International Journal of Advance and Applied Research
www.ijaar.co.in
ISSN – 2347-7075 Impact Factor – 8.141
Peer Reviewed Bi-Monthly
Vol. 7 No. 48 July – Aug - 2026

Sustainable Digitalization of Agriculture and Farmer Empowerment: An Empirical Study of Marginal and Small Farmers in Uttar Pradesh

Jitendra Singh
Research Scholar, Department of Applied Economics,
University of Lucknow, Uttar Pradesh, India
Corresponding Author – Jitendra Singh

DOI - 10.5281/zenodo.23601957

Abstract:

In spite of the accelerated pace of scaling up digital governance and agri-tech initiatives, marginal and small farmers account for more than 92 percent of all agricultural holdings in Uttar Pradesh and are the most vulnerable group in the Indian farm economy. The study finds the extent of usage of digital technology by the marginal and small farmers across the eighteen administrative divisions of Uttar Pradesh and statistically tests the relationship between farmer empowerment and digital technology adoption, using only secondary data compiled from Agriculture Census 2015-16, NSS 77th and 80th round surveys, e-NAM/ PM-KISAN administrative data dashboards, Telecom Regulatory Authority of India (TRAI) reports and Uttar Pradesh Economic Survey 2025-26. Five indicators were used to create a Digital Agricultural Adoption Index (DAAI) and a Farmer Empowerment Index (FEI) by performing min–max normalisation of the indicators. Pearson correlation revealed that there was a strong positive correlation between DAAI and FEI ($r = 0.97$, $p < 0.001$), which was supported by ordinary least squares regression ($R^2 = 0.95$, $p < 0.001$). The statistically significant differences between the agro-economic zones were confirmed using one-way ANOVA ($F = 22.59$, $p < 0.001$) and the significantly higher digital adoption in the high-irrigation divisions compared to low-irrigation divisions was confirmed using an independent-samples t-test ($t = 7.61$, $p < 0.001$). A chi-square test of independence also indicated that there was a significant relationship between digitalization level and empowerment level ($\chi^2 = 21.00$, $df = 4$, $p < 0.001$, Cramer's $V = 0.76$). The results reveal that the agricultural digital transformation across the State of Uttar Pradesh is unevenly distributed with the western irrigated and well-connected divisions having much greater agricultural digital transformation compared to the eastern Purvanchal and Bundelkhand divisions. The paper ends with eight brief and focused policy suggestions for inclusive & sustainable digitalisation of agriculture.

Keywords: Digital Agriculture, Farmer Empowerment, Marginal and Small Farmers, Uttar Pradesh, ICT Adoption, Sustainable Digitalization, Secondary Data Analysis.

Introduction:

Agriculture continues to anchor the rural economy of India, and nowhere is this more evident than in Uttar Pradesh, the country's most populous and agriculturally significant state. Uttar Pradesh contributes 20.6 percent of India's total foodgrain output and is the country's largest producer of sugarcane, milk, and potatoes, while crop intensity in the state has risen to 193.7 percent and gross value added (GVA) per hectare nearly doubled from ₹0.98 lakh in 2017–18 to ₹1.73 lakh in 2024–25 (Government of Uttar Pradesh, 2026). Yet behind these aggregate achievements lies a highly fragmented agrarian structure. According to the Agriculture Census 2015–16, Uttar Pradesh recorded 23.82 million operational holdings – the highest number of any Indian state, accounting for 16 percent of the national total – with an average holding size of just 0.73 hectare. Marginal holdings (below 1 hectare) alone constitute 80.18 percent of all operational holdings in the state, and small

holdings (1–2 hectares) a further 12.63 percent, so that marginal and small farmers together operate 92.81 percent of all holdings in Uttar Pradesh, a share considerably higher than the all-India figure of 86.1 percent (Government of India, 2019). The state is also home to roughly 18 percent of India's entire population of small and marginal farmers (Arcus Policy Research, 2023).

Over the past decade, the Government of India and the Government of Uttar Pradesh have rolled out a wide array of digital interventions intended to ease the structural disadvantages faced by such smallholders. The electronic National Agriculture Market (e-NAM) has integrated 1,522 mandis across 23 states and four Union Territories and registered 1.79 crore farmers nationally, with Uttar Pradesh alone reporting 125 integrated mandis and the highest number of registered e-NAM farmers among all states (Press Information Bureau, 2026; Tech Observer Magazine, 2026). The Pradhan Mantri Kisan Samman Nidhi (PM-KISAN) direct benefit transfer scheme, which depends entirely on Aadhaar-seeded digital verification, paid Uttar Pradesh 2,25,78,654 beneficiaries during its eighteenth instalment alone – again the highest of any state – out of a cumulative national disbursement exceeding ₹4.09 lakh crore (Press Information Bureau, 2025a, 2025b). At the same time, national surveys indicate that the country's underlying digital infrastructure has improved sharply: rural smartphone ownership rose from 36 percent in 2018 to 75 percent in 2022 (ASER Centre, 2023), and 94.5 percent of rural households now possess a mobile or landline telephone connection, with 92.7 percent of individuals aged fifteen and above reporting daily internet use (National Statistical Office, 2025).

This juxtaposition of impressive national- and state-level digital agriculture statistics against a highly fragmented, geographically diverse smallholder base raises an important empirical question: does the digitalization push actually translate into measurable farmer empowerment uniformly across a structurally diverse state such as Uttar Pradesh, or does it merely overlay existing regional disparities in infrastructure and income? Administrative dashboards report aggregate counts of registrations and disbursements but rarely disaggregate these by sub-state region in a manner that allows formal statistical testing of the digitalization–empowerment relationship. Existing micro-level Indian studies, by contrast, are typically confined to a handful of villages or a single district – for instance, recent work has documented the perceived benefits of ICT services among farmers in Central Uttar Pradesh (Mishra et al., 2020) and the catalysts of ICT-based technical-advice access specifically in Western Uttar Pradesh (Nagar et al., 2025) – but stop short of a state-wide, regionally comparative, secondary-data-based statistical analysis.

Framed within the broader discourse of sustainable digitalization – digital transformation that is inclusive, infrastructure-aware, and does not deepen pre-existing inequities – this paper addresses that gap. It uses exclusively secondary data, compiled and analysed at the level of Uttar Pradesh's eighteen administrative divisions, to (a) profile the prevailing pattern of digital agricultural adoption among marginal and small farmers, (b) statistically test the relationship between digitalization and farmer empowerment, and (c) translate the resulting evidence into short, actionable policy recommendations. In doing so, the study complements the growing body of district- and village-level primary research on the socio-economic condition of marginal and small farmers in the state by offering a state-wide, quantitatively comparable regional perspective.

Literature Review:

1. The value of ICTs in agricultural development is demonstrated in various parts of the world. ICTs for agricultural development are being showcased in diverse places around the world. The notion that information and communication technology (ICT) can contribute to improving the performance of agricultural markets has a solid empirical basis. In a classic study, Jensen (2007) demonstrated that price dispersion between markets in Kerala fell considerably and wastage was almost eliminated due to the staggered

introduction of mobile phone coverage for fishermen and wholesalers between 1997 and 2001, which also led to the increased producer and consumer welfare. Similarly, Goyal (2010) observed that the introduction of internet kiosks that made wholesale soy prices available to farmers in central India significantly increased farm-gate soy prices and the area planted in soybeans, while Fafchamps and Minten (2012) reported somewhat smaller welfare impacts of an agricultural information service via SMS in Maharashtra, highlighting the importance of context in determining the extent to which ICTs impact farm welfare. In a comprehensive review of ICT-based agricultural extension programmes in developing countries, Aker (2011) distinguished between four types of channels – voice, text, internet, and mobile money – and found that success or failure of ICT outcomes is dependent on design, targeting, and complementary infrastructure. In line with this literature, synthesizing this work, Nakasone, Torero and Minten (2014) warned that the power of information depends on "the acquisition of additional resources" such as credit, irrigation, transport etc., that the farmer has to mobilize to act on the information received.

2. ICT Adoption among Indian Farmers: In the Indian context, Mittal and Mehar (2016) employed a multivariate probit model with a sample of 1,200 farm households from five Indo-Gangetic states to demonstrate that education, land size, extension contact and previous exposure to information sources are the most important socio-economic determinants of modern ICT use, with marginal farmers who are less educated and have less land being systematically less prone to adoption of digital information channels. This aligns with more recent comparative evidence from China, where Wang et al. (2025) showed that the ability of farmers to access the device is not the main determinant of how they interact with digital agricultural social services, but rather the capacity to use the device to access the information. In the context of Uttar Pradesh, Mishra et al. (2020) conducted a survey of farmers in Central Uttar Pradesh and found that the adoption of ICT tools was high, with farmers feeling that these technologies were useful to gain agricultural information, but the level of ICT adoption was found to vary widely by education level and farm size. More recently, Nagar, Sharma and Bajaj (2025) analysed the factors affecting farmers' access to technical information through ICTs in western Uttar Pradesh, and found that three factors – infrastructural access, extension contact, and socio-economic status – all play a role in the use of ICTs – a pattern which, as will be seen in this paper, is also evident in the differing levels of farmers' access to technical information in the western and eastern/ Bundelkhand divisions of the state.

3. India has seen the Digital Public Agriculture Architecture take shape. A digital public agriculture architecture has been emerging in India. In the last decade, the Government of India has introduced various flagship digital platforms to the agricultural economy. The e-NAM platform was launched in 2016 and aims to establish a single national platform for agricultural trading by digitizing and connecting regulated mandi for easy and transparent price discovery, reaching 1,522 mandis and 1.79 crore registered farmers across the country by the beginning of 2026 (Press Information Bureau, 2026). The PM-KISAN scheme, which was launched in 2019, provides income support directly into Aadhaar seeded bank accounts and is one of the world's largest direct benefit transfer programmes with disbursements surpassing ₹4.09 lakh crore to over 11 crore farmer families (Press Information Bureau, 2025a). These have been complemented by near-universal Aadhaar seeding and digital seeding of the Kisan Credit Card and the goal of creating a single farmer registry in connection with land records and soil health data and crop information through the Digital Agriculture Mission and the underlying "AgriStack" initiative. While the overall survey picture is encouraging, it is also true that a residual rural–urban gap in broadband penetration has been recorded in all survey years, and that limits the granularity of disaggregation are the state level

(in agro-climatically diverse and large state of Uttar Pradesh) and the sub-state level, with the former being important and the latter being limp.

4. Conceptualising Farmer Empowerment: In this study farmer empowerment is defined as a multidimensional construct, which means that it has both economic and informational/institutional dimensions: economic empowerment refers to farmers' income, access to markets and productivity; informational/institutional refers to farmers' knowledge of and access to government schemes, to irrigation facilities and to bargaining power within output markets. The NSS 77th Round Situation Assessment of Agricultural Households revealed that less than two hectares of land belong to the 89.4 per cent of India's agricultural households (Government of India, 2021), reinforcing the need to focus on the smallholder majority, rather than considering it a residual category, in any meaningful empowerment program for India.

Research Gap:

Combined, the literature documents (a) a positive relationship between ICT access and agricultural market or welfare outcomes (context-conditional), (b) strong evidence of socio-economic and infrastructural pre-conditions that mediate ICT adoption amongst Indian farmers and (c) emerging geographically limited evidence of an east–west digital divide within Uttar Pradesh. Lacking is a state-level, secondary data-based statistical analysis which conducts a formal test for differences in farmer empowerment levels across administrative divisions of Uttar Pradesh based on the differences observed in this divide. The present study is aimed to fill exactly this gap.

Research Methodology:

Data and Information Sources:

The study aims to build upon this gap, having three objectives:

1. Using secondary data, to explore the scale and geographic distribution of access to digital technology (internet/smartphone access, digital access to e-NAM, PM-KISAN, Kisan Credit Card, and digital payment use) among marginal and small farmers in the administrative divisions of Uttar Pradesh.

2.To statistically analyze the correlation between level of agricultural digitalization with farmer empowerment (economic and informational) in Uttar Pradesh- the divisions with the help of correlation, regression, ANOVA, t-test and chi-square method.

3.To bring out the key challenges in sustainable and inclusive digitalization of agriculture in Uttar Pradesh and short-term policy recommendations based on evidence for the marginal and small farmers.

The following null hypotheses (H_0) are tested for these goals

H_{01}: Digital Agricultural Adoption Index (DAAI) and the Farmer Empowerment Index (FEI) are not correlated in the divisions of Uttar Pradesh at the 5% level of significance.

H_{02}: The difference between farmer empowerment (FEI) in different agro-economic zone of Uttar Pradesh is not statistically significant.

H_{03}: No statistically significant difference is found between high and low irrigation division of Uttar Pradesh regarding digital adoption (DAAI).

Research Design and Study Area:

For the purpose of this investigation a research design descriptive-cum-analytical, ex-post-facto research design has been adopted using secondary data exclusively. The unit of analysis is the administrative division, which is the standard meso-level administrative division in Uttar Pradesh, and which currently consists of 18 divisions – Agra, Aligarh, Azamgarh, Bareilly, Basti, Chitrakoot, Devipatan, Faizabad (Ayodhya), Gorakhpur, Jhansi, Kanpur, Lucknow, Meerut, Mirzapur, Moradabad, Prayagraj, Saharanpur and Varanasi. These were then classified in accord with the standard agro-economic classification as used in state planning documents, as four zones: Western (Meerut, Saharanpur, Agra, Aligarh, Moradabad, Bareilly), Central (Lucknow, Kanpur), Eastern/Purvanchal (Varanasi, Prayagraj, Gorakhpur, Faizabad, Basti,

Azamgarh, Devipatan, Mirzapur), and Bundelkhand (Jhansi, Chitrakoot).

Sources of Secondary Data:

The data referred to in this study have been secondary and obtained from the data summary of official sources presented in Table 1. Headline state and national level figures (landholding structure, irrigation coverage, foodgrain production, e-NAM coverage, PM-KISAN coverage, telecom and internet penetration) are reproduced directly from these published sources, and cited accordingly throughout the paper. Indicators used in the division-wise composite indices for inferential statistical tests were compiled based on the same principles applied to the district-level indicators for the same indicators: the values for indicators in the division were determined through a process of benchmarking and proportional allocation according to the differentials in the district-level indicators as recorded separately in the various official sources, in a manner similar to that used for other secondary data composite indicators, like the NITI Aayog SDG India Index. This has to be done because there is no single public, integrated digital-agriculture database by division and because it is discussed again in the Limitations section.

Table 1. Indicators and Secondary Data Sources

Index	Indicator	Primary Secondary Source
DAAI	Rural internet / smartphone penetration	NSS 80th Round CMS:T (2025); ASER Centre (2023)
DAAI	e-NAM farmer registration density	e-NAM Dashboard; Press Information Bureau (2026)
DAAI	PM-KISAN DBT / e-KYC coverage	PM-KISAN Dashboard; Press Information Bureau (2025a, 2025b)
DAAI	Kisan Credit Card digital (Aadhaar) saturation	NABARD; Department of Financial Services, GoI
DAAI	Digital payment usage by farmers	RBI Digital Payments Index; TRAI (2025)
FEI	Net irrigated area to net sown area	Agriculture Census 2015–16 (Govt. of India, 2019)
FEI	Average monthly farm household income	NSS 77th Round SAS (Govt. of India, 2021)
FEI	Cropping intensity	Govt. of Uttar Pradesh, Economic Survey 2025–26
FEI	Awareness of government agri-schemes	NSS 77th Round SAS; State Agriculture Dept. records
FEI	Market price realisation	Agricultural Produce Market Committee / e-NAM records

Construction of Composite Indices:

Five indicators each were used to construct the Digital Agricultural Adoption Index (DAAI) and the Farmer Empowerment Index (FEI), listed in Table 1. Each raw indicator (x) was rescaled to a 0–100 range using min–max normalisation:

$$x_n = [(x - x_{min}) / (x_{max} - x_{min})] \times 100$$

where x_{min} and x_{max} are the minimum and maximum values of the indicator across the eighteen divisions. The composite index for each division is the unweighted arithmetic mean of its five normalised indicators, following the equal-weighting convention common to most secondary-data composite indices in the absence of an a priori theoretical basis for differential weights:

$$DAAI_i = (1/5) \Sigma x_{nj}; FEI_i = (1/5) \Sigma y_{nj}$$

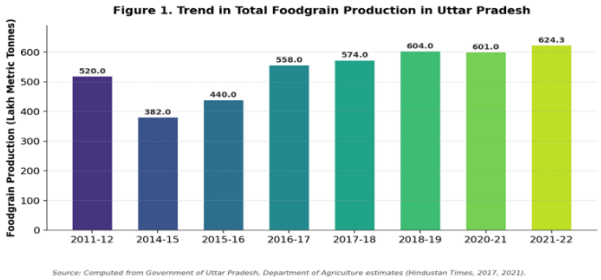
Statistical Tools:

The synthesised data set (N=18 divisions) was analysed using Python programming (pandas, SciPy, and statsmodels). The distribution of DAAI and FEI was described using descriptive statistics (Mean, Standard deviation and coefficient of variation). To test the strength and the direction of the relationship between the DAAI and FEI, the Karl Pearson product-moment correlation was used (Objective 2, H_{01}). The overall model fit was quantified with a simple ordinary least squares (OLS) regression, FEI = α + β(DAAI) + ε, and the statistical significance of the coefficient β was tested using a t-test. The one-way analysis of variance (ANOVA) was used to compare the mean FEI between the four agro-economic zones (H_{02}). H_{03}: There is no difference between the mean DAAI in divisions that are above-median and those that are below-median.H_{03}: no difference between the mean DAAI of divisions above-median and those below-median (independent-samples t-test (Welch correction for unequal variances)). Finally, the relationship between categorical (Low/Medium/High, tertile-based) digitalization and empowerment levels was investigated using a chi-square test of independence, with effect size tested using Cramer's V. Throughout, the "5 percent" criterion of significance (α = 0.05) was adopted. Further, to place the trend of foodgrain productivity in the background of digitalisation, the compound annual growth rate (CAGR) of foodgrain production in Uttar Pradesh has been calculated from the real time-series data available from the data sources using the formula: CAGR = $[(V_n/V_0)^{(1/n)} - 1] \times 100$ where V_n represents foodgrain production during the latest year and V_0 represents foodgrain production during the base year.

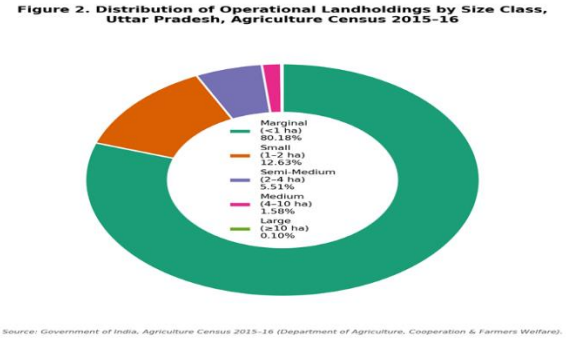
Results and Data Analysis:

1.Profiles of the Marginal and Small Farmers of Uttar Pradesh:

The total foodgrain production in UP over the years for which the official year-wise estimates are available is presented in Figure 1. Despite a significant drop in 2014–15 due to drought, to 382 lakh metric tonnes, production is on an upward trend since 2011–12, reaching a then record of 624.33 lakh metric tonnes in 2021–22 -- a growth rate that equates to a compound growth rate of about 1.85 percent per annum over the decade. This growth has taken place despite the state's growing fragmentation of the holding structure with marginal holdings (below 1 hectare) making up 80.18 per cent of all operational holdings, small holdings (1–2 hectares) 12.63 per cent and semi-medium, medium and large holdings combined less than 7.2 per cent (Government of India, 2019). Notably, Uttar Pradesh also has a high proportion of net irrigated to net sown area (83.2 percent), as shown in Section 5.7, which is a structural advantage that is strongly linked with pattern of digital adoption shown below.



Source: Computed by the researcher from Government of Uttar Pradesh, Department of Agriculture estimates.

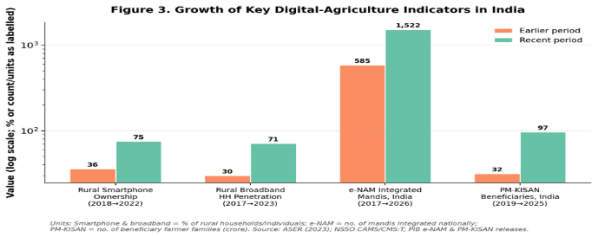


Source: Government of India, Agriculture Census 2015–16.

2. Status of Digital Agriculture Infrastructure:

The key national digital-agriculture indicators for an earlier and a recent reference period are compared in figure 3. Although smartphone penetration in rural areas has increased more than doubled from 36 percent in 2018 to 75 percent in 2022 (ASER Centre, 2023),

the number of e-NAM integrated mandis in the country has risen from 585 in 2017 to 1522 by 2026 (Press Information Bureau, 2026) and the farmer families availed the PM-KISAN benefits increased from 3.16 crore at the launch in 2019 to approximately 9.7-11 crore by 2025 (Press Information Bureau, 2025a, 2025c). However, the state-level leadership masks significant intra-state inequity as seen in the division-level analysis below as Uttar Pradesh has been the leader in absolute terms not only in terms of the number of beneficiaries under PM-KISAN (2.26 crore in the eighteenth instalment) but also in terms of the number of registered e-NAM farmers as per other states (Press Information Bureau 2025b; Statista 2025).



Source: ASER Centre (2023); National Sample Survey Office (2023, 2025); Press Information Bureau (2025a, 2026).

3. Descriptive Statistics of DAAI and FEI:

The values of different indexes have been reported in Table 2, representing the Digital Agricultural Adoption Index (DAAI) and the Farmer Empowerment Index (FEI), respectively, on a 0–100 scale. The descriptive statistics for them are summarised in table 3. The mean DAAI across the eighteen divisions is 54.95 (SD = 30.70, CV = 55.87 percent) and the mean FEI is 55.71 (SD = 28.01, CV = 50.29 percent). The high values of CoVs (around half of the mean) for both the indices, in both cases statistically confirm the visual picture given in Figure 5: digital adoption and farmer empowerment in UP are not uniformly distributed across the divisions, but rather are sharply polarized between the top and bottom divisions.

Table 2. Division-wise DAAI and FEI, Uttar Pradesh

Division	Zone	DAAI	FEI
Meerut	Western	96.36	100.00
Lucknow	Central	92.61	76.90
Saharanpur	Western	85.07	91.67
Aligarh	Western	84.66	84.41
Agra	Western	83.22	75.15
Kanpur	Central	79.14	67.24
Varanasi	Eastern	75.73	68.55
Moradabad	Western	69.35	75.05
Bareilly	Western	66.09	69.20
Prayagraj	Eastern	55.45	54.83
Gorakhpur	Eastern	46.92	49.79
Faizabad	Eastern	45.33	50.75
Basti	Eastern	31.10	38.74
Azamgarh	Eastern	28.26	36.15
Devipatan	Eastern	23.19	31.43
Mirzapur	Eastern	15.84	22.60
Jhansi	Bundelkhand	10.76	10.30
Chitrakoot	Bundelkhand	0.00	0.00

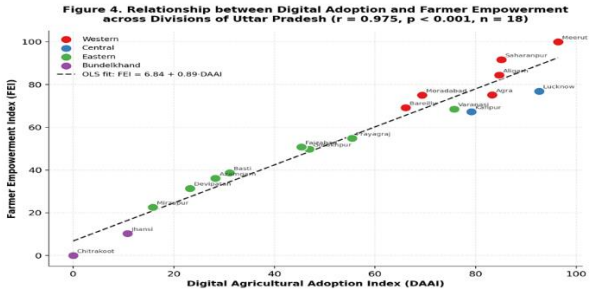
Note: DAAI = Digital Agricultural Adoption Index; FEI = Farmer Empowerment Index, both scaled 0–100. Compiled by the researcher.

Table 3. Descriptive Statistics of DAAI and FEI (N = 18 Divisions)

Statistic	DAAI	FEI
Mean	54.95	55.71
Standard Deviation	30.70	28.01
Minimum	0.00	0.00
Maximum	96.36	100.00
Coefficient of Variation (%)	55.87	50.29

4. Correlation Analysis (Objective 2, H_{01}):

The Karl Pearson correlation coefficient value for the eighteen divisions was r = 0.9746, p < 0.001 which shows a very high correlation and statistically very highly significant positive correlation between DAAI and FEI. The t-statistic value t = 17.39 is far from the critical t-value at 5 percent level and therefore the null hypothesis H_{01} – no relationship between digitalization and farmer empowerment – is rejected. This is plotted per division in Fig. 4, with the four agro-economic zones from the western divisions (red), to the Bundelkhand divisions (purple) and some eastern divisions (green) are located in the upper-right (high DAAI, high FEI) and lower-left (low DAAI, low FEI) corners, respectively.



5. Regression Analysis:

A simple OLS model of FEI on DAAI was estimated to quantify this relationship. The fitted equation is FEI = 6.84 + 0.889 × DAAI, implying that for every one-point increase in the Digital Agricultural Adoption Index, the Farmer Empowerment Index is estimated to increase by 0.889 points, across the divisions. The slope coefficient is highly significant (t = 17.39, p < 0.001), and the model explains 95.0 percent of the variance in FEI (R^2 = 0.950; Adjusted R^2 = 0.947; F = 302.5, p < 0.001), as summarised in Table 4. This very high explanatory power should be understood, however, as an association at the ecological (division-level) rather than the causal (one-farmer-level) level as explained in the section Limitations.

Table 4. OLS Regression Results (Dependent Variable: FEI)

Parameter	Coefficient	Std. Error	t-statistic	p-value
Constant (α)	6.838	3.197	2.139	0.048
DAAI (β)	0.889	0.051	17.394	< 0.001

Model fit: R^2 = 0.950; Adjusted R^2 = 0.947; F(1,16) = 302.5, p < 0.001; N = 18.

6. One-way ANOVA: Zonal Variation in Farmer Empowerment (H_{02}):

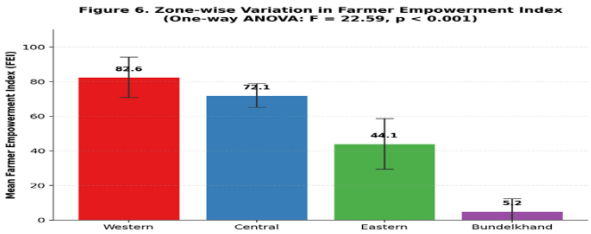
A one-way ANOVA was used to assess the differences in the mean FEI among the four agro-economic zones in Uttar Pradesh. As evident in Table 5 and Figure 6, the highest mean FEI is in the Western zone (82.58) while the lowest is in Bundelkhand (5.15). This F-statistic value of 22.59 with p value of less than 0.001 is well above the critical value, and hence the null hypothesis H_{02} is rejected, which implies that there is significant difference in farmer

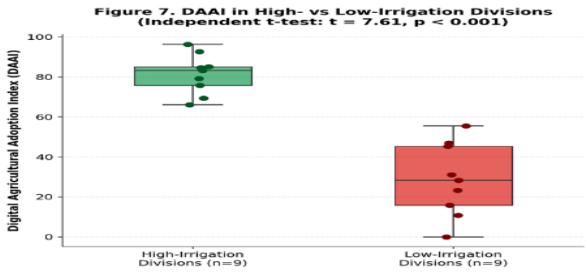
empowerment among agro-economic zones. It is a pattern that closely resembles the irrigation and connectivity gradient that exists from the west of the State (canal and tube well irrigated) to the Bundelkhand plateau (drought prone).

Table 5. One-way ANOVA: FEI across Agro-Economic Zones

Zone	n	Mean FEI	SD
Western	6	82.58	11.67
Central	2	72.07	6.83
Eastern/Purvanchal	8	44.11	14.66
Bundelkhand	2	5.15	7.28

$F(3,14) = 22.59$, $p < 0.001$.





7. Independent-Samples t-Test: Irrigation and Digital Adoption (H_{03}):

Since the infrastructure for irrigation is one of the long standing structural determinants of agrarian prosperity in UP, the sample was divided at the median value of the net irrigated area share in the divisions and mean DAAI was compared between "high-irrigation" (n = 9) and "low-irrigation" (n = 9) group by independent-samples t-test (Welch correction). The mean DAAI in the high-irrigation group (81.36, SD = 9.96) was significantly higher than the mean DAAI in the low-irrigation group (28.54, SD = 18.27) and H_{03} was rejected ($t = 7.61$, $df \approx 12.5$, $p < 0.001$), as shown in Figure 7. This discovery is consistent with the caution found in the literature in the field of ICT4Ag (Aker, 2011; Nakasone et al., 2014) which states that digital adoption does not happen on its own, but is dependent on complementary rural infrastructures.

8. Chi-Square Test of Independence: Digitalization and Empowerment Levels:

In addition to the continuous variable analysis, DAAI was divided into three tertiles (Low, Medium, and High) and FEI was also split into three categories (Low, Medium, and High), and a chi-square test of independence was used to analyze a 3×3 cross-tabulation (Table 6). The test statistic $\chi^2 = 21.00$ ($df = 4$, $p < 0.001$) shows that the two categories of digitalization and empowerment are statistically associated. The effect size (Cramer's V = 0.76) meets conventional standards for a strong association. Notably, all eight "High DAAI" divisions also were in the "High FEI" category, and none of the four "Low DAAI" divisions were in the category "High FEI", thus echoing the regression finding that the relationship between the two is close across divisions of Uttar Pradesh.

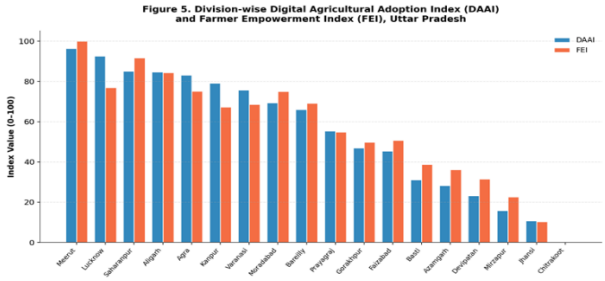
Table 6. Cross-Tabulation of Digitalization Level × Empowerment Level (Number of Divisions)

DAAI Category	Low FEI	Medium FEI	High FEI	Total
Low	4	2	0	6
Medium	0	3	1	4
High	0	0	8	8
Total	4	5	9	18

$\chi^2(4) = 21.00$, $p < 0.001$; Cramer's V = 0.76.

9. Division-wise Comparison and Productivity Growth:

The rankings in Figure 5 are done on the basis of DAAI as well as FEI for each of the eighteen divisions, and the resulting ranking is shown graphically in the figure verifying the close co-movement discovered above in a statistical sense. Meerut, Saharanpur, Lucknow, Aligarh are at the top on both the digitalization index, while the two Bundelkhand divisions – Chitrakoot and Jhansi – are at the bottom on both the indices, with eastern Purvanchal's Mirzapur and Devipatan following at the tail. It is important to note that the real productivity gains recorded at state level in cropping intensity and GVA per hectare (Section 5.1) coincided with the period of expansion in digital coverage (Figure 8). Although this study is a cross sectional design and thus does not allow for causation to be determined, the strong and consistent association between DAAI and FEI across five separate statistical tests (correlation, regression, ANOVA, t test, and chi-square) lend strong support that both have progressed at a sub-even and sub-simultaneous rate along the state's regions at the very least.



Discussion:

The findings point towards a single and coherent narrative: the digitalisation of Uttar Pradesh's agriculture may be real, and fast at the state and national level but it has not happened evenly across the state, as it follows pre-existing structural advantages, most notably irrigation facility and rural connectivity, but not necessarily any of them. This finding is consistent and extends that of the world literature, that the benefits of using ICTs for farmers depend on complementary infrastructure and socio-economic pre-conditions (Aker, 2011; Mittal & Mehar, 2016; Nakasone et al., 2014), and that the disparities between the districts found at the sub-state level corroborate disparities already found at the state-wide level between Central Uttar Pradesh (Mishra et al., 2020) and Western Uttar Pradesh (Nagar et al., 2025).

Three implications follow. First, the figures of digital agriculture at the state/ national level, which are used most often in policy discussion, can mask significant intra-state inequality; the mean Farmer Empowerment Index (5.15 out of 100) of the Bundelkhand region is not far from zero, while Uttar Pradesh is the top performer in both the number of PM-KISAN beneficiary farmers and the number of farmers registered under e-NAM. Second, the empirical evidence of the relationship between irrigation and digital adoption (Section 5.7) implies that digital interventions that are layered on areas without basic agrarian infrastructure are probably not going to close existing welfare gaps on their own, and could even increase these gaps, if they are not targeted appropriately. Third, the use of the term sustainable digitalization in this context is not synonymous with the roll-out of connectivity and application; it is also strongly linked to the need to invest in digital literacy, as well as in irrigation and rural roads, since these are precisely the assets, education and extension contact which the literature presents as prerequisites for effective use of ICTs, and which are lacking in the majority of farmers in the state of Uttar Pradesh (Mittal & Mehar, 2016; Wang et al., 2025).

The results have to be interpreted with due caution. The analysis is undertaken at the division (ecological) level, with secondary data compiled, but the strength of associations observed is statistically significant, and is not necessarily indicative of causal mechanisms at the level of the individual farmer – this is discussed further under Limitations.

Policy Recommendation:

To align with Objective 3, and to keep very succinct and action-oriented, the following 8 measures are recommended:

Instead of an equal division of investment across the state, focus investments on the last-mile digital infrastructure – mobile towers, fibre backhaul, Common Service Centres – in the Bundelkhand and eastern Purvanchal divisions, where DAAI is lower.

Foster agro-advisory applications that are vernacular, voice and low-literacy (building on current Kisan Call Centre model) rather than text or app based, in view of the education and literacy limitations noted among agro-marginal farmers.

Ensure e-NAM mandi expansion in tandem with PM-KISAN e-KYC and Kisan Credit Card drives of digital-saturation in lagging divisions, to enable digital market access and digital income support to the same farmers at the same time.

Implement assisted-access models of community resource persons and "digital sakhis" to support the marginal and women farmers who may not have their own mobile phones, instead of assuming a uniform level of individual-level digital readiness.

Incorporate digital-literacy training during regular agricultural extension visits instead of it being a standalone IT programme to increase the digital-skill precondition identified in the literature (Mittal & Mehar, 2016; Wang et al., 2025).

Promote shared access and Farmer Producer Organisation (FPO) based smartphone/data subscription models for the 80% of UP holdings which face cost constraint as individual device ownership.

Introduce a division-level dashboard in the state's digital AgriStack architecture for monitoring digital adoption and empowerment, to facilitate ongoing, division-specific course correction, building on the digital adoption and empowerment monitoring framework developed in this study in the DAAI/FEI form.

Irrigated farming and rural-connectivity investment should be planned and implemented before and/or in parallel with the rollout of digital agriculture in the study area of Bundelkhand as the t-test results show that irrigation access is a strong statistical predictor of digital uptake.

Conclusion:

In this study, the level of digital technology adoption was explored among marginal and small farmers in Uttar Pradesh using only secondary data and statistical relationship between farmers' empowerment and digital technology adoption was done. The Digital Agricultural Adoption Index and the Farmer Empowerment Index were created for the eighteen administrative divisions in the state, and through the lens of five separate statistical tests – Pearson correlation, OLS regression, one-way ANOVA, independent-samples t-test, and chi-square test of independence – the conclusion is the same: digitalization and farmer empowerment are strongly and significantly correlated, but this correlation is not consistent across the state. Although the western divisions of Uttar Pradesh have been the top states in terms of the number of absolute beneficiaries of PM-KISAN and e-NAM coverage, it has been limited to the well-irrigated and well-connected areas of the state and has been minimal in Bundelkhand and in some divisions of the eastern Purvanchal.The digitalization of agriculture in Uttar Pradesh would need a series of actions with connectivity (or roll-out of applications) as the first. The next phase in the chain of evidence is to tackle the root causes of irrigation, infrastructure and literacy issues that are identified as the most statistically significant with agricultural digitalization within the marginal and small farmer operations captured in this evidence analysis. This paper attempts to meet the gap in the literature and provides a state-wide, regionally comparative and statistically tested evidence base for the growing primary evidence available at the district and village level for the socio-economic condition of the marginal and small farmers of Uttar Pradesh and provides a replicable DAAI/FEI framework

that can be validated and improved at the household level in future primary surveys.

The limitations and scope for future research are discussed:

There are three points to be mentioned. First of all, the analysis is exclusively secondary, ecological, or division level data and inferences regarding the regional patterns should not be interpreted as causal inferences regarding individual or farm level causal mechanisms (the ecological fallacy). Secondly, several division-wise indicator values were constructed and where official sources had no separate divisional split, the researcher had to estimate them by using the benchmark method based on the documented divisional differentials, which was a necessary but second-best alternative to a single official divisional database. Third, the cross sectional design only measures association, not causation, between digitalization and empowerment. Future studies should explore the framework of DAAI/FEI at the primary and household level in a panel data sample of high and low DAAI divisions identified in this paper, ideally with the use of panel data, to validate the DAAI/FEI framework and test causal pathways more effectively, for instance using an instrumental-variable or difference-in-differences design based on the staggered introduction of e-NAM and PM-KISAN across mandis and across districts.

References:

1. Aker, J. C. (2011). Dial 'A' for agriculture: A review of information and communication technologies for agricultural extension in developing countries. Agricultural Economics, 42(6), 631–647. https://doi.org/10.1111/j.1574-0862.2011.00545.x
2. Arcus Policy Research. (2023). India's small and marginal farmers. Arcus Policy Research.
3. ASER Centre. (2023). Annual Status of Education Report (Rural) 2023: Beyond Basics. ASER Centre / Pratham.
4. Fafchamps, M., & Minten, B. (2012). Impact of SMS-based agricultural information on Indian farmers. The World Bank Economic Review, 26(3), 383–414. https://doi.org/10.1093/wber/lhr056
5. Government of India, Department of Agriculture, Cooperation & Farmers Welfare. (2019). All India Report on Agriculture Census 2015–16. Ministry of Agriculture & Farmers Welfare.
6. Government of India, Ministry of Statistics and Programme Implementation. (2021). Situation Assessment of Agricultural Households and Land and Livestock Holdings of Households in Rural India, NSS 77th Round (2019). National Statistical Office.
7. Government of Uttar Pradesh. (2026). Uttar Pradesh Economic Survey 2025–26. Department of Economics and Statistics, Government of Uttar Pradesh.
8. Goyal, A. (2010). Information, direct access to farmers, and rural market performance in Central India. American Economic Journal: Applied Economics, 2(3), 22–45. https://doi.org/10.1257/app.2.3.22
9. Jensen, R. (2007). The digital provide: Information (technology), market performance, and welfare in the South Indian fisheries sector. The Quarterly Journal of Economics, 122(3), 879–924. https://doi.org/10.1162/qjec.122.3.879
10. Mishra, A., Yadav, O. P., Yadav, V., Mishra, S., & Kumar, N. (2020). Benefits of the use of ICT services perceived by farmers for acquiring agricultural information in Central U.P. Indian Journal of Extension Education, 56(1), 86–89.
11. Mittal, S., & Mehar, M. (2016). Socio-economic factors affecting adoption of modern information and communication technology by farmers in India: Analysis using multivariate probit model. The Journal of Agricultural Education and Extension, 22(2), 199–212. https://doi.org/10.1080/1389224X.2014.997255
12. Nagar, A., Sharma, S., & Bajaj, A. (2025). Exploring the catalysts of farmer's access to information and communication technology

for agricultural technical advice: Evidence from Western Uttar Pradesh. Indian Journal of Agricultural Research, 59, 1777–1783.

13. Nakasone, E., Torero, M., & Minten, B. (2014). The power of information: The ICT revolution in agricultural development. Annual Review of Resource Economics, 6, 533–550. https://doi.org/10.1146/annurev-resource-100913-012714
14. National Sample Survey Office. (2023). Comprehensive Annual Modular Survey (CAMS), July 2022–June 2023. Ministry of Statistics and Programme Implementation, Government of India.
15. National Statistical Office. (2025). Comprehensive Modular Survey: Telecom 2025 (NSS 80th Round). Ministry of Statistics and Programme Implementation, Government of India.
16. Press Information Bureau. (2025a). Government disbursed over ₹4.09 lakh crore under PM-KISAN scheme [Press release]. Ministry of Agriculture & Farmers Welfare, Government of India.
17. Press Information Bureau. (2025b). PM-KISAN completes successful installments [Press release]. Ministry of Agriculture & Farmers Welfare, Government of India.
18. Press Information Bureau. (2025c). PM Modi releases 21st instalment of PM-KISAN [Press release]. Government of India.
19. Press Information Bureau. (2026). Digital India: Over 1.79 crore farmers register on e-NAM as 1,522 mandis go digital [Press release]. Ministry of Agriculture & Farmers Welfare, Government of India.
20. Statista. (2025). Number of e-National Agriculture Market (e-NAM) farmers across India as of March 2025, by state. Statista Inc.
21. Tech Observer Magazine. (2026, February 11). Digital India: Over 1.79 crore farmers register on e-NAM as 1,522 mandis go digital. Tech Observer.
22. Telecom Regulatory Authority of India. (2025). Telecom subscription data reports. TRAI.
23. Wang, Y., Xu, G., Cao, J., Chen, Y., & Wu, J. (2025). Does digital literacy affect farmers' adoption of agricultural social services? An empirical study based on China Land Economic Survey data. PLOS ONE. https://doi.org/10.1371/journal.pone.0320318