved yields compared to traditional practices. In 2023, T. Aman rice trials at 34 locations showed a 34% reduction in fertilizer costs and approximately 7% higher yields, translating to a minimum profit of 15,615 Taka per hectare. During the 2023-24 season, Boro rice trials at 60 locations reported an 18% reduction in fertilizer costs and about a 6% increase in yield, providing farmers an additional 16,222 Taka per hectare (Chowdhury *et al.*, 2025).

Production cost savings

Balanced and timely nutrient application supports sustainable improvements in both crop yield and quality, promotes plant health, and reduces environmental risks. Balanced nutrition with mineral fertilizers can assist in integrated pest management and reduce damage from infestations of pests and diseases and save inputs required to control them (Magen, 2008). Careful fertilizer use by monitoring soil nutrient levels and applying fertilizers appropriately at different growth stages helps farmers avoid wasting valuable resources. The purpose of this approach is to reduce the cost of over-fertilizing crop production, thereby compelling the farmers to adopt more environmentally friendly agricultural methods (Andrianto *et al.*, 2023).

MATERIALS AND METHODS

In developing fertilizer recommendations, soil fertility data from the Upazila Nirdeshika, prepared by the Soil Resource Development Institute (SRDI), serve as the primary foundation. These data are derived from detailed soil analyses conducted at approximately 200-hectare intervals within each upazila and are used to formulate fertilizer doses in accordance with the BARC Fertilizer Recommendation Guide (Ahmmed *et al.*, 2018). The integration of geospatial technologies including Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Remote Sensing (RS) has substantially enhanced the capacity of farmers and policymakers to assess land quality, crop suitability, and site-specific nutrient requirements. These technologies provide critical decision-support insights that enable stakeholders to respond more effectively to production challenges and opportunities. Consequently, the adoption of agricultural software represents not merely a modernization initiative, but a strategic approach to empowering farmers and strengthening the resilience and sustainability of food systems (Sarma *et al.*, 2024). In this context, the Crop Zoning System and its integration with the Khamari mobile app exemplify an effective model for delivering geospatial intelligence directly to the farmer level.

Selection of Study Area

The demonstration trials were conducted across 12 AEZs representing 63% of Bangladesh's total cultivable land (Table 2). These AEZs cover diverse soil textures, fertility levels, pH conditions and rainfall patterns. Shill *et al.* 2016 stated that the fertility status of most of the studied soils (except AEZ 10, 12, 13, and to some extent 11) appeared to be low to very low, which demands judicious management in order to achieve food security and to conserve the soil fertility.

Crops Studied

A total of 48 demonstration trials were conducted on 14 crops, including potato, onion, mustard, jute, wheat, maize, mungbean, lentil, sesame, brinjal, tomato, yardlong bean, broccoli, and country bean. These trials were implemented during the Rabi and Kharif-1 seasons

Table 2: List of AEZs with their areas and key features

Agro-ecological Zone	**Cultivable Area (ha); Percent**	**Key features**
Old Himalayan Piedmont Plain (AEZ-1)	373989 (3.23%)	HL (63%), MHL (36%), MLL (1%); Sandy loam (26%), Loam (57%), Clay loam (12%) soils; Strongly acidic (6%), Moderately acidic (94%); Annual rainfall 1600 - 2500mm
Tista Meander Floodplain (AEZ-3)	858957 (7.43%)	HL (38%), MHL (56%), MLL (5%), LL (1%); Predominately Loam (83%), Clay loam (9%) soils; Moderately acidic (95%), Neutral (5%); Annual rainfall 1500 - 2300mm
Young Brahmaputra and Jamuna Floodplain (AEZ-9)	518561 (4.49%)	HL (21%), MHL (47%), MLL (22%), LL (10%); Loam (44%), Clay loam (25%), Clay (40%) soils; Strongly acidic (1%), Moderately acidic (69%), Neutral (30%); Annual rainfall 1500 - 2500mm
Old Brahmaputra Floodplain (AEZ-8)	651010 (5.63%)	HL (31%), MHL (39%), MLL (22%), LL (8%); Loam (38%), Clay loam (8%), Clay (50%) soils; Strongly acidic (2%), Moderately acidic (95%), Neutral (3%); Annual rainfall 2000 - 4000mm
High Ganges River Floodplain (AEZ-11)	1171049 (10.13%)	HL (48%), MHL (36%), MLL (14%), LL (2%); Loam (23%), Clay loam (16%), Clay (61%) soils; Moderately acidic (43%), Neutral (57%); Annual rainfall 1400 - 1800mm
Low Ganges River Floodplain (AEZ-12)	703547 (6.09%)	HL (14%), MHL (33%), MLL (35%), LL (16%), VLL (2%); Loam (6%), Clay loam (15%), Clay (78%) soils; Moderately acidic (34%), Neutral (66%); Annual rainfall 1600 - 2000mm
Ganges Tidal Floodplain (AEZ-13)	957595 (8.28%)	HL (4%), MHL (94%), MLL (2%); Loam (6%), Clay loam (14%), Clay (79%) soils; Extremely acidic (5%), Moderately acidic (71%), Neutral (24%); Annual rainfall 1700 - 3300mm
Old Meghna Estuarine Floodplain (AEZ-19)	641220 (5.55%)	HL (2%), MHL (29%), MLL (39%), LL (26%), VLL (4%); Loam (56%), Clay loam (12%), Clay (31%) soils; Moderately acidic (90%), Neutral (10%); Annual rainfall 2000 - 3000mm
Northern and Eastern Piedmont Plain (AEZ-22)	364016 (3.15%)	HL (36%), MHL (35%), MLL (18%), LL (10%), VLL (1%); Sand (2%), Sandy loam (10%), Loam (45%), Clay loam (13%) and Clay (28%) soils; Strongly acidic (17%), Moderately acidic (83%); Annual rainfall 2000 - 5000mm
Level Barind Tract (AEZ-25)	457752 (3.96%)	HL (33%), MHL (60%), MLL (5%), LL (2%); Loam (72%), Clay loam (23%), Clay (5%) soils; Strongly acidic (13%), Moderately acidic (87%); Annual rainfall 1300 - 2000mm
High Barind Tract (AEZ-26)	150855 (1.30%)	HL (99%), MHL (1%); Loam (77%), Clay loam (20%), Clay (2%) soils; Strongly acidic (1%), Moderately acidic (96%), Neutral (3%); Annual rainfall 1300 - 1400mm

Madhupur Tract (AEZ-28)	381512 (3.30%)	HL (61%), MHL (20%), MLL (8%), LL (11%); Loam (56%), Clay loam (24%), Clay (19%) soils; Strongly acidic (66%), Moderately acidic (33%), Neutral (1%); Annual rainfall 2000 - 2300mm
Total	7230063 (62.54%)	HL-Highland, MHL-Medium Highland, MLL-Medium Lowland, LL-Lowland, VLL-Very Lowland

Source: Land Resources Appraisal of Bangladesh for Agricultural Development. FAO/UNDP Project (BGD/81/035), 1988

of 2022-23 and 2024-25 with support from institutions under the National Agricultural Research System (NARS), including the Bangladesh Agricultural Research Institute (BARI), Bangladesh Institute of Nuclear Agriculture (BINA), Soil Resource Development Institute (SRDI) and Bangladesh Wheat and Maize Research Institute (BWMRI). The Crop Zoning Project of BARC was responsible for the establishment, monitoring, and overall coordination of all demonstration activities. The number of trials conducted for each crop varied depending on the respective institute's capacity and available project resources. Detailed information on the implementation of the trials is presented in Table 3.

Demonstration Trial Plot

To encourage farmers to adopt the 'Khamari' mobile app for fertilizer recommendations, demonstration trials were set up in farmers' fields. Each demonstration plot spanned 10/15 decimals, with separate plots for the 'Khamari' app-based recommendations and farmers' traditional practices (Figure 1). In Khamari plot fertilizer applied according to app recommendations and in Farmers' plot fertilizer applied based on conventional farmer practice. While fertilizer doses differed, all other crop management and intercultural operations were kept consistent across the trials to ensure accurate comparisons.

Table 3: Demonstration Trials by Season, Crop, and Implementing Institutions

Cropping Season and Year of Implementation	**Name of Crops and Number of Demonstration Trials within parenthesis**	**Institutions Conducted the Trials**
Rabi: 2022-23	Wheat (3), Maize (2), Potato (2), Mustard (3), Lentil (2), Onion (2)	BARI, BINA, SRDI, BWMRI
Kharif-1: 2023	Jute (4), Sesame (2), Mung bean (1)	BARI, BINA, SRDI, BWMRI
Rabi: 2024-25	Wheat (3), Maize (4), Potato (3), Mustard (2), Onion (4), Tomato (1), Brinjal (2), Hyacinth bean (1), Broccoli (1)	BARI, BINA, SRDI, BWMRI
Kharif-1: 2025	Yardlong bean (1), Mung bean (3), Jute (2)	BARI, BINA, SRDI

Data Collection

Data collection was carried out at different stages of the demonstration trials, as outlined below:

Before establishment of the demonstration trials: Location data (latitude and longitude) and farmer information were recorded.

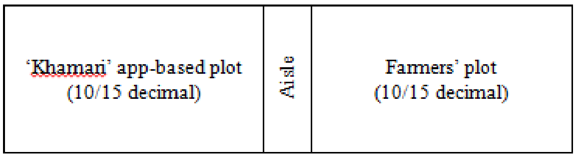

Figure 1: Demonstration Trial Plot

During the demonstration trials: Quantities of fertilizer inputs (urea, TSP, MOP, and gypsum) were documented to calculate fertilizer cost per hectare. Several monitoring visits were also conducted throughout the trial period.

At harvest: Crop yield data (t/ha or kg/ha) were collected.

After harvest: Market prices of produce (BBS, 2024) and economic returns per hectare were calculated for both Khamari and Farmer's plot yield.

Field information can be roughly divided into soil attribute, location, crop growth, farmland surrounding environment, and crop yield information ((He, *et al.*, 2011; Mahan, *et al.*, 2016). After harvest, crop weights were measured at a standardized moisture content of 14% to determine yield per plot. Fertilizer costs were calculated based on government-fixed selling prices.

Statistical Analysis

Descriptive statistics were used to summarize and compare key metrics; fertilizer costs, crop yields, and net financial gains. A crop-wise analysis was conducted to account for geographical variability. For national-scale projections, financial gains were extrapolated using official cultivated area statistics from the Bangladesh Bureau of Statistics (BBS).

To robustly assess the effectiveness of the 'Khamari' app's recommendations, data from the demonstration trials were subjected to Analysis of Variance (ANOVA) and Multivariate Analysis of Variance (MANOVA) at a 5% significance level (α = 0.05). These tests determined whether observed differences in yield and fertilizer cost between the app-recommended and conventional practices were statistically significant.

RESULTS AND DISCUSSION

Under the Crop Zoning activities, a total of 48 demonstration trials were conducted to evaluate the effectiveness of fertilizer recommendations provided by the Khamari mobile app. These trials were implemented by institutions under the National Agricultural Research System (NARS) during the Rabi seasons of 2022-23 and 2024-25 on 10 crops and during the Kharif-1 season on 4 crops (Table 4).

Fertilizer costing and Yield impact through the Use of the Khamari App

Analysis of the results shows that fertilizer recommendations provided by the Khamari app resulted in fertilizer savings ranging from 10.57% to 78.22% and yield increases of 0.84% to 26.33% compared with farmers' conventional practices for all crops except wheat and maize. In the cases of wheat and maize, fertilizer use was 6-7% higher than traditional farmer practices; however, yields increased substantially, by 24.33% and 12.21%, respectively (Table 4). Based on the trial results, comparative fertilizer savings and yield differences between Khamari app-based fertilizer application and farmers' conventional practices are presented in Figures 2 and 3.

Table 4: Results of Validation of Fertilizer Recommendations Provided by the Khamari App.

Sl. No.	Crop Name and Number of Demo Trials	Average Fertilizer Cost (Tk/ha)		Khamari Cost Compared to Farmer (+/-)	Yield (t/ha)		Khamari Yield Compared to Farmer (+/-)
		Khamari	Farmer		Khamari	Farmer	
1	Potato (5 demos)	19,797	41,160	-51.90%	28.09	27.74	1.26%
2	Onion (6 demos)	22,334	40,642	-45.05%	18.06	17.91	0.84%
3	Mustard (5 demos)	14,316	16,636	-13.95%	1.64	1.52	7.89%
4	Jute (6 demos)	9,993	13,682	-26.96%	3.29	3.00	9.67%
5	Wheat (6 demos)	27,124	25,454	+6.56%	4.40	3.54	24.29%
6	Maize (6 demos)	42,886	39,748	+7.89%	13.94	12.42	12.24%
7	Mungbean (4 demos)	8,283	14,733	-43.78%	1.64	1.33	23.31%
8	Lentil (2 demos)	3,057	4,553	-32.86%	2.10	1.94	8.25%
9	Sesame (2 demos)	10,799	12,076	-10.57%	1.79	1.60	11.88%
10	Brinjal (2 demos)	22,551	35,856	-37.11%	30.19	29.29	3.07%
11	Tomato (1 demo)	24,321	76,438	-68.18%	57.20	50.90	12.38%
12	Yardlong bean (1 demo)	7,523	34,535	-78.22%	8.06	6.38	26.33%
13	Broccoli (1 demo)	47,982	70,316	-31.76%	19.69	16.23	21.32%
14	Country bean (1 demo)	16,401	27,483	-40.32%	11.15	10.90	2.29%

The demonstration trials conducted on 14 crops across 48 locations demonstrated substantial benefits from adopting the scientifically informed fertilizer recommendations provided by the Khamari app (Table 5). The average yield in plots following Khamari app recommendations was 11.62 t/ha, compared with 10.89 t/ha under farmers' conventional practices, representing a 6.63% yield increase in favor of Khamari-based management. In addition, fertilizer costs per hectare were reduced by 28.43% in the Khamari plots relative to farmers' traditional practice plots. Both the yield improvement and fertilizer cost savings were statistically significant.

The analysis yielded statistically significant results across multiple dimensions. A one-way ANOVA confirmed

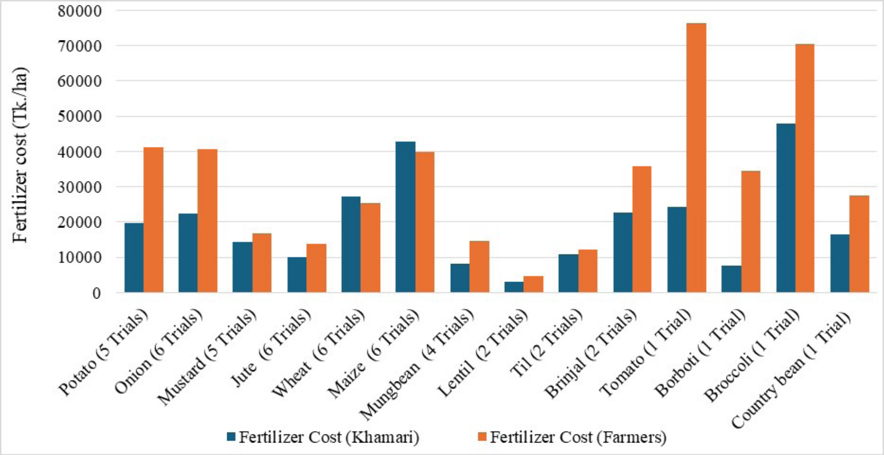

Figure 2: Fertilizer Cost Savings Using Khamari App Recommendations Compared to Farmers' Conventional Practices

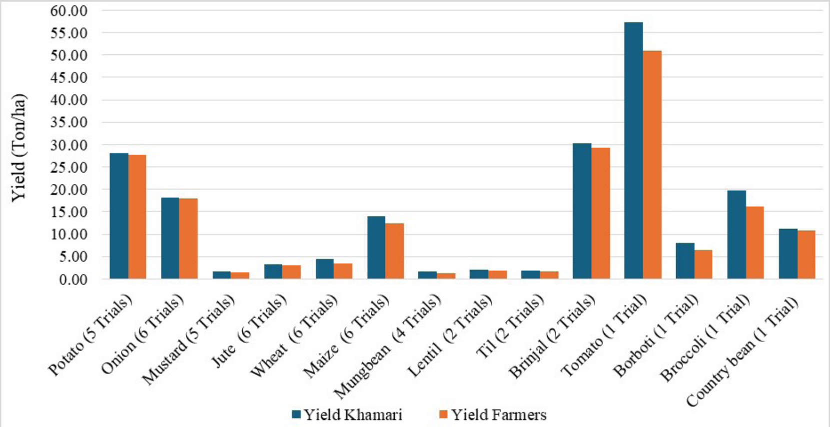

Figure 3: Yield Increased Using Khamari App Fertilizer Recommendations Compared to Farmers' Conventional Practices

substantial variation among the 14 crops for both fertilizer cost (F(12) = 15.73, *p* < .001) and yield (F(12) = 92.20, *p* < .001). Descriptive statistics (Table 5) show that, on average, plots following the Khamari app recommendations incurred 27.6% lower fertilizer costs (M = Tk 20,558, SD = [12747.434]) and achieved 6.7% higher yields (M = 11.62 t/ha, SD = [12.19327]) compared to plots under conventional farmer practices (Cost: M = Tk 28,725; Yield: M = 10.89 t/ha).

Furthermore, a two-way ANOVA examining the crop by Agro-Ecological Zone (AEZ) interaction revealed significant effects on fertilizer cost (F(12) = 2.49, *p* = .023) and yield (F(12) = 3.33, *p* = .004). Post-hoc comparisons indicated the 'Khamari' method reliably produced higher yields and lower input costs across all AEZs.

A multivariate analysis of variance (MANOVA) was conducted to assess the overall effect of the crop-AEZ factor on the combined dependent variables of fertilizer management (Khamari vs. conventional). The results were significant across all four multivariate test statistics: Pillai's Trace (V = 1.116, F(24, 56) = 2.946, *p* < .001), Wilks' Lambda (Λ = 0.189, F(24, 54) = 2.919, *p* < .001), Hotelling's Trace (T^2 = 2.666, F(24, 52) = 2.888, *p* < .001), and Roy's Largest Root (Θ = 1.738, F(12, 28) = 4.056, *p* < .001). This confirms that the crop-AEZ interaction exerts a statistically significant multivariate influence on fertilizer management practices.

Use of Fertilizers through the Khamari Mobile App

Results from demonstration trials conducted with support from institutions under the National Agricultural Research System (NARS) indicate that substantial fertilizer savings can be achieved by following the fertilizer recommendations provided by the Khamari app. In contrast, fertilizer application in farmers' practice plots

Table 5: Outcomes of the demonstration trials for 14 crops

Average Fertilizer Cost (Tk/ha)		**Khamari Cost Compared to Farmer**	**Average Yield (Ton/ha)**		**Khamari Yield Compared to Farmer**
Khamari	**Farmers**		**Khamari**	**Farmers**	
20,558	28,725	-27.6%	11.62	10.89	+6.7%

often showed imbalanced use sometimes exceeding and at other times falling below the app-recommended levels. Balanced fertilization ensures that crops receive nutrients in the right proportions, at the right time, and through appropriate methods, in line with crop demand and soil conditions. This approach improves nutrient use efficiency, sustains soil fertility, enhances crop productivity, and minimizes environmental losses.

The use of fertilizers (urea, TSP, MoP, and gypsum) across 14 crops in the demonstration trials following Khamari app recommendations is presented below.

Use of Urea in 14 Crops across Demonstration Trials

Across 14 crops, Urea dose recommended by the Khamari Mobile App generally differed substantially from farmers' traditional practices. Significant reductions in Urea use were observed in potato, onion, mungbean, tomato, yardlong bean and country bean (31-70% lower), indicating considerable potential for input saving. In contrast, moderate increases in Urea use were recorded for mustard, sesame, lentil, and some minor crops, suggesting correction of under-fertilization by farmers (Figure-4). Overall, the results demonstrate that app-based recommendations can rationalize fertilizer use by reducing excess application while ensuring adequate nutrition where deficiencies exist.

Use of TSP (Triple Super Phosphate) in 14 Crops across Demonstration Trials

The Khamari mobile app consistently recommended lower TSP doses than farmers' conventional practices across nearly all crops and demonstration trials. Substantial TSP savings were particularly evident in jute, potato, onion, brinjal, yardlong bean, and maize, with reductions ranging from approximately 50% to more than 80%. Sesame was the only crop that showed a marginal increase in TSP application under app-based recommendations (Figure 5). Overall, these findings underscore the potential of digital decision-support tools to promote balanced fertilization by reducing excessive fertilizer use without compromising crop nutrient requirements.

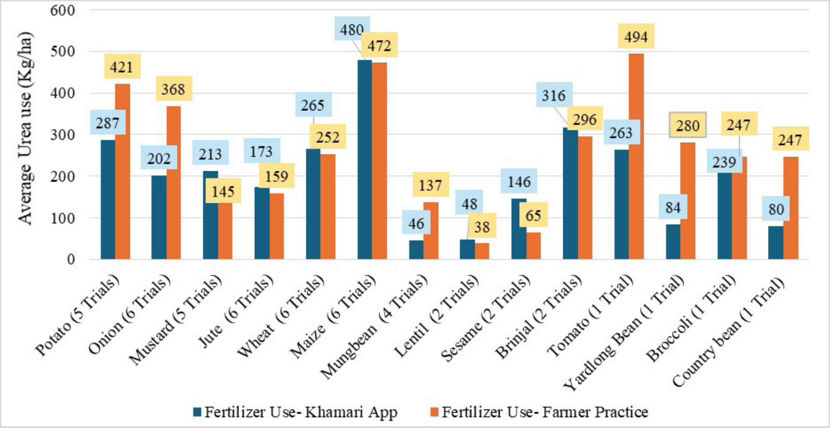

Figure 4: Use of Urea in 14 Crops across Demonstration Trials

Use of MoP (Muriate of Potash) in 14 Crops across Demonstration Trials

Khamari Mobile App recommendation of MoP dose was consistently lower than farmers' traditional practices across nearly all crops and trials. Figure 6 indicates that MoP application under the Khamari App was generally

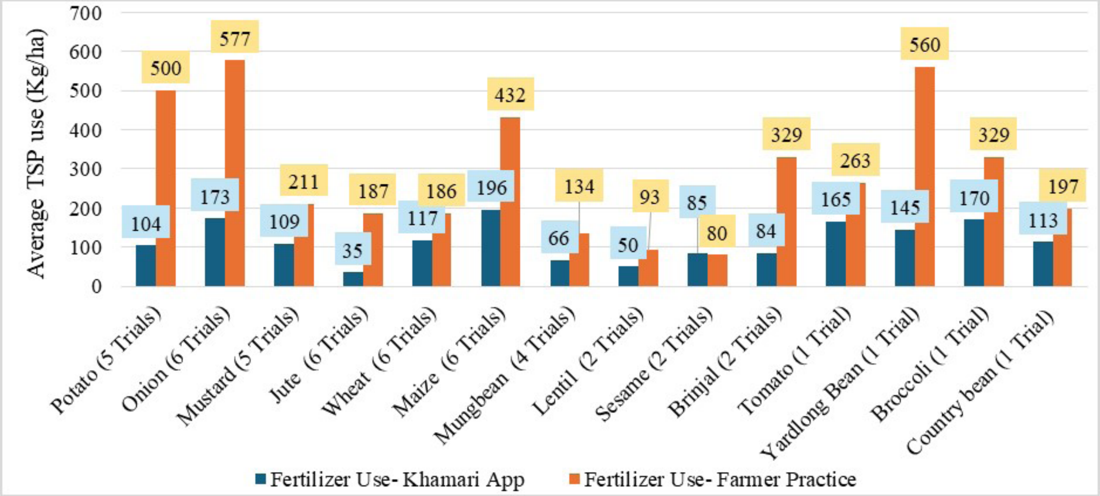

Figure 5: Use of TSP in 14 Crops across Demonstration Trials

lower than farmers' traditional practices across most crops, resulting in substantial fertilizer savings. Major reductions were observed in potato, onion, maize, mungbean, tomato and yardlong bean, with savings ranging from approximately 55% to over 75%. In contrast, wheat and brinjal showed slightly higher MoP use under app-based recommendations, suggesting correction of potential under-application by farmers. Overall, the results demonstrate the role of digital advisory tools in promoting crop-specific, balanced fertilizer management.

Use of Gypsum in 14 Crops across Demonstration Trials

Figure 7 summarizes gypsum application rates under Khamari app recommendations compared with farmers' conventional practices across 14 crops. Gypsum use was substantially reduced in most crops-particularly tomato, brinjal, yardlong bean, lentil, and mungbean-indicating correction of excessive application under farmers' practices. Conversely, higher gypsum rates were recommended for jute, wheat, maize, and potato, suggesting mitigation of under-application in these crops. Overall, the results demonstrate that app-based advisories help optimize gypsum use through crop-specific, balanced nutrient management.

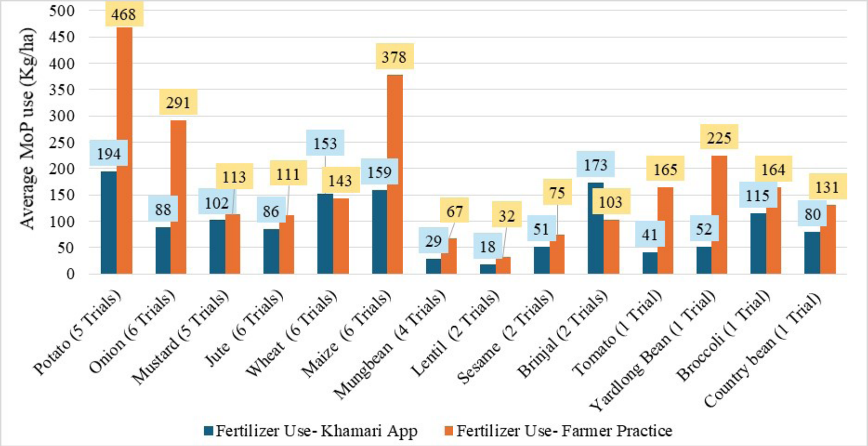

Figure 6: Use of MoP in 14 Crops across Demonstration Trials

Economic Impact Assessment of Fertilizer Recommendations Provided by the Khamari Mobile App

The effectiveness of fertilizer recommendations provided by the Khamari mobile app was evaluated through 48 demonstration trials covering 14 different crops. Analysis of the trial results shows that adherence to the app's fertilizer recommendations substantially reduced fertilizer expenditures while simultaneously increasing crop yields, thereby leading to improved economic returns for farmers (Table 6).

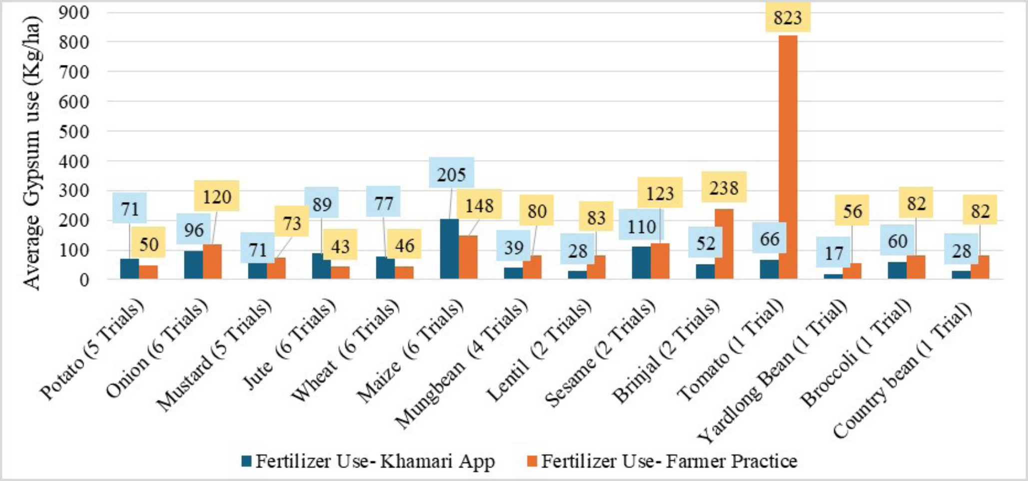

Figure 7: Use of Gypsum in 14 Crops across Demonstration Trials

Since only one or two demonstration trials were conducted for the following crops (Table 7), the financial benefits per hectare derived from the additional yield and fertilizer savings achieved through Khamari app-based fertilizer application compared to farmers' conventional practices have been presented for these crops. The potential financial gains at the national scale have not been included.

The results of the demonstration trials show that:

Table 6: Crop-wise Economic Impact of Using Khamari App Recommended Fertilizer

Sl. No.	Crop Name	Season	No. of Demo	Fertilizer Cost Compared to Farmer's Practices (Tk./ha)	Increased Yield (kg/ha)	Minimum Average Market Price Received by Farmers (Tk. /kg)*	Price of Increased Yield (BDT/ha)	Total Financial Gain per Hectare (BDT)	Total Cultivated Area (ha)**	Total Potential Financial Gain (Million BDT)
1	Potato	Rabi	5	-21,363	350	22.57	7,899	29,262	456,979	13,370
2	Onion	Rabi	6	-18,308	150	45.21	6,782	25,090	207,817	5,210
3	Mustard	Rabi	5	-2,320	120	63.88	7,665	9,985	462,986	4,620
4	Jute	Kharif-1	6	-3,689	290	50.81	14,735	18,424	723,639	13,330
5	Wheat	Rabi	6	+1,670	860	38.19	32,843	31,173	311,551	9,700
6	Maize	Rabi	6	+3,138	1,520	24.35	37,012	33,874	514,791	17,430
7	Mungbean	Kharif-1	4	-6,450	310	70.2	21,762	28,212	49,079	1,380

Source: *Bangladesh Bureau of Statistics (BBS, 2024), ** Yearbook of Agricultural Statistics- 2024 (BBS)

Note: (+) indicates additional cost, (-) indicates cost savings

- Adopting the fertilizer recommendations provided by the 'Khamari' app led to cost savings ranging from an average of 14% to as high as 52% across major crops such as potato, onion, mustard, and jute, clearly demonstrating enhanced efficiency in fertilizer use.

- Adopting the fertilizer recommendations of the 'Khamari' app in pulse crops such as mungbean, lentil, and sesame resulted in cost savings ranging from an average of 10% to as high as 44%, clearly demonstrating improved efficiency in fertilizer use.

Table 7: Crop-wise per-hectare Profit of Using Khamari App Recommended Fertilizer

Sl. No.	**Crop Name**	**Season**	**No. of Demo**	**Fertilizer Cost Compared to Farmer's Practices (Tk./ha)**	**Increased Yield (kg/ha)**	**Minimum Average Market Price Received by Farmers (Tk. /kg)***	**Price of Increased Yield (BDT/ha)**	**Total Financial Gain per Hectare (BDT)**
8	Lentil	Rabi	2	-1,496	160	72.71	11,634	13,130
9	Sesame	Kharif-1	2	-1,277	190	84.86	16,123	17,400
10	Brinjal	Rabi	2	-13,305	900	24.18	21,762	35,067
11	Tomato	Rabi	1	-52,117	6,300	13.5	85,050	137,167
12	Yardlong Bean	Kharif-1	1	-27,012	1,680	17.82	29,938	56,950
13	Broccoli	Rabi	1	-22,334	3460	20.00	69,200	91,534
14	Country Bean	Rabi	1	-11,082	250	23.6	5,900	16,982

*Source: *Bangladesh Bureau of Statistics (BBS, 2024)*

Note: (-) indicates cost savings

- Applying the 'Khamari' app's fertilizer recommendations to vegetable crops like brinjal, tomato, yard long bean, broccoli, and country bean resulted in cost savings ranging from an average of 32% to as high as 78%, clearly demonstrating improved efficiency in fertilizer use.

- In wheat and maize, although fertilizer application was 6-7% higher than conventional farmer practices, yields increased by 24.33% and 12.21%, respectively, ensuring substantial overall financial gains.

- The economic impact for seven crops namely potato, onion, mustard, jute, wheat, maize, and mungbean indicates that full-scale adoption of the Khamari app's fertilizer recommendations could generate an estimated additional financial gain of BDT 65,040 million.

- For the other seven crops (lentil, sesame, brinjal, tomato, yard long bean, broccoli, and country bean), the economic benefit are derived from both fertilizer cost savings and yield increases.

Overall, the results of the demonstration trials clearly indicate that the fertilizer recommendation module of the Khamari mobile app ensures scientific and location-specific fertilizer application, which is highly effective in both reducing farmers' input costs and increasing crop production.

As shown in Table 8, a comparative analysis of productivity data reveals that crop yields from 'Khamari' app demonstration trials exceeded the national average by 15% to 47%, underscoring the efficacy of the app's recommendations.

These findings underscore the Khamari app's significant potential as a practical, scalable tool for promoting cost-efficiency and sustainability in agriculture. By enabling balanced nutrient management, the app directly supports sustainable farming practices. Its widespread adoption could substantially enhance productivity, profitability, and long-term food security within the agricultural sector.

CONCLUSION

The Khamari Mobile App has demonstrated significant effectiveness in improving fertilizer-use efficiency, increasing crop yields, and enhancing economic returns for farmers. Beyond yield improvement, the app contributes to sustainable agricultural development by promoting balanced fertilizer use, preserving soil health, and improving overall resource-use efficiency.

Table 8: Comparison of average productivity in Khamari app-based demonstration trials and national productivity (BBS 2024) for selected key crops

Sl. No.	Crop Name	Khamari app-based Productivity (Ton/ha)	National Productivity (Ton/ha) BBS-2024	Khamari app-based Increased Yield compared to National Yield (%)
1	Potato	28.09	23.2	21.08
2	Onion	18.06	14.03	28.72
3	Mustard	1.64	1.38	18.84
4	Jute	15.11 bale	13.24 bale	14.12
5	Wheat	4.4	3.76	17.02
6	Maize	13.94	9.47	47.2

These results underscore the transformative potential of scaling digital advisory tools such as the Khamari app at the national level. Widespread adoption could modernize Bangladesh's agricultural sector by supporting sustainable soil management, reducing fertilizer wastage, and strengthening long-term food security. To fully realize these benefits, a coordinated approach is required to address challenges related to digital infrastructure, farmer digital literacy, and supportive policy environments. In addition, field-level demonstration trials for both rice and non-rice crops, farmers' field days to showcase practical benefits, and public awareness campaigns through television, radio, social media, and video documentaries should be planned to promote wider adoption of the Khamari app.

The present study highlights the potential of the Khamari app to reshape agricultural advisory services by enhancing crop productivity and fertilizer-use efficiency. However, it is acknowledged that the design of demonstration plots can be further improved to more clearly and rigorously communicate trial outcomes.

Evidence from this study, supported by global experience, emphasizes the importance of:

- Localized adaptation of technologies to agro-ecological and socio-economic conditions;
- Farmer-centric design that ensures usability across varying literacy levels; and
- Strong governance frameworks to ensure data quality, content validation, and institutional coordination.

With appropriate institutional support and policy alignment, the Khamari app has strong potential to serve as a scalable model for digital agriculture, not only in Bangladesh but also in other developing regions seeking to modernize agricultural advisory systems through smart, sustainable, and inclusive digital solutions.

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