Data-Driven Decisions in Agriculture: The Khamari App for Site-Specific Crop and Fertilizer Recommendation

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Authors' contributions

This work was carried out in collaboration among all authors. Author MAHC designed the study, performed the statistical analysis. Author HMHR wrote the protocol and reviewed the first draft of the manuscript. Author NZ managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The Bangladesh Agricultural Research Council (BARC) has developed the 'Khamari' mobile application as an innovative tool to enhance agricultural productivity and optimize use of natural resources. This digital solution provides farmers with precise, location-specific recommendations to promote sustainable and efficient farming practices.

The Khamari app serves as a crop production advisory tool, aiming to increase productivity, profitability, and drive overall growth within the agricultural sector by equipping farmers and

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stakeholders with essential information directly at their fingertips. A unique feature of the Khamari app is its integration of geospatial technology, which enables users to access pertinent information while standing on their own land.

Through the Khamari app, farmers can make informed decisions on selecting a suitable crop, enhancing crop yields through balanced fertilizer use, maintaining soil health and environmental sustainability. By aligning with the Crop Zoning System of Bangladesh, the app supports local-level crop production planning and has demonstrated significant potential to increase food production and foster the adoption of precision agriculture nationwide.

Field trials on rice crops have demonstrated that the app's recommendations lead to significant fertilizer savings and improved yields compared to traditional farming practices. For T. Aman rice trials in 34 locations in 2023, the app's recommendations led to a 34% reduction in fertilizer costs and approximately 7% increase in yield, resulting in a minimum profit of 15,615 Taka per hectare. Boro rice trials in 60 locations during the 2023-24 season showed an 18% reduction in fertilizer costs and around a 6% increase in yield, offering farmers an additional 16,222 Taka per hectare. These findings highlight the substantial benefits of the 'Khamari' app in enabling smart, sustainable agricultural practices, positioning it as a valuable tool for both economic gains and long-term agricultural resilience.

1. INTRODUCTION

Agriculture plays a vital role in Bangladesh's economic development and remains the largest employment sector. In FY 2023–24, the agriculture sector contributed about 11.55% to the country's GDP (BBS, 2024) and employed approximately 44.42% of the total labor force (BBS, 2023). The sector's performance has a significant impact on key macroeconomic objectives, including employment generation, poverty reduction, human resource development, and national food security.

Despite its importance, the agriculture sector faces numerous challenges, such as the loss of arable land, rapid population growth, and the adverse effects of climate change. These pressures pose serious threats to the sustainability of agricultural production. Without timely and strategic interventions, they may undermine the sector's ability to meet the food demands of a growing population.

In this context, sustainable land use planning based on crop zoning has emerged as a critical strategy. Crop zoning aligns agricultural production with the biophysical and socio-economic characteristics of specific regions, thereby ensuring more efficient resource use, protecting soil health, and enhancing long-term productivity. This approach supports both physical sustainability through conservation of soil quality and fertility and economic sustainability by guiding investment in suitable crops and farming systems tailored to local conditions (De Wrachien, 2003).

Crop zoning has been recognized as essential for sustainable agricultural planning to meet increasing food demands (Pereira, 1983; Sivakumar and Valentin, 1997). Bangladesh's 8th Five-Year Plan identifies crop zoning as a cornerstone for land use planning and production management (Bangladesh Planning Commission, 2020). Similarly, the land resources appraisal of Bangladesh provide a unique basis for the rational planning of agricultural research, extension and development (Brammer et al. 1988).

To support this initiative, the Bangladesh Agricultural Research Council (BARC) has taken a leading role in implementing a national Crop Zoning System to identify regions with optimal agro-ecological conditions for specific crops. This system is designed to maximize the productive potential of land and water resources, improve economic returns, reduce environmental degradation, and promote sustainable farming practices.

The online Crop Zoning System (available at cropzoning.gov.bd) and a robust geodatabase has been developed using advanced geospatial technologies, including Geographic Information System (GIS), Remote Sensing (RS), and Global Positioning System (GPS). The system consists of four core components:

1. **Crop Zoning Information System (CZIS):** A centralized GIS-based analytical platform that enables data management, crop suitability assessment, and map visualization.
2. **Crop Zoning Dashboard:** A real-time decision-support interface designed for policymakers, researchers, and agricultural planners.
3. **Agri-Advisory Portal:** A web-based platform for disseminating agricultural knowledge and guidance.
4. **Khamari Mobile App:** A user-friendly mobile application developed in Bangla, providing farmers with localized, real-time agricultural advisory services.

Among these components, the Khamari Mobile App plays a key role in supporting precision agriculture. The app empowers farmers with site-specific recommendations for crop selection, fertilizer application, and resource optimization. Leveraging geospatial data, it allows users to access advisory services while standing on their own land, helping them make informed decisions that enhance productivity and sustainability.

Positioned as a smart agriculture tool, the Khamari app addresses critical challenges such as declining arable land, rising input costs, and environmental degradation. Its localized guidance promotes efficient use of fertilizers and natural resources, contributing to improved soil health and increased crop yields.

Mobile-based advisory services like Khamari are increasingly being used to deliver site-specific information, including crop suitability, input use, pest and disease alerts, and market prices. Research by Mittal and Mehar (2016) shows that such services significantly influence farmer knowledge, behavior, and productivity, particularly in South Asia. Bangladesh has made notable progress in digitalizing its agricultural extension services.

1.1 Khamari Mobile App

The Khamari app is an innovative smart farming technology that delivers location-specific crop production advice to farmers, aiming to boost productivity. A distinctive feature of the app is its integration of geospatial technology, enabling farmers to make precise decisions on crop selection and fertilizer use directly on their lands. This targeted approach promotes better soil health, higher yields, and increased profitability.

Developed in Bangla for accessibility, the Khamari app is user-friendly and available for both Android and iOS, making it a convenient and valuable resource for Bangladeshi farmers. The app provides essential information for:

i. Crop Suitability Recommendations: Tailored guidance based on land and soil conditions, and agro-climate for enhanced productivity.
ii. Balanced Fertilizer Guidance: Customized fertilizer doses for crop type and rotation based on soil fertility and also application methods by crop.
iii. Agricultural Technology Insights: Information on crop varieties, yield potential, crop life spans and production technology.
iv. Upazila-wise Crop Planning: Supports efficient production planning with data on suitable crop areas per Upazila.
v. Soil Information: Details on land and soil characteristics, organic content, and fertility levels.
vi. Profitability Assessment: Insights on selecting crops for farming based on profitability.
vii. Soil Nutrient Management: Guidelines on nutrient management practices for sustainable crop production.

Positioned as a smart farming tool, the Khamari app redefines traditional practices with sustainable, efficient solutions tailored to local conditions. By integrating geospatial technology and localized advisory services, the app enables data-driven decision-making at the farm level, helping farmers adopt best practices in crop selection, fertilizer use, and land management. Its use in local-level crop production planning holds significant promise for boosting food production, enhancing resource efficiency, and advancing smart agriculture across Bangladesh. As a scalable digital innovation, Khamari stands to become a cornerstone in the country's transition toward climate-resilient and precision-based agricultural systems. By enabling precise management of inputs such as water, fertilizers, pesticides, and seeds, precision agriculture (PA) technologies help optimize resource use, minimize environmental impact, and maximize yield potential (Khaspuria et al. 2024).

1.2 Key Objectives

The primary objective of this study was to assess the impact of fertilizer recommendations provided

by the **'Khamari' mobile app** on crop yield and fertilizer input efficiency. The findings are intended to support data-driven decision-making for sustainable land use and optimized agricultural input management. The key objectives are as follows:

i. **Enhanced Crop Productivity:** To validate the effectiveness of the Khamari app in improving crop growth and increasing yields under field conditions.
ii. **Cost and Input Efficiency:** To evaluate the economic benefits and input savings—particularly fertilizer use—achieved by farmers following Khamari app-based recommendations compared to traditional practices.

2. LITERATURE REVIEW

The emergence of digital agriculture technologies has transformed traditional farming practices by promoting data-driven and site-specific decisions. These innovations align with the growing global need for sustainable, efficient, and climate-resilient food production systems.

2.1 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 excessive demand for food due to increase in population in the coming years can be potentially met by smart agriculture. 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). 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 and Mishra, 2024).

2.2 Geospatial Technologies in Agriculture

The integration of geospatial tools such as Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Remote Sensing (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 remote sensing technology consider ecological and environmental parameters, soil factors, crop conditions, and plant-soil diversity to optimize yields and agricultural productivity (Pandey and Pandey, 2023).

2.3 Site-Specific Nutrient Management and Fertilizer Recommendation Systems

Traditional blanket fertilizer application often leads to overuse or underuse of inputs, affecting both yields and soil health. Site-specific nutrient management (SSNM) addresses this by tailoring fertilizer recommendations based on local soil fertility and crop needs. 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) provides science-based guidance, which serves as the backbone for apps like Khamari to deliver 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). Site specific nutrient management (SSNM) increased rice yield in Nepal by 36% (1.68 t ha−1) compared to traditional practices and 12% over blanket recommendations, while reducing N and P_2O_5 use by 4% and 28%, respectively (Marahatta et al. 2025).

2.4 Field Demonstrations and Adoption

Field demonstrations are a critical component for technology transfer, validating the effectiveness of recommendations in real-world conditions. Farmers' participation in extension training and demonstration programs may unleash farmers' potential and enable them to adopt improved production techniques to bring about sustainable farm productivity improvement. Training and

demonstration programs improved the adoption intensity of rice production technologies practices (RPTPs) by 64.4% in Tanzania and governments and other stakeholders should invest more in them (Mgendi et al., 2022).

Engagement in agricultural extension services was associated with technology adoption and production risk reduction. The agricultural extension services increased, technology adoption by 4.2 % and decreased production risk by 2.4% (Alam et al. 2024).

The Khamari app's effectiveness, validated through demonstration trials on T. Aman and Boro rice, supports this approach, revealing significant improvements in yield and cost savings.

3. METHODOLOGY

In developing fertilizer recommendations, soil fertility data from Upazila Nirdeshika, prepared by the Soil Resource Development Institute (SRDI), serves as the foundation. Derived from detailed soil analyses at 200-hectare intervals within each upazila, these data guide fertilizer dose formulation, strictly following the guidelines in the Bangladesh Agricultural Research Council (BARC) Fertilizer Recommendation Guide (Ahmmed et al. 2018). In Bangladesh, the BARC Fertilizer Recommendation Guide provides science-based guidance, which serves as the backbone for apps like Khamari to deliver localized fertilizer schedules.

The integration of geospatial tools such as Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Remote Sensing (RS) has enhanced the capacity of farmers and policymakers to assess land quality, crop suitability, and nutrient needs. Technologies are essential for land-use planning and achieving sustainable agricultural intensification (De Wrachien, 2003). Technologies provide critical insights and support systems that empower farmers to navigate challenges effectively and seize opportunities for growth. As such, the adoption of agricultural software is not just a modernization effort but a strategic imperative to empower farmers and ensure the resilience and sustainability of global food systems (Sarma et al. 2024). The Crop Zoning Information System (CZIS) and its linkage with the Khamari mobile app illustrate an effective model of applying geospatial intelligence at the farmer level.

3.1 Demonstration Trials by Season and AEZ

To encourage farmers to adopt the 'Khamari' mobile app for fertilizer recommendations, demonstration trials were set up in farmers' fields. Fertilizer used in these trials are, Urea, DAP, TSP, MoP, Gypsum and Zinc Sulphate. These trials aimed to raise awareness and assess the impact of app-prescribed fertilizer doses on crop yield by comparing two approaches:

Fertilizer Prescription Based on Khamari Mobile App: Recommendations derived from scientifically informed soil test results.

Farmers' Traditional Practice: Reflecting customary fertilizer application methods.

While fertilizer doses differed, all other crop management and intercultural operations were kept consistent across the trials to ensure accurate comparisons.

The Department of Agricultural Extension (DAE), Bangladesh Agricultural Research Institute (BARI), Bangladesh Rice Research Institute (BRRI), Bangladesh Institute of Nuclear Agriculture (BINA), Soil Resource Development Institute (SRDI), and Bangladesh Wheat and Maize Research Institute (BWMRI) conducted these trials to demonstrate the 'Khamari' app's efficacy. Field trials focused on comparing recommended doses by the app with traditional farmer practices during the Kharif-2 season (July 1–October 15) in 2023, and the Rabi season (October 16–March 15) in 2023-24 for transplanted Aman rice and Boro rice, respectively.

Demonstration trials for T. Aman rice were conducted across 34 locations during the Kharif-2 season, and for Boro rice across 60 locations during the Rabi season. These trials were carried out within 20 Agro-Ecological Zones (AEZs) (Brammer et al. 1988) which collectively represent approximately 93% of the total cultivable land area (Table 1).

Each demonstration plot spanned 10 decimals, with separate plots for the 'Khamari' app-based recommendations and farmers' traditional practices. Post-harvest, crop weights were measured with 14% moisture content to determine yield per plot. The cost of fertilizer was

calculated according to the selling price fixed by the government.

3.2 Statistical Analysis

To assess the effectiveness of the 'Khamari' app recommendations, data from the demonstration trials were analyzed using a t-test at a 5% significance level, providing insight into whether differences in yield and fertilizer costs were statistically significant.

3.3 Sustainable Land Use

The Khamari mobile app adopts a scientific and data-driven approach to land and soil management to help farmers optimize crop production sustainably. It integrates detailed geospatial agro-edaphic and soil fertility data to guide farmers in making informed decisions.

At the core of Khamari's land and soil management strategy is soil resource mapping and land suitability analysis. The app uses digital soil maps and agro-ecological zoning data to evaluate the physical and chemical characteristics of land parcels, such as pH, salinity, land relief, landtype, texture, water recession, and drainage capacity. Based on this, it recommends crops best suited to the specific conditions of a farmer's land.

For fertility management, Khamari provides tailored fertilizer recommendations by balancing nutrient supply with crop demand and existing soil conditions. This reduces wasteful input use, cuts costs, and prevents environmental degradation from over-fertilization. The app also supports crop rotation and diversification strategies to maintain long-term soil health and productivity.

Overall, Khamari's management approach links scientific expertise with user-friendly technology, making advanced soil and land care accessible even to smallholder and illiterate farmers- ultimately enhancing resilience, yields, and food security.

By combining scientific soil analysis, localized crop planning, and digital advisory services, Khamari ensures sustainable land use while boosting agricultural productivity. Its approach reflects global best practices in soil conservation, as highlighted by FAO's emphasis on healthy soils for sustainable food security (Rojas et al. 2016).

3.4 Contribution of the Khamari App in Implementation

The Khamari app serves as a digital extension of the Crop Zoning System developed by BARC, translating complex agro-ecological and crop suitability data into actionable advice for farmers. Its key contributions include:

1. Field-Level Application: Translates zoning data into crop-specific, location-based advice for farmers.
2. Crop Suitability Guidance: Helps farmers choose the right crops based on agro-ecological conditions for sustainable land use.
3. Efficient Input Use: Recommends optimal fertilizer, seed, and irrigation practices.
4. Climate-smart Agriculture: Delivers localized weather forecasts, drought/flood warnings, and crop-stage-specific agromet advisories.
5. Monitoring & Feedback: Collects usage data to improve policy and model accuracy. Help track the adoption of zoning-based recommendations across regions.
6. Scalability: Designed for wide use with local language support and simple interfaces.

Khamari ensures that the zoning recommendations are implemented on the ground, enhancing alignment with national agricultural plans.

4. RESULTS AND DISCUSSION

4.1 T. Aman demo trial (2023)

The demonstration trials conducted in 2023 for transplanted Aman rice across 34 locations have revealed the substantial benefits of adopting the scientifically informed fertilizer recommendations provided by the 'Khamari' app (Table 2). The average yield in plots using the 'Khamari' app recommendations was 5.32 tons/ha, while farmers' traditional practices yielded an average of 4.98 tons/ha. This marks a 6.83% increase in yield, or an additional yield of 340 kg/ha in favour of 'Khamari' app-recommended plots. Furthermore, the per-hectare fertilizer costs were significantly reduced by 33.99% in the 'Khamari' plots compared to the farmers' traditional practices plots. The graph showing demonstration trial result of T. Aman rice is presented in Fig. 1.

Table 1. List of AEZs with their areas and key features

Agro-ecological Zone	Cultivable Area (ha); Percent	Key features
Old Himalayan Piedmont Plain	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	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
Karatoya-Bangali Floodplain	221181 (1.91%)	HL (27%), MHL (52%), MLL (16%), LL (5%); Loam (40%), Clay loam (12%), Clay (44%) soils; Moderately acidic (72%), Neutral (28%); Annual rainfall 1500 - 1800mm
Lower Atrai Basin	81350 (0.70%)	HL (2%), MHL (9%), MLL (22%), LL (67%); Loam (14%), Clay loam (3%), Clay (83%) soils; Strongly acidic (49%), Moderately acidic (49%), Neutral (2%); Annual rainfall 1500 - 1600mm
Young Brahmaputra and Jamuna Floodplain	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	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	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	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	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
Gopalganj-Khulna Bils	215706 (1.87%)	HL (3%), MHL (13%), MLL (42%), LL (30%), VLL (12%); Loam (7%), Clay loam (14%), Clay (75%), Peat (3%) soils; Strongly acidic (4%), Moderately acidic (67%), Neutral (29%); Annual rainfall 1600 - 2000mm
Young Meghna Estuarine Floodplain	487261 (4.21%)	MHL (86%), MLL (14%); Loam (53%), Clay loam (30%), Clay (16%) soils; Moderately acidic (10%), Neutral (90%); Annual rainfall 2500 - 3000mm
Old Meghna Estuarine Floodplain	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
Eastern Surma-Kusiyara Floodplain	398529 (3.45%)	HL (6%), MHL (29%), MLL (23%), LL (42%); Sandy loam (2%), Loam (23%), Clay (74%) soils; Strongly acidic (2%), Moderately acidic (98%); Annual rainfall 2500 - 5000mm
Sylhet Basin	409204 (3.54%)	MHL (4%), MLL (22%), LL (48%), VLL (26%); Loam (9%), Clay loam (6%), Clay (85%) soils; Strongly acidic (1%), Moderately acidic (99%); Annual rainfall 2500 - 5000mm
Northern and Eastern	364016 (3.15%)	HL (36%), MHL (35%), MLL (18%), LL (10%), VLL (1%); Sand (2%), Sandy loam (10%), Loam (45%),

Agro-ecological Zone	Cultivable Area (ha); Percent	Key features
Piedmont Plain		Clay loam (13%) and Clay (28%) soils; Strongly acidic (17%), Moderately acidic (83%); Annual rainfall 2000 - 5000mm
Chittagong Coastal Plain	273134 (2.36%)	HL (23%), MHL (60%), MLL (17%); Sand (4%), Loam (49%), Clay loam (22%), Clay (24%) soils; Extremely acidic (3%), Strongly acidic (3%), Moderately acidic (74%), Neutral (18%), Moderately alkaline (2%); Annual rainfall 2500 - 3500mm
Level Barind Tract	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	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	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
Northern and Eastern Hills	1422796 (12.31%)	HL (96%), MHL (3%), MLL (1%); Sandy loam (37%), Loam (58%) and Clay loam (4%) soils; Strongly acidic (83%), Moderately acidic (17%); Annual rainfall 2000 - 5000mm
Total	**10739224 (92.88%)**	

HL-Highland, MHL-Medium Highland, MLL-Medium Lowland, LL-Lowland, VLL-Very Lowland

Table 2. Outcomes of the demonstration trials for T. Aman rice conducted in Kharif-2 season

Crop Name and Number of demonstration trials	Demo Trial (Year)	Fertilizer Cost (Tk/ha)		Khamari Fertilizer Cost Compared to Farmer (%)	Yield (Ton/ha)		Khamari Yield Compared to Farmer (%)
		Khamari	Farmers		Khamari	Farmers	
T. Aman (34)	2023	9,194	13,929	-33.99%	5.32	4.98	+6.83%

Note: Number of demonstration trial sites are presented within parenthesis

The paired sample t-test conducted for the demonstration trials aimed to statistically analyze the differences in yield and fertilizer cost between the fertilizer recommendations provided by the 'Khamari' app and farmer's traditional practices. There is a statistically significant increase in yield with the 'Khamari' app (Mean = 5.32, SD = 0.746) compared to farmers' practices (Mean = 4.98, SD = 0.794) with t-test result, t(33) = 4.915, p = .000. A significant reduction in fertilizer cost was also observed between 'Khamari' app (Mean = 9194, SD = 1675.30) and farmers' practices (Mean = 13929, SD = 5831.20) with t-test result, t(33) = -4.520, p = .000.

Analyzing the results of 34 demonstration trials of T. Aman rice shows that using the fertilizer recommendations provided by the 'Khamari' app can save farmers 4,735/- Taka per hectare in fertilizer costs. Due to increased yields, additional production of 0.34 metric tons per hectare can be achieved, which is worth 10,880/- Taka (at the rate of 32/- Taka per kg). In total, using the fertilizer recommendations from the Khamari app would provide farmers a net financial gain of 15,615/- Taka per hectare (Table 3). This analysis clearly demonstrates the economic and productivity advantages of scientifically guided fertilizer recommendations provided by the 'Khamari' app.

4.1.1 Fertilizer use in T. Aman demo trial

In the demonstration trials, the per-hectare use of various fertilizers such as DAP, TSP, MoP and Gypsum was significantly lower with Khamari app-based recommendations compared to farmers' traditional practices. The use of Urea decreased by 12%, DAP by 59%, TSP by 72%, MoP by 14% and Gypsum by 20%. These results are illustrated in Fig. 2.

4.2 Boro Demo Trial (2023-24)

The results of the demonstration trials for Boro rice, conducted during 2023-24, in 60 locations across different AEZ using the 'Khamari' mobile app for fertilizer recommendations, are presented in the following sections.

In summary, the outcome of demonstration trials are presented in Table 4. The average yield of Khamari app based fertilizer recommendation plot was 7.36 ton/ha while yield of farmers' traditional practice based fertilizer application plot was 6.97 ton/ha, highlighting the positive impact of scientific fertilizer prescriptions. The yield of boro rice averaged on 60 demonstration trials is 5.59% higher for Khamari plot compared to

Farmers' plot. In contrast the fertilizer cost is 18.21% lower in case of Khamari app based fertilizer recommendation compared to farmer's fertilizer application. The graph showing demonstration trial result of Boro rice yield and fertilizer cost are presented in Fig. 3.

A paired sample t-test confirmed significant differences in yield: 'Khamari' plots (Mean = 7.36, SD = 1.167) vs. Farmers' plots (Mean=6.97, SD=1.174); t(59) = 5.997, p = .000; and fertilizer cost: 'Khamari' plots (Mean=16809, SD=5444.96) vs. farmers' plots (Mean=20551, SD=6278.52); t(59) = -5.143, p = .000.

It was observed from both T. Aman and Boro rice demonstration trials that, the paired sample t-test strongly supports the benefits of the 'Khamari' app in enhancing yield and reducing fertilizer costs, promoting sustainable agricultural practices.

Analyzing the results of 60 demonstration trials of Boro rice shows that using the fertilizer recommendations provided by the 'Khamari' app can save farmers 3,742/- Taka per hectare in fertilizer costs. Due to increased yields, additional production of 0.39 metric tons per hectare can be achieved, which is worth 12,480/- Taka (at the rate of 32/- Taka per kg). In total, using the fertilizer recommendations from the Khamari app would provide farmers a net financial gain of 16,222/- Taka per hectare (Table 5).

4.2.1 Fertilizer use in Boro demo trial

In the demonstration trials, the per-hectare use of various fertilizers such as DAP, TSP, MoP and Gypsum was significantly lower with Khamari app-based recommendations compared to traditional farmers' practices. Specifically, the use of DAP decreased by 44.57%, TSP by 56.18%, MoP by 15.32% and Gypsum by 9.72%. However, the use of urea was 0.91% higher than in traditional practices. These results are illustrated in Fig. 4.

Field demonstrations are a critical component for technology transfer, validating the effectiveness of recommendations in real-world conditions. The Khamari app's effectiveness, validated through demonstration trials on T. Aman and Boro rice, supports this approach, revealing significant improvements in crop yields and substantial fertilizer savings compared to conventional practices, underscoring the app's potential to promote efficient input use and sustainable productivity gains.

Table 3. Expected financial benefits of using Khamari App recommended fertilizer

| Crop Name and Number of demonstration trials	Fertilizer cost saving using Khamari app (Taka/ha)	Increased yield using Khamari app (Ton/ha)	Price of additional yield (Taka/ha)	Financial benefit of using Khamari app (Taka/ha)
T. Aman (34)	4,735	0.34	10,880	15,615
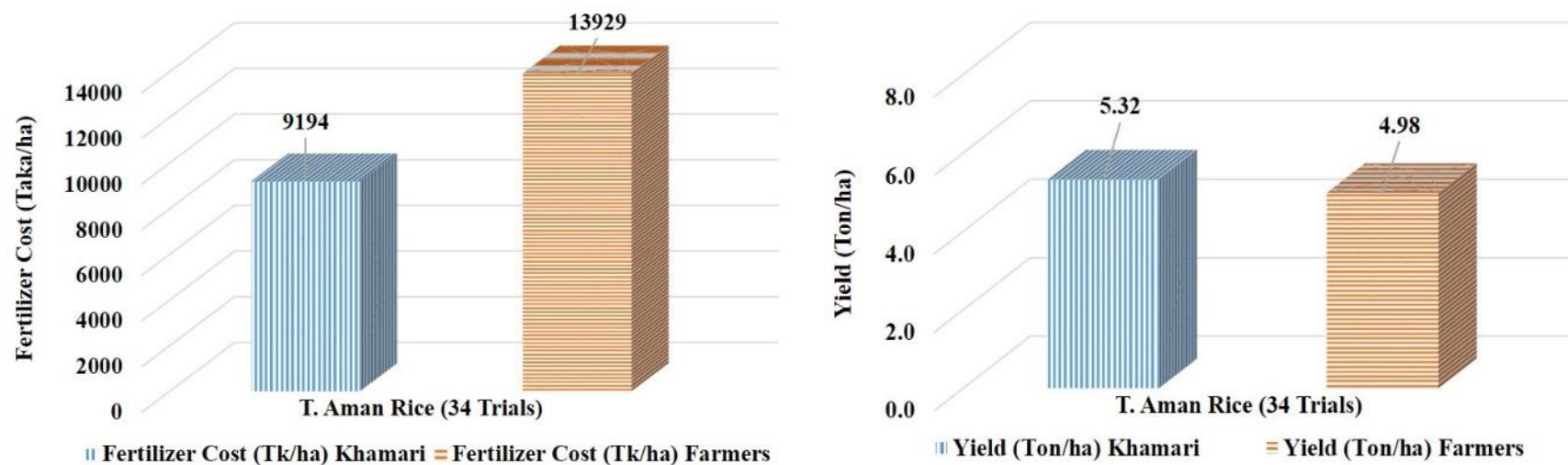
Fig. 1. Yield and fertilizer cost of T. Aman rice averaged on 34 demonstration trial

Table 4. Outcomes of the demonstration trials for Boro rice conducted in Rabi season

Crop Name and Number of demonstration trials	Demo Trial (Year)	Fertilizer Cost (Tk/ha)		Khamari Fertilizer Cost Compared to Farmer (%)	Yield (Ton/ha)		Khamari Yield Compared to Farmer (%)
		Khamari	Farmers		Khamari	Farmers	
Boro rice (60)	2023-24	16,809	20,551	-18.21%	7.36	6.97	+5.59%

Note: Number of demonstration trial sites are presented within parenthesis
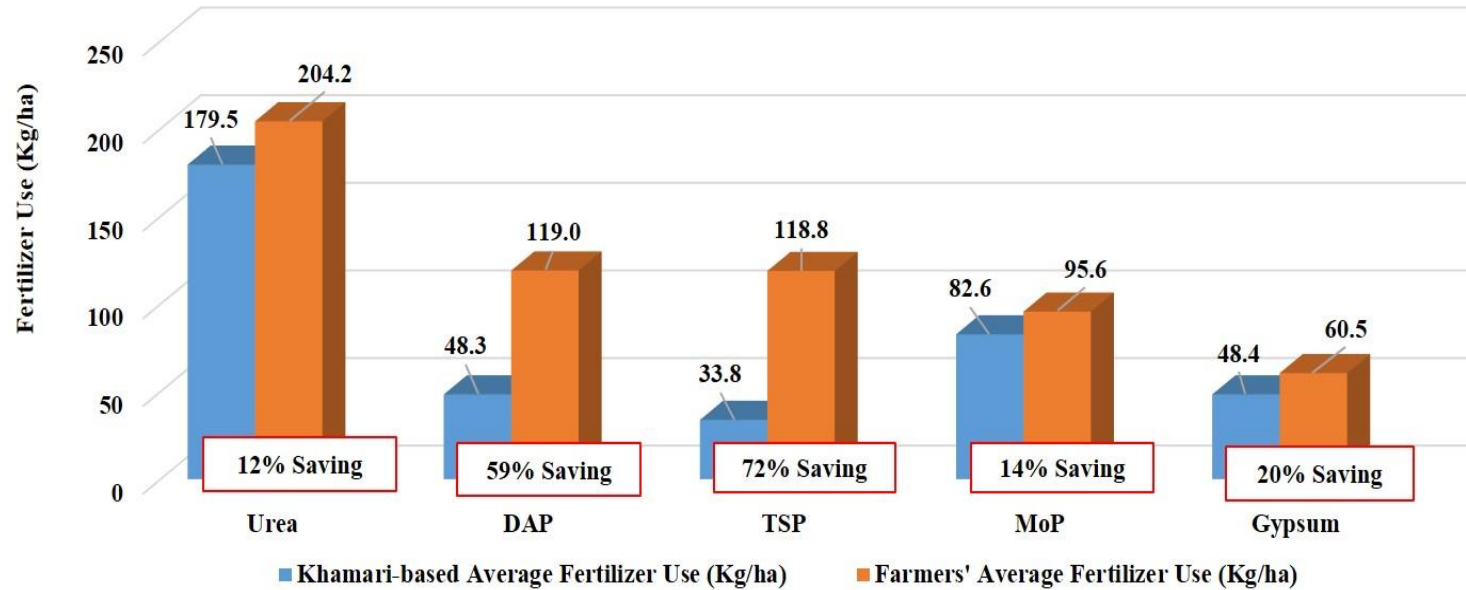
Fig. 2. Average fertilizer use in T. Aman rice demonstration trials conducted in 34 locations

Table 5. Expected financial benefits of using Khamari App recommended fertilizer

Crop Name and Number of demonstration trials	Fertilizer cost saving using Khamari app (Taka/ha)	Increased yield using Khamari app (Ton/ha)	Price of additional yield (Taka/ha)	Financial benefit of using Khamari app (Taka/ha)
Boro rice (60)	3,742	0.39	12,480	16,222
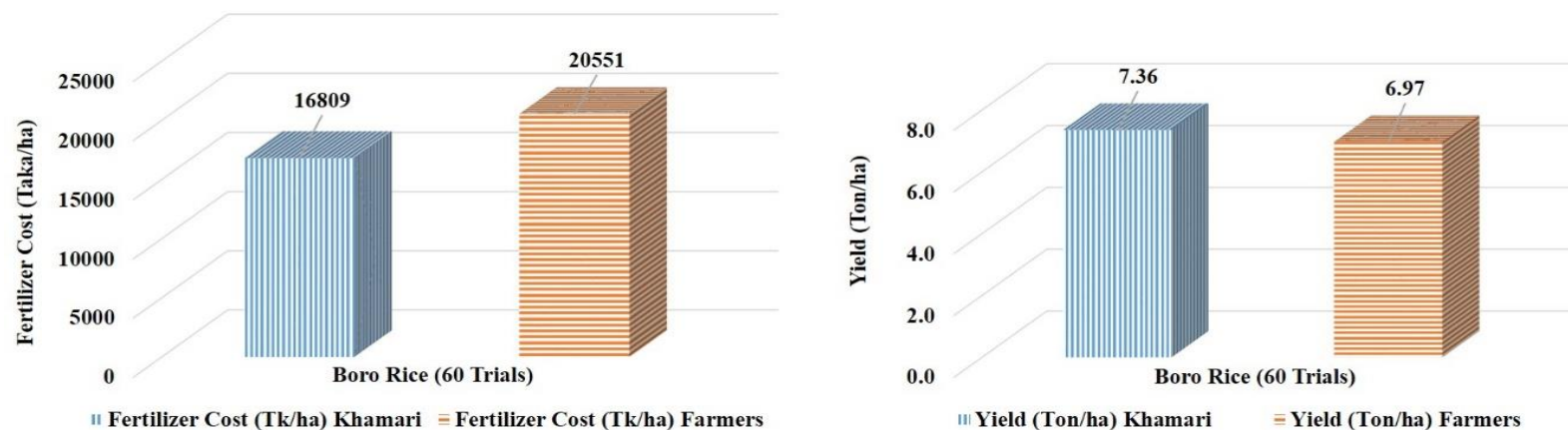
**Fig. 3. Yield and fertilizer cost of boro rice averaged on 60 demonstration trials**
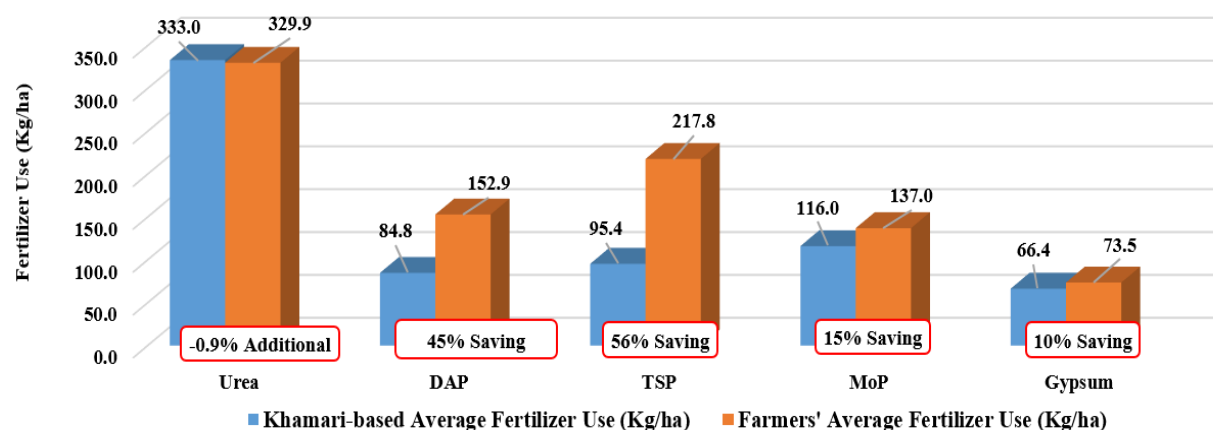
Fig. 4. Average fertilizer use in Boro rice demonstration trials conducted in 60 locations

5. OUTCOME/IMPACTS

The results from demonstration trials of the 'Khamari' app for Aman and Boro rice emphasize the app's considerable economic impact potential on Bangladesh's agricultural sector.

With 5.7 million hectares (Mha) of Aman rice cultivated in Bangladesh, using the Khamari app's fertilizer recommendations could generate an estimated 89,655.3 million BDT in financial benefits across the nation. Given that Boro rice is grown on 5.058 Mha, widespread adoption of the app's fertilizer recommendations could yield a financial benefit of 82,050.8 million BDT.

These results highlight the potential financial gains of 171,706.1 million BDT if Khamari app recommendations were broadly adopted, illustrating how digital agricultural tools can transform productivity.

6. FUTURE INTENTION

Although significant progress has been made, several essential agricultural services are yet to be integrated into the Khamari app. These include pest and disease management, weather and agrometeorological advisories, market price information, and seed availability and variety recommendations. Integrating these services will enable Khamari to evolve into a comprehensive one-stop digital platform for all farming needs. This transformation is crucial to achieving a smarter, more efficient, and sustainable agricultural future for Bangladesh and can serve as a model for digital agriculture in other countries/regions as well.

7. CONCLUSION

The 'Khamari' mobile app is a vital tool for promoting smart agriculture by integrating technology to optimize resource management and support data-driven decision-making. Through real-time recommendations, the app enables farmers to make informed choices, leading to increased crop yields, reduced input costs, and greater efficiency in agricultural practices. By offering precise fertilizer recommendations, the app not only cuts expenses but also boosts crop productivity and supports environmentally sustainable farming practices. Additionally, by fostering eco-friendly approaches, it has the potential to decrease greenhouse gas emissions, enhance soil health, and save the government significant costs, especially since fertilizers are imported.

The 'Khamari' app aligns closely with the goals of sustainable development (SDGs), encouraging resource conservation, environmental stewardship, and food security. By delivering localized, actionable insights and encouraging eco-friendly agricultural practices, it supports the resilience of farming systems, promotes rural economic development, and reinforces national food security. As such, it is a valuable asset for farmers, extension workers, and policymakers committed to building a more sustainable agricultural future in Bangladesh.

The Khamari App exemplifies the integration of precision agriculture and mobile-based advisory services tailored to the context of Bangladesh. Initial field trial results have demonstrated measurable gains in efficiency and productivity. However, scaling its impact will require concerted efforts to overcome challenges related to digital infrastructure, farmer digital literacy, and supportive policy environments.

Research and global experiences emphasize the importance of:

- Localized adaptation of technology to agro-ecological and socio-economic conditions,
- Farmer-centric design that ensures usability regardless of literacy levels, and
- Robust governance frameworks that ensure data accuracy, content validation, and institutional collaboration.

With the right support mechanisms in place, the 'Khamari' app can serve as a model for digital agriculture, not only within Bangladesh but also across other developing regions aiming to modernize their agricultural advisory systems through smart, sustainable, and inclusive digital solutions.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Ahmmed, M., Rahman, M. A., Hossain, M. A., & Ahmed, M. M. (2018). *Fertilizer recommendation guide-2018.* Bangladesh Agricultural Research Council (BARC). Farmgate, Dhaka 1215. 223p.

Alam, M. J., Sarma, P. K., Begum, I. A., Connor, J., Crase, L., Sayem, S. M., & McKenzie, A. M. (2024). Agricultural extension service, technology adoption, and production risk nexus: Evidence from Bangladesh. *Heliyon, 10,* e34226. https://doi.org/10.1016/j.heliyon.2024.e34226

Arun, D. P., & Mishra, A. (2024). Enabling digital platforms: Toward smart agriculture. In S. S. Chouhan, A. Saxena, U. P. Singh, & S. Jain (Eds.), *Artificial intelligence techniques in smart agriculture* (pp. 1–14). Springer. https://doi.org/10.1007/978-981-97-5878-4_14

Bangladesh Planning Commission. (2020). *Eighth Five Year Plan (July 2020–June 2025).* Ministry of Planning, Government of Bangladesh. https://plancomm.gov.bd/sites/default/files/files/plancomm.portal.gov.bd/files/68e32f08_13b8_4192_ab9b_abd5a0a62a33/2021-02-03-17-04-ec95e78e452a813808a483b3b22e14a1.pdf

BBS. (2023). *Labor force survey 2022 Bangladesh.* Bangladesh Bureau of Statistics, Ministry of Planning, Government of Bangladesh. https://bbs.portal.gov.bd/sites/default/files/bbs.portal.gov.bd/page/b343a8b4_956b_45ca_872f_4cf9b2f1a6e0/2023-10-25-07-38-4304abd7a3f3d8799fbcb59ff91007b1.pdf

BBS. (2024). *Yearbook of agricultural statistics-2024.* Bangladesh Bureau of Statistics, Ministry of Planning, Government of Bangladesh. https://bbs.portal.gov.bd/sites/default/files/bbs.portal.gov.bd/page/1b1eb817_9325_4354_a756_3d18412203e2/2025-06-25-05-43-178708b039d7df3fb55328436ac1b80c.pdf

Brammer, H., Antoine, J., Kassam, A. H., & van Velthuizen, H. T. (1988). *Land resources appraisal of Bangladesh for agricultural development.* Technical Reports 1–7. FAO/UNDP: BGD/81/035 Agricultural Development Advisor Project, Dhaka, Bangladesh.

De Wrachien, D. (2003). Land use planning: A key to sustainable agriculture. In L. Garcia-Torres, J. Benites, A. Martinez-Vilela, & A. Holgado-Cabrera (Eds.), *Conservation agriculture* (pp. 471–484). Springer. https://doi.org/10.1007/978-94-017-1143-2_57

Khaspuria, G., Khandelwal, A., Agarwal, M., Bafna, M., Yadav, R., & Yadav, A. (2024). Adoption of precision agriculture technologies among farmers: A comprehensive review. *Journal of Scientific Research and Reports, 30*(7), 671–686. https://doi.org/10.9734/jsrr/2024/v30i72180

Marahatta, S., Sah, S. K., McDonald, A. J., Timsina, J., Karn, R., & Devkota, K. (2025). Site-specific nutrient management: A robust approach to estimating indigenous nutrient supply, recommending fertilizer, and increasing rice yield in Nepal. https://dx.doi.org/10.2139/ssrn.5205910

Mgendi, G., Mao, S., & Qiao, F. (2022). Does agricultural training and demonstration matter in technology adoption? The empirical evidence from small rice farmers in Tanzania. *Technology in Society, 70,* 102024. https://doi.org/10.1016/j.techsoc.2022.102024

Mittal, S., & Mehar, M. (2016). Socio-economic factors affecting adoption of modern information and communication technology by farmers in India. *Agricultural Economics Research Review, 29*(2), 249–260. https://doi.org/10.1080/1389224X.2014.997255

Pampolino, M. F., Johnston, A., Sato, S., Crutz, D. C., & Gerard, B. (2012). Development approach and evaluation of the Nutrient

Expert software for rice. *Agronomy Journal, 104*(2), 196–209. https://doi.org/10.2134/agronj2011.0301

Pandey, P. C., & Pandey, M. (2023). Highlighting the role of agriculture and geospatial technology in food security and sustainable development goals. *Sustainable Development, 31*(5), 3175–3195. https://doi.org/10.1002/sd.2600

Pereira, A. R. (1983). Crop planning for different environments. *Symposium on Potential Productivity of Field Crops under Different Environments*, International Rice Research Institute, 415–420.

Rojas, R. V., Achouri, M., & Maroulis, J. (2016). Healthy soils: A prerequisite for sustainable food security. *Environmental Earth Sciences, 75*, 180. https://doi.org/10.1007/s12665-015-5099-7

Sarma, H. H., Borah, S. K., Chintey, R., Nath, H., & Talukdar, N. (2024). Site specific nutrient management (SSNM): Principles, key features, and its potential role in soil, crop ecosystem, and climate resilience farming. *Journal of Advances in Biology & Biotechnology, 27*(8), 211–222. https://doi.org/10.9734/jabb/2024/v27i81133

Sarma, H. H., Das, B. C., Deka, T., Rahman, S., Medhi, M., & Kakoti, M. (2024). Data-driven agriculture: Software innovations for enhanced soil health, crop nutrients, disease detection, weather forecasting, and fertilizer optimization in agriculture. *Journal of Advances in Biology & Biotechnology, 27*(8), 878–896. https://doi.org/10.9734/jabb/2024/v27i81209

Shawan, M. U., Sohel, M. R., & Mahedi, H. (2024). Smart agriculture in the context of the fourth industrial revolution: Opportunities and challenges for Bangladesh. In *Smart systems: Methodological approaches and applications* (1st ed., pp. 68–95). CRC Press. https://doi.org/10.1201/9781003495314

Sivakumar, M. V. K., & Valentin, C. (1997). Agroecological zones and the assessment of crop production potential. *Philosophical Transactions of the Royal Society B: Biological Sciences, 352*(1356), 907–916. https://doi.org/10.1098/rstb.1997.0070

Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming – A review. *Agricultural Systems, 153*, 69–80. https://doi.org/10.1016/j.agsy.2017.01.023

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