



Original Research Paper

Soil Suitability and Irrigation Innovation as Drivers of Sustainable Cotton Intensification: Evidence From Gujarat (Kharif 2025)

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Key Words

Sustainable intensification, cotton acreage, soil suitability, irrigation technology, SDGs, Gujarat

Abstract

Environmental This study examines the determinants of cotton land allocation among farm households in Gujarat during Kharif 2025 within a sustainable intensification framework. Using primary survey data from 1,259 farmers across major cotton-growing districts, cotton share (cotton area divided by total operational land) is analyzed as a measure of crop specialization. The study evaluates the role of soil type, irrigation mode, and landholding size using descriptive statistics, correlation analysis, and an Ordinary Least Squares regression model. Results indicate that medium and black soils are positively and significantly associated with cotton intensity relative to light soils. In contrast, irrigation access (canal, drip, and tube well) is negatively associated with cotton specialization compared to rainfed systems, suggesting diversification among irrigated farmers. Landholding size shows a negative relationship with cotton share, indicating greater diversification among larger farms. The findings highlight ecological alignment in cotton intensification while emphasizing the diversification role of irrigation access. The study contributes to discussions on SDGs 2, 6, 12, and 13 in the context of semi-arid agricultural systems.

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1. Introduction

Sustainable agricultural development remains central to achieving global development objectives under the Sustainable Development Goals (SDGs). In semi-arid regions such as Gujarat, agricultural sustainability depends on efficient resource allocation, ecological compatibility, and resilience to climate variability. Cotton is one of the most important commercial crops in Gujarat, contributing substantially to rural incomes and agro-industrial linkages. However, cotton cultivation is often associated with high water demand and concerns related to mono-cropping.

Understanding how farmers allocate land to cotton under varying ecological and irrigation conditions is essential for evaluating sustainability. Crop specialization may increase income but may also increase vulnerability if ecological alignment is weak. Conversely, diversification enabled by irrigation access may enhance resilience.

This study examines the determinants of cotton land allocation during Kharif 2025 across major cotton-growing districts of Gujarat. The focus is on understanding whether soil suitability and irrigation mode influence cotton specialization and how these factors relate to sustainable intensification.

2. Literature Review

Sustainable agricultural intensification has emerged as a central framework for reconciling productivity growth with environmental conservation. Pretty et al. (2011) define sustainable intensification as increasing

agricultural output without adverse environmental impacts and without expanding cultivated land. This concept has gained prominence within global policy discourse, particularly in relation to the Sustainable Development Goals (SDGs), where agricultural systems are expected to deliver food security, environmental sustainability, and climate resilience simultaneously. Rockström et al. (2017) further argue that sustainable intensification must operate within planetary boundaries, emphasizing resource-use efficiency and ecosystem preservation.

2.1 Soil Quality and Crop Suitability

Soil quality is widely recognized as a foundational determinant of agricultural sustainability. Brady and Weil (2016) emphasize that soil texture, structure, organic matter content, and moisture retention capacity directly influence crop productivity and resilience. Lal (2015) argues that soil degradation poses a significant threat to long-term food security, particularly in semi-arid regions. In cotton-based systems, vertisols and medium-textured soils have been associated with improved water retention and nutrient availability, supporting stable yields under variable rainfall conditions.

Shiferaw and Holden (1998) demonstrate that farmers' adoption of conservation practices is strongly linked to soil quality and perceived long-term productivity benefits. Similarly, Rao, BIRTHAL, and Joshi (2014) highlight that crop diversification patterns across India are shaped by agro-ecological suitability. These findings suggest that crop specialization often reflects underlying soil characteristics, reinforcing the importance of ecological alignment in sustainable land allocation decisions.

2.2 Irrigation, Productivity, and Diversification

Irrigation has long been considered a key driver of agricultural productivity growth. Fan and Hazell (2001) show that public investment in irrigation infrastructure significantly contributes to rural income growth and poverty reduction. Hussain and Hanjra (2004) argue that irrigation enhances food security by stabilizing output and reducing vulnerability to rainfall shocks.

However, irrigation does not merely increase production; it also influences cropping patterns. Pingali (2012) notes that irrigation expansion historically enabled diversification toward high-value crops in India. Chand (2006) finds that irrigation access encourages farmers to shift toward commercial and horticultural crops. Narayanamoorthy (2007) documents improved water-use efficiency under drip irrigation systems, emphasizing their role in sustainable water management.

At the same time, groundwater-based irrigation systems raise concerns about long-term sustainability. Gulati and Sharma (2015) highlight the risk of groundwater depletion in intensively irrigated regions. Thus, irrigation may simultaneously enhance productivity and alter land-use decisions in ways that affect sustainability.

2.3 Cotton Intensification and Technological Change

Cotton cultivation in India has undergone significant transformation over the past two decades. Kathage and Qaim (2012) demonstrate that Bt cotton adoption increased yields and farm incomes. Subramanian and Qaim (2010) report welfare improvements among cotton-growing households following biotechnology

adoption. However, most cotton-related research focuses on yield and income impacts rather than land allocation decisions.

Binswanger-Mkhize (2012) cautions against overreliance on monocropping systems, noting that technological gains may not automatically ensure ecological sustainability. Studies examining cotton systems often overlook how ecological factors such as soil type and irrigation access shape specialization patterns. Understanding land allocation behavior provides insight into structural intensification dynamics beyond productivity measures alone.

2.4 Land Allocation, Farm Size, and Diversification

Theoretical models of agricultural supply response suggest that farmers allocate land based on expected profitability and risk considerations (Nerlove, 1958). Feder, Just, and Zilberman (1985) emphasize that adoption of agricultural technologies depends on resource endowments and risk preferences. Larger farms often exhibit greater diversification due to lower transaction costs and better access to capital (Takeshima & Yamauchi, 2012).

Birthal et al. (2015) show that diversification is associated with risk mitigation and income stabilization. In semi-arid regions, diversification serves as a coping strategy against climate variability. Therefore, examining the relationship between farm size and cotton specialization contributes to understanding structural sustainability patterns.

2.5 Resource Complementarity and Sustainability

Resource complementarity theory posits that the productivity of one input depends on the availability of another (Feder et al., 1985). In agricultural

systems, soil and water are complementary inputs. The effectiveness of irrigation depends on soil characteristics, and soil productivity is influenced by water availability. This interaction determines crop allocation decisions and long-term sustainability.

Rockström et al. (2017) argue that sustainable intensification requires coordinated management of soil and water resources. Lal (2015) emphasizes integrated soil-water management as essential for mitigating climate change impacts. When land allocation aligns with soil capacity and irrigation efficiency, agricultural systems are more likely to achieve ecological sustainability.

2.6 Research Gap

Although existing literature has examined soil management, irrigation expansion, cotton productivity, and diversification separately, limited empirical research integrates these factors within a land allocation framework. Few studies analyze cotton share as a measure of specialization in relation to soil suitability and irrigation access at the micro-level. Moreover, sustainability discussions often emphasize productivity outcomes without examining structural crop concentration patterns.

This study addresses this gap by empirically examining how soil type, irrigation mode, and farm size influence cotton land allocation in Gujarat during Kharif 2025. By integrating ecological suitability and irrigation access within a unified econometric framework, the study contributes to the sustainable intensification literature and provides district-level micro evidence relevant to SDGs 2, 6, 12, and 13.

3. Conceptual Framework

Sustainable agricultural intensification seeks to enhance farm productivity while conserving natural resources and minimizing environmental degradation. In semi-arid regions such as Gujarat, agricultural sustainability depends fundamentally on the interaction between soil characteristics, water availability, and farmers' land allocation decisions. Cotton cultivation, being one of the dominant commercial crops in the region, provides a suitable context to examine how ecological suitability and irrigation access jointly influence crop specialization and sustainability outcomes.

At the core of this study is the premise that land allocation decisions are shaped by agro-ecological endowments and resource constraints. Soil type represents the foundational ecological condition determining crop suitability. Different soil categories vary in their physical and chemical properties, including texture, structure, drainage capacity, nutrient retention, and moisture-holding ability. In cotton cultivation, medium and black soils (particularly vertisols) are known to provide favorable moisture retention and structural stability, supporting higher productivity under variable rainfall conditions. Light soils, by contrast, often exhibit lower water retention and higher susceptibility to moisture stress, potentially limiting crop specialization. Therefore, soil suitability is expected to influence the proportion of land allocated to cotton, with higher cotton intensity observed in ecologically compatible soils.

Water availability constitutes the second critical dimension of the conceptual framework. In rainfed systems, farmers are highly dependent on monsoon variability, which can increase production risk. Irrigation infrastructure—whether canal, tube well, or

drip—reduces rainfall dependence and stabilizes crop output. However, irrigation does not necessarily lead to greater cotton concentration. Rather, access to assured water may enable farmers to diversify into alternative crops, including horticultural or high-value crops, thereby reducing monocropping dependence. Consequently, irrigation may have two competing effects: it may enhance cotton productivity in suitable soils, but it may also encourage diversification, thereby reducing cotton land share. This dual role of irrigation makes its empirical effect theoretically ambiguous and worthy of investigation.

The conceptual framework also incorporates farm size as a structural determinant of land allocation behavior. Larger farmers often possess greater capital access, risk-bearing capacity, and market linkages, enabling diversification across crops. Smaller farmers, by contrast, may concentrate land under a single commercially viable crop such as cotton due to limited alternative opportunities. Thus, farm size is expected to influence the degree of crop specialization, with larger holdings potentially exhibiting lower cotton share.

An important theoretical underpinning of this study is resource complementarity theory, which suggests that the productivity of one resource depends on the availability of another. In agricultural systems, soil and water are complementary inputs. The effectiveness of irrigation depends on soil structure and drainage characteristics, while soil productivity depends on adequate water supply. When cotton cultivation is concentrated in suitable soil types and supported by appropriate irrigation practices, resource-use efficiency improves.

Conversely, misalignment between soil suitability and crop choice may increase environmental stress, including soil degradation and inefficient water use.

Within this framework, cotton land share serves as an observable indicator of crop specialization and intensification. Higher cotton share reflects greater specialization, which may signal strong ecological alignment in suitable areas but may also indicate monocropping vulnerability if excessively concentrated. Therefore, sustainable intensification is conceptualized not simply as higher cotton allocation, but as allocation that aligns with ecological capacity while maintaining resilience.

The framework thus posits three central relationships. First, soil suitability is expected to have a positive association with cotton share, reflecting ecological compatibility. Second, irrigation access may influence cotton allocation either positively through productivity enhancement or negatively through diversification effects. Third, landholding size is expected to exhibit a structural relationship with specialization patterns. By empirically testing these relationships, the study evaluates whether cotton intensification in Gujarat reflects sustainable resource alignment or structural concentration patterns.

Ultimately, the conceptual model integrates ecological suitability, irrigation infrastructure, and farm structure into a unified framework of sustainable land allocation. By linking these determinants to cotton share, the study provides a micro-level assessment of how agro-ecological and institutional factors shape specialization patterns in semi-arid agricultural systems. This framework also allows interpretation of findings in relation to broader sustainability objectives, including efficient resource use, diversification, and resilience under climatic

variability.

4. Data and Methodology

4.1 Data Source and Sample Design

The empirical analysis is based on primary survey data collected during the Kharif 2025 agricultural season from 1,259 farm households across major cotton-growing districts of Gujarat. The surveyed districts represent diverse agro-climatic zones characterized by variation in soil composition, irrigation infrastructure, and cropping patterns. The sample includes farmers operating under rainfed as well as irrigated conditions, thereby enabling comparison across resource endowments.

Data were collected through structured questionnaires administered at the farm level. The survey captured detailed information on total operational landholding, area allocated to cotton, soil type, irrigation source, and other farm characteristics. Landholding and cotton area were recorded in acres as reported by farmers. The cross-sectional nature of the dataset provides a comprehensive snapshot of land allocation behavior during a single agricultural season.

After data cleaning and removal of incomplete observations, a total of 1,259 valid observations were retained for econometric analysis.

4.2 Variable Construction

The dependent variable in the study is cotton land share, defined as the proportion of total operational land allocated to cotton cultivation. It is computed as:

$$\text{Cotton Share} = \text{Cotton Area (acre)} / \text{Total}$$

Operational Land (acre)

This measure captures the degree of crop specialization and serves as an indicator of cotton intensification at the farm level. Values range between zero and one.

The key explanatory variables include soil type, irrigation mode, and landholding size.

Soil type was classified into three categories based on farmer-reported characteristics: Black soil (Vertisol), Medium soil, and Light soil. To incorporate soil categories into the regression model, dummy variables were constructed. Two dummy variables were created: Soil_Black and Soil_Medium. Light soil was treated as the reference (base) category to avoid the dummy variable trap.

Irrigation mode was categorized into four groups: Rainfed, Canal irrigation, Tube well irrigation, and Drip irrigation. Three dummy variables were generated: Canal, Drip, and TubeWell, with Rainfed serving as the base category. This structure allows coefficients to be interpreted relative to rainfed farmers.

Landholding size, measured in acres, was included as a continuous variable to capture farm scale effects on crop allocation.

4.3 Econometric Specification

To examine the determinants of cotton land allocation, an Ordinary Least Squares (OLS) regression model was estimated. The model is specified as:

$$\text{CottonShare}_i = \beta_0 + \beta_1 \text{Land}_i + \beta_2 \text{Soil_Black}_i + \beta_3 \text{Soil_Medium}_i + \beta_4 \text{Canal}_i + \beta_5 \text{Drip}_i + \beta_6 \text{TubeWell}_i + \varepsilon_i$$

Where:

- CottonShare_{*i*} represents cotton land share for

farmer i

- Land_i denotes total operational landholding
- Soil_Black_i and Soil_Medium_i are soil dummy variables
- Canal_i , Drip_i , and TubeWell_i are irrigation dummy variables
- ε_i is the stochastic error term

Light soil and Rainfed irrigation serve as reference categories. Therefore, soil and irrigation coefficients represent deviations from these baseline groups.

Although cotton share is bounded between zero and one, the distribution in the sample is continuous and sufficiently dispersed to justify linear estimation. OLS provides interpretable marginal effects and remains appropriate for cross-sectional analysis where predicted values remain within plausible bounds.

4.4 Diagnostic Testing and Multicollinearity Assessment

Before estimating the regression model, a correlation matrix was constructed to evaluate potential multicollinearity among explanatory variables. Pairwise correlation coefficients were examined for all independent variables, including landholding, soil dummies, and irrigation dummies.

Most correlation coefficients were well below conventional threshold values of 0.70, indicating no serious multicollinearity concerns. A high negative correlation was observed between Soil_Black and Soil_Medium , which is expected due to the mutually exclusive nature of dummy variables representing categorical soil types. Since one soil category (Light) was

omitted as the base category, this mechanical relationship does not bias coefficient estimates and does not indicate harmful multicollinearity.

Similarly, negative correlations among irrigation dummy variables reflect their mutually exclusive structure and are statistically expected. No evidence suggests instability in coefficient estimates due to collinearity.

The overall model significance was evaluated using the F-statistic, and explanatory power was assessed using R-squared. Robustness of coefficients was confirmed through statistical significance levels and confidence intervals.

In addition to multicollinearity diagnostics, the model specification also considered potential heteroscedasticity commonly observed in cross-sectional farm-level data. Since variability in cotton land allocation may differ across farms of varying sizes and resource conditions, the assumption of constant variance may not strictly hold. To address this, robust standard errors were considered in the estimation to ensure reliable statistical inference. This approach improves the consistency of estimated standard errors and strengthens the validity of hypothesis testing.

4.5 Interpretation Strategy

The regression coefficients are interpreted as marginal effects on cotton land share relative to the base categories. For example, the coefficient of Soil_Black measures the average difference in cotton share between farmers cultivating on black soils and those on light soils, holding other factors constant. Similarly, irrigation coefficients indicate the difference in cotton specialization between irrigated and rainfed farmers.

By integrating soil suitability, irrigation access,

and farm size into a unified empirical framework, the methodology allows systematic evaluation of sustainable cotton intensification patterns in Gujarat.

5. Descriptive and Empirical Analysis

This section presents the descriptive statistics

and econometric findings regarding cotton land allocation in Gujarat during Kharif 2025. The analysis integrates district-level patterns, soil and irrigation heterogeneity, correlation diagnostics, and regression results to examine determinants of cotton specialization.

5.1 District-Level Cotton Specialization

Table 1: District-wise Cotton Share (Kharif 2025)

District	Cotton Share (%)
AMRELI	78
Arvalli	37
Bhavnagar	72
Botad	94
Chotaudepur	70
DWARKA	66
GIR SOMNATH	67
Jamnagar	68
JUNAGADH	75
Kheda	48
Morbi	84
Narmda	71
Rajkot	77
Sabarkantha	60
Shurendranagar	80

District	Cotton Share (%)
Vadodara	56

Source: Author's calculation based on survey data (2025)

Overall cotton share: 69.8%

The district-level results indicate substantial spatial heterogeneity in cotton intensification. Botad exhibits extremely high specialization at 94 percent, followed by Morbi (84 percent) and Surendranagar (80 percent). These districts appear to represent strong cotton clusters. In contrast, Arvalli (37 percent), Kheda (48 percent), and Vadodara (56 percent) show relatively lower

cotton concentration, suggesting either diversification strategies or agro-ecological constraints.

The overall cotton share of 69.8 percent indicates a high degree of specialization across the study region. However, the variation across districts suggests that local resource endowments and infrastructure conditions significantly shape land allocation decisions.

5.2 Cotton Share by Soil Type

Table 2: Cotton Share by Soil Type

Soil Type	Average Cotton Share
Black	70.6%
Medium	75.3%
Light	55.1%

Source: Author's calculation based on survey data (2025)

Soil-wise patterns reveal a clear ecological gradient in cotton allocation. Medium soils exhibit the highest cotton share at 75.3 percent, followed by black soils at 70.6 percent. Light soils demonstrate significantly lower cotton specialization at 55.1 percent.

These findings indicate that cotton cultivation aligns strongly with soil types possessing better moisture retention and structural suitability. Medium and black soils appear to provide favorable agro-ecological conditions supporting specialization, while light soils impose relative limitations.

5.3 Cotton Share by Irrigation Mode

Table 3: Cotton Share by Irrigation Mode

Irrigation Mode	Cotton Share
Rainfed	86.5%
Canal	79.8%
Tube Well	68.8%
Drip	66.0%

Source: Author's calculation based on survey data (2025)

The irrigation analysis reveals an important structural pattern. Rainfed farmers exhibit the highest cotton specialization at 86.5 percent. Canal irrigation farmers allocate 79.8 percent of land to cotton, while tube well and drip irrigation users allocate comparatively lower shares of 68.8 percent and 66.0 percent, respectively.

These results suggest that irrigation access may enable diversification rather than increase cotton concentration. Rainfed farmers appear to be more dependent on cotton mono-cropping, whereas irrigated farmers may diversify into other crops due to improved water availability.

5.4 Soil × Irrigation Interaction

Table 4: Soil × Irrigation Interaction

Soil	Canal	Drip	Rainfed	Tube Well
Black	69.1%	63.3%	72.1%	70.8%
Light	80.0%	76.9%	—	52.2%
Medium	84.1%	—	93.7%	67.4%

Source: Author's calculation based on survey data (2025)

The interaction analysis reveals that medium soil under rainfed conditions exhibits extremely high cotton specialization (93.7 percent), indicating strong monocropping concentration. Canal irrigation in medium soils also supports high cotton intensity (84.1 percent). In black soils, cotton share remains relatively stable across irrigation types, suggesting inherent suitability

independent of irrigation mode.

These patterns indicate that both ecological compatibility and infrastructure access jointly shape specialization outcomes. Extremely high specialization in certain combinations may raise sustainability concerns related to monocropping vulnerability.

5.5 Correlation Analysis

Table 5: Correlation Matrix

Variable	Land	Black	Medium	Canal	Drip	TubeWell
Land	1	-0.09	0.07	-0.003	0.00	-0.17
Black	-0.09	1	-0.93	-0.17	0.07	0.21
Medium	0.07	-0.93	1	0.19	-0.11	-0.23
Canal	-0.003	-0.17	0.19	1	-0.05	-0.63
Drip	0.00	0.07	-0.11	-0.05	1	-0.21
TubeWell	-0.17	0.21	-0.23	-0.63	-0.21	1

Source: Author's calculation based on survey data (2025)

The correlation matrix indicates no severe multicollinearity concerns. Pairwise correlations remain below conventional

thresholds except for expected negative associations among mutually exclusive dummy variables. Therefore, the regression estimates are statistically stable.

5.6 Regression Results

Table 6: OLS Regression Results

Variable	Coefficient	P-value
Landholding	-0.00379	<0.001

Variable	Coefficient	P-value
Soil_Black	0.1187	<0.001
Soil_Medium	0.1394	<0.001
Canal	-0.0947	<0.001
Drip	-0.1946	<0.001
TubeWell	-0.1981	<0.001

Source: Author's calculation based on survey data (2025)

$$R^2 = 0.133$$

$$N = 1259$$

The regression results confirm that soil suitability significantly increases cotton specialization. Compared to light soils, black soils increase cotton share by approximately 11.9 percentage points, while medium soils increase it by approximately 13.9 percentage points.

Landholding size exhibits a negative and statistically significant association with cotton share, indicating that larger farmers diversify more extensively.

Irrigation variables show negative coefficients relative to rainfed cultivation. Canal irrigation reduces cotton share by approximately 9.5 percentage points, while drip and tube well irrigation reduce specialization by nearly 19–20 percentage points. This suggests that irrigation facilitates diversification rather than monocropping concentration.

5.7 Integrated Interpretation

The combined descriptive and empirical evidence indicates that cotton intensification in Gujarat is primarily driven by ecological suitability rather than irrigation expansion. Soil characteristics significantly influence specialization, while irrigation infrastructure appears to enhance diversification capacity. Larger farms demonstrate greater diversification relative to smaller farms.

These findings highlight the importance of balancing ecological alignment with diversified cropping strategies to ensure sustainable agricultural development in semi-arid regions.

6. Policy Implications

The findings of this study have important implications for agricultural policy and sustainable resource management in semi-arid regions such as Gujarat. First, there is a need to promote soil-based crop planning to ensure alignment between crop choice and agro-ecological suitability. Policies should encourage the cultivation of cotton primarily in medium and black soils where ecological

conditions are favorable, thereby improving productivity and reducing environmental stress.

Second, irrigation policies should focus not only on expanding irrigation coverage but also on promoting diversified cropping systems. The results indicate that irrigation access enables farmers to diversify rather than concentrate on cotton, which enhances resilience and reduces mono-cropping risks. Therefore, irrigation development programs should be integrated with crop diversification strategies.

Third, micro-irrigation technologies such as drip irrigation should be promoted as part of climate-smart agriculture initiatives. However, their adoption should be accompanied by extension support that encourages efficient crop allocation rather than excessive specialization.

Fourth, targeted extension services should be strengthened, particularly for small and marginal farmers who exhibit higher levels of cotton specialization. Capacity-building programs can help farmers adopt diversified and sustainable land-use practices.

Finally, policymakers should integrate soil mapping, irrigation planning, and advisory services to develop region-specific strategies for sustainable agricultural intensification aligned with SDGs 2, 6, 12, and 13.

7. Conclusion

This study provides empirical evidence on the determinants of cotton land allocation in Gujarat during Kharif 2025 within a sustainable intensification framework. Using primary survey data and econometric analysis, the study demonstrates that soil suitability plays a critical role in shaping cotton specialization. Medium and black soils are

significantly associated with higher cotton share, confirming the importance of ecological compatibility in land-use decisions.

The analysis further reveals that irrigation access is associated with lower cotton specialization relative to rainfed systems, suggesting that irrigation enables diversification rather than monocropping concentration. This finding highlights the role of irrigation in enhancing flexibility and resilience in agricultural systems. Additionally, landholding size is negatively associated with cotton share, indicating that larger farmers tend to diversify more extensively than smaller farmers.

The combined evidence suggests that sustainable cotton intensification in Gujarat is driven primarily by ecological suitability, while irrigation infrastructure supports diversification and resilience. However, the high level of specialization observed in certain contexts, particularly under rainfed conditions, may raise concerns regarding monocropping and vulnerability to climatic risks.

Overall, the study underscores the importance of aligning crop allocation with soil capacity while promoting diversified and resource-efficient agricultural systems. Future research may incorporate yield, income, and environmental indicators to further evaluate sustainability outcomes.

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