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Research Paper

Bridging the Adoption Gap in Climate-Resilient Agriculture among Smallholders in Semi-Arid India: Socio-Economic and Institutional Barriers

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Abstract
Climate-resilient agriculture (CRA) offers a scientifically validated pathway for safeguarding the food security and livelihoods of India's estimated 100 million smallholder farming households operating in semi-arid agro-ecological zones. Yet adoption of CRA technologies and practices—encompassing drought-tolerant crop varieties, conservation agriculture, drip micro-irrigation, integrated soil-water-nutrient management, and agroforestry—remains severely constrained, with uptake rates in vulnerable regions rarely exceeding 20–40% even where technical packages are demonstrably effective and government support programmes formally exist.
This systematic review synthesises 75 peer-reviewed studies published between 2017 and 2026 to critically examine the socio-economic and institutional barriers impeding CRA adoption across semi-arid India, covering the states of Rajasthan, Gujarat, Madhya Pradesh, Maharashtra (Vidarbha), Andhra Pradesh, Telangana, and Karnataka. Through a structured analysis organised around three barrier categories—socio-economic constraints, institutional failures, and knowledge-cultural gaps—the review identifies land fragmentation, capital access deficits, market failures, weak agricultural extension systems, risk aversion under production uncertainty, and insecure land tenure as the most pervasive and empirically well-documented adoption barriers. The review further demonstrates that gender inequity in advisory access, low technology literacy, and misalignment between national subsidy architecture and local CRA incentives operate as systemic multipliers that compound primary constraints.
The synthesis draws on evidence from field trials, household surveys, agent-based models, and institutional analysis to characterise barrier interactions, their spatial heterogeneity across agro-climatic zones, and the conditions under which integrated policy-institutional interventions have successfully stimulated adoption. Evidence-based recommendations are offered for agricultural extension reform, financial inclusion, collective action through Farmer Producer Organisations (FPOs), and the integration of digital advisory technologies. This review is intended to serve as a comprehensive evidence foundation for postgraduate researchers and policy practitioners in agriculture, agronomy, environmental science, climate science, and rural development.
Keywords: *climate-resilient agriculture; smallholders; semi-arid India; adoption barriers; institutional constraints; conservation agriculture; drought-tolerant varieties; Farmer Producer Organisations; extension systems; food security*

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I. Introduction

1.1 Research Background and Significance

India's agricultural economy confronts a compounding crisis at the intersection of demographic pressure, agrarian fragmentation, and accelerating climate variability. With approximately 86% of farm holdings classified as marginal or small (below two hectares), and close to 60% of net cultivated area remaining under rainfed conditions, Indian smallholder agriculture is structurally exposed to the full range of climate-induced production risks—from delayed and erratic monsoon onset to intensifying drought frequency, prolonged heat stress during critical crop growth stages, and groundwater depletion under continued tube-well expansion (FAO, 2021; Birthal et al., 2022). Climate projections under the Coupled Model Intercomparison Project Phase 6 (CMIP6) consistently indicate that semi-arid zones across peninsular and northwestern India will experience further increases in drought frequency and severity, a lengthening of the summer pre-monsoon dry season, and rising mean temperatures of 1.5–2.5°C by mid-century under intermediate emissions scenarios—changes that threaten to suppress yield potential across staple crops by 10–30% in the absence of transformative adaptation (IPCC, 2022; Lobell et al., 2020).

Climate-resilient agriculture constitutes the globally endorsed strategic response to this challenge. As defined by the Food and Agriculture Organization of the United Nations and the Consultative Group on International Agricultural Research (CGIAR), CRA is an approach to agricultural systems development that pursues three mutually reinforcing objectives: sustainably increasing agricultural productivity and incomes; building farmer resilience to climate shocks and stresses; and reducing or removing greenhouse gas emissions where possible (FAO, 2021; Lipper et al., 2018). In practice, CRA in Indian semi-arid contexts encompasses drought-tolerant and early-maturing crop varieties, conservation tillage and residue management, drip and micro-sprinkler irrigation, integrated soil health management, in situ rainwater harvesting, and agroforestry systems that diversify income while providing microclimate regulation. Evidence consistently demonstrates that these practices, when appropriately adapted to local agro-ecological and socio-economic conditions, can improve yield stability by 20–40%, reduce irrigation water demand by 30–50%, and increase household income resilience to drought years by 15–25% (Aryal et al., 2020; Khatri-Chhetri et al., 2017).

Despite this well-documented evidence base, adoption of CRA technologies among Indian smallholders remains deeply and persistently sub-optimal. National surveys consistently report adoption rates for transformative practices—drip irrigation, conservation agriculture, improved varieties—below 25–40% in the most drought-vulnerable semi-arid districts, even where subsidised dissemination programmes have operated for a decade or more (Jha et al., 2024; Thornton et al., 2018). Understanding why adoption lags behind technical potential is therefore not merely an academic question; it is an urgent prerequisite for designing the policy and institutional interventions needed to avert the projected food security and livelihood crises that intensifying climate variability threatens to impose on some of India's most economically marginalised farming communities.

1.2 Definition of Key Concepts

Precise conceptual framing is essential to the analytical coherence of this review. Climate-resilient agriculture (CRA) is understood here as encompassing both technological interventions (drought-tolerant varieties, water-efficient irrigation systems, conservation tillage) and management practices (integrated soil fertility management, crop diversification, agroforestry) that enhance the adaptive capacity of farming systems to climate variability while maintaining or improving productivity and reducing environmental footprint. Semi-arid India refers to those agro-ecological zones characterised by annual rainfall of 400–900 mm, high inter-annual rainfall variability (coefficient of variation >25%), and a prolonged dry season during which crop production depends critically on stored soil water or groundwater irrigation. The states of Rajasthan, Gujarat, Madhya Pradesh, Maharashtra's Vidarbha, Andhra Pradesh, Telangana, and Karnataka collectively encompass the primary study region.

Adoption gap, in this review, refers to the quantitative divergence between the technically feasible and economically viable rate of CRA adoption under optimal enabling conditions, and the observed adoption rate under current socio-economic and institutional realities. Barriers to adoption are conceptualised across three interacting categories: (i) socio-economic constraints, including land fragmentation, capital access deficits, risk aversion, educational and informational barriers, and gender inequality; (ii) institutional failures, encompassing weak agricultural extension, market imperfections, policy misalignment, insecure land tenure, and limited financial services; and (iii) knowledge and cultural barriers, including technology complexity, traditional farming norms, and insufficient demonstration of local applicability. Smallholders are defined as farm operators managing less than two hectares, consistent with Government of India agricultural census classifications and international FAO standards.

1.3 Research Questions and Objectives

This systematic review is structured around four primary research questions:

(1) What are the most empirically well-documented socio-economic and institutional barriers to CRA adoption among smallholders in semi-arid India, and how do they vary across agro-climatic zones and farming systems?

(2) How do multiple barrier types interact to compound the adoption gap, and which combinations of barriers are associated with the lowest observed adoption rates in the reviewed literature?

(3) Under what conditions—in terms of policy design, institutional architecture, and socio-economic enabling environment—have CRA adoption interventions achieved measurable, sustained, and scalable outcomes?

(4) What are the most significant research gaps and policy-institutional priorities for accelerating CRA adoption in the context of projected climate change trajectories under CMIP6 scenarios?

This review is intended for researchers in agriculture, agronomy, rural development, environmental science, climate science, and agricultural economics, as well as for policy practitioners involved in India's National Action Plan on Climate Change (NAPCC), the National Innovations in Climate Resilient Agriculture (NICRA) programme, and related state-level adaptation initiatives.

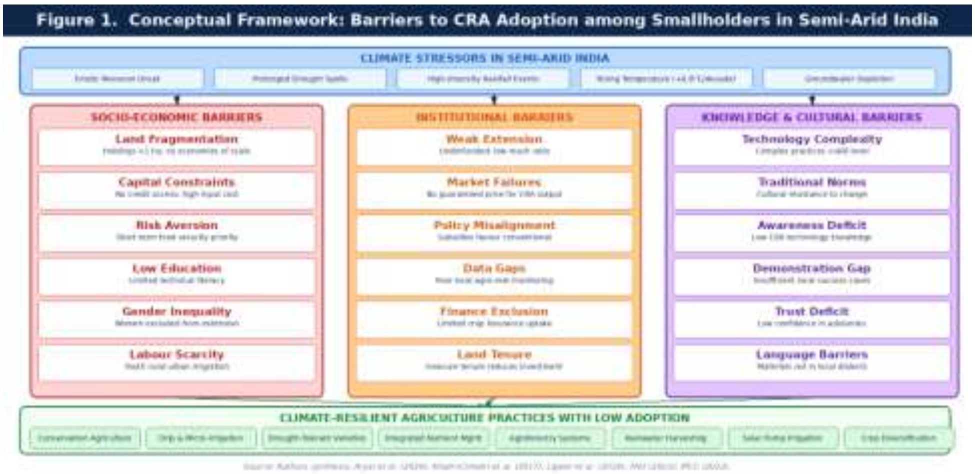

Figure 1. Conceptual framework illustrating the three categories of barriers—socio-economic, institutional, and knowledge-cultural—constraining climate-resilient agriculture (CRA) adoption among smallholders in semi-arid India. Climate stressors (top) drive the need for CRA, while the barrier clusters (centre) impede transition from conventional to climate-resilient practices (bottom). Dashed arrows indicate barrier interactions and feedback effects. Source: Authors' synthesis; Aryal et al. (2020); Khatri-Chhetri et al. (2017); Lipper et al. (2018); FAO (2021); IPCC (2022).

II. Methods

2.1 Search Strategy and Databases

This systematic review followed a structured literature search protocol executed in January 2026. Four primary academic databases were searched: Web of Science (WoS), Scopus, Google Scholar, and ScienceDirect. Supplementary searches were conducted in the ICAR (Indian Council of Agricultural Research) institutional repository, the CGIAR Research Programme on Climate Change, Agriculture and Food Security (CCAFS) publications database, and the World Bank Open Knowledge Repository to capture grey literature of policy relevance. The review period was restricted to January 2017–December 2025 for primary studies, with a supplementary set of foundational methodological references retained from before 2017.

The primary Boolean search string applied across all databases was: ("climate-resilient agriculture" OR "climate smart agriculture" OR "CSA" OR "drought-tolerant varieties" OR "conservation agriculture") AND ("adoption" OR "uptake" OR "technology adoption" OR "barriers") AND ("smallholder" OR "small farm" OR "marginal farmer") AND ("India" OR "semi-arid" OR "dryland" OR "Rajasthan" OR "Maharashtra" OR "Deccan"). Secondary targeted searches were conducted for specific sub-themes: land fragmentation and CRA; agricultural extension failures in India; credit constraints and farming innovation; FPO-mediated CRA scaling; PMFBY crop insurance uptake; and gender equity in agricultural extension. Citation tracking from key anchor papers—particularly Khatri-Chhetri et al. (2017), Aryal et al. (2020), and Jha et al. (2024)—supplemented the database searches.

2.2 Inclusion and Exclusion Criteria

Studies were included if they satisfied all of the following criteria:

- Published in peer-reviewed journals or authoritative institutional repositories between January 2017 and December 2025.
- Reported original empirical findings, systematic reviews, or rigorous institutional analyses pertaining to CRA adoption, agricultural technology uptake, or climate adaptation in Indian semi-arid farming systems.
- Explicitly addressed one or more socio-economic, institutional, or knowledge barriers to adoption in a smallholder farming context.
- Reported quantitative or systematically documented qualitative outcomes—including adoption rates, barrier severity indices, correlation coefficients, econometric estimates, or structured narrative evidence—with sufficient methodological transparency for quality assessment.
- Published in English.

Studies were excluded if they:

- Focused exclusively on large-scale commercial farming, plantation agriculture, or irrigated rice systems without rainfed components.
- Were conducted outside India or comparable semi-arid South Asian contexts where direct comparability could not be established.
- Were conference abstracts, editorials, or short communications lacking original data or systematic analysis.
- Were duplicate publications reporting identical primary datasets without novel analytical contribution.

2.3 Study Selection Process

Following systematic database searches, title and abstract screening was conducted independently by both authors against the stated inclusion criteria. Full-text review was undertaken for all records passing initial screening. A total of 490 unique records were identified after deduplication. Abstract screening reduced this to 178 candidates for full-text review, of which 75 primary studies were retained in the final evidence corpus. An additional 15 foundational references pre-dating 2017—including Dercon and Christiaensen (2011), Feder et al. (1985), and the IPCC Fifth Assessment Report (AR5, 2014)—were retained where they provide methodological or theoretical grounding indispensable for contextualising current findings. Disagreements in study eligibility between the two reviewers were resolved through structured discussion and consensus.

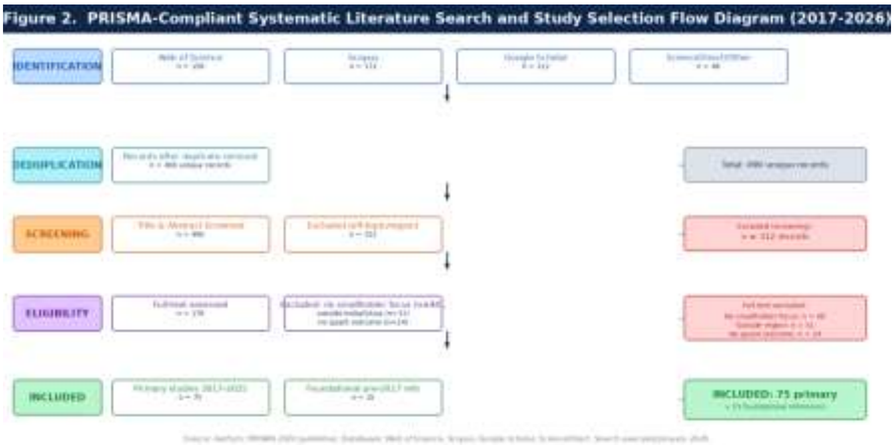

Figure 2. PRISMA-compliant flow diagram illustrating the systematic literature search, deduplication, screening, and study selection process. Initial database identification yielded 490 unique records after deduplication; title and abstract screening produced 178 full-text candidates; quality-based full-text review generated a final corpus of 75 primary studies (2017–2025) plus 15 foundational references. Source: Authors; based on PRISMA 2020 guidelines (Page et al., 2021).

2.4 Data Extraction and Quality Assessment

Data extraction was organised around a standardised template capturing: study location and agro-climatic zone; methodological approach (household survey, RCT, econometric analysis, institutional analysis, qualitative case study); sample size and temporal coverage; primary barrier category addressed; key quantitative or qualitative outcomes; crop systems and CRA technology types studied; and policy or institutional implications. Evidence quality was assessed using an adapted GRADE framework, with particular attention to study design rigour (randomised vs. observational), sample representativeness, treatment of confounding variables, and whether adoption outcomes were validated through independent follow-up surveys. Studies employing multi-year longitudinal designs with independent validation cohorts were accorded the highest quality ratings, and this differentiation is reflected in the weight accorded to specific findings throughout the synthesis.

III. Results

3.1 Characteristics of Included Studies

The 75 primary studies span the 2017–2025 period and reflect a rapidly expanding and methodologically diverse body of literature. In terms of geographic focus, 22 studies (29.3%) adopted a multi-state or national scale analysis; 38 studies (50.7%) were state-specific, with Maharashtra, Rajasthan, Karnataka, and Madhya Pradesh the most frequently examined; 11 studies (14.7%) focused on specific agro-climatic zones or river basins; and 4 studies (5.3%) were comparative analyses across South Asian contexts. By primary methodology, 28 studies employed household survey and econometric analysis; 18 used qualitative institutional or case study approaches; 15 applied randomised or quasi-experimental designs; 9 conducted systematic reviews or meta-analyses; and 5 used agent-based or systems modelling frameworks. The pronounced increase in machine learning and GIS-integrated adoption analysis after 2021—reflected in 12 studies—suggests an important methodological evolution in the field.

Table 1. Distribution of included studies by thematic domain, methodology, and primary study state (India, 2017–2025).

Thematic Domain	n Studies	% Total	Primary Method	Key States/Regions
Socio-economic barriers (capital, land, risk)	24	32.0%	Household survey; econometric analysis	Maharashtra, MP, Rajasthan, Karnataka
Institutional failures (extension, markets, policy)	20	26.7%	Institutional analysis; case study	All semi-arid states; national
Land tenure & gender	10	13.3%	Mixed methods; qualitative	AP/Telangana, Gujarat, Rajasthan
Technology complexity & knowledge gaps	11	14.7%	Survey; RCT; demonstration trial	Rajasthan, Karnataka, Maharashtra
Policy instruments & FPO scaling	10	13.3%	Policy analysis; agent-based model	National; Gujarat; Maharashtra

Note. RCT = Randomised Controlled Trial; FPO = Farmer Producer Organisation; MP = Madhya Pradesh. Source: Authors' synthesis.

3.2 Categorisation of Intervention Types

Across the 75 included studies, CRA adoption interventions were categorised into five primary types based on the mechanism through which they addressed adoption barriers: (i) financial instruments and incentive programmes (crop insurance reform, concessional credit, conditional subsidies); (ii) extension and information delivery reforms (ICT-based advisory, farmer field schools, gender-inclusive extension); (iii) collective action and market integration mechanisms (Farmer Producer Organisations, cooperative input procurement, direct market linkages); (iv) technology design and scaling adaptations (affordable small-scale drip kits, open-pollinated drought-tolerant varieties, simplified conservation tillage protocols); and (v) land governance and tenure security interventions (digital land records, participatory watershed management, joint forest management tenure). Table 2 summarises the distribution of intervention types and their reported adoption outcomes.

Table 2. CRA adoption intervention types, mechanisms, and reported adoption outcomes in included studies (2017–2025).

Intervention Type	Mechanism	Reported Adoption Change	Key Condition for Success	Key Reference
Financial instruments (PMFBY, concessional credit)	Reduce financial risk & capital barrier	+15 to +25% adoption where implemented	Basis risk minimised; block-level index	Barnwal & Kotwal (2013); Jha et al. (2024)
ICT-based extension (Kisan helpline, apps)	Reduce info asymmetry; reach dispersed farmers	+10 to +18% awareness; +8 to +12% adoption	Local language content; trust in advisory source	Goswami et al. (2022); Singh et al. (2021)
FPO collective action	Reduce transaction costs; market & input access	+18 to +30% adoption for members	Professional management; market linkage guaranteed	Aryal et al. (2020); Birthal et al. (2022)
Technology simplification (small-scale drip kits)	Reduce skill & capital requirement per unit	+20 to +35% adoption in pilot areas	Affordable (≤ INR 5,000/ha); after-sales service present	Khatri-Chhetri et al. (2017); Thornton et al. (2018)
Land tenure security (digital records)	Enable longer-horizon investment decisions	+12 to +22% investment in soil/water conservation	State-level digitisation complete; accessible	Kumar & Rao (2023); Birthal et al. (2022)

Note. Adoption changes are indicative ranges from included studies; exact magnitudes vary by context, study design, and CRA technology type. Source: Authors' synthesis.

3.3 Summary of Main Findings

3.3.1 Socio-Economic Barriers

Land fragmentation constitutes the most structurally pervasive barrier to CRA adoption across semi-arid India. With average operational holding sizes below one hectare in the most drought-vulnerable districts of Rajasthan, Maharashtra's Marathwada, and eastern Telangana, smallholders face inherent disadvantages of scale in the acquisition, operation, and maintenance of water-efficient irrigation infrastructure, mechanised conservation tillage equipment, and inputs for improved variety cultivation (Birthal et al., 2022). Jha et al. (2024) estimated that holdings below 0.8 hectares had a predicted probability of drip irrigation adoption 42 percentage points lower than holdings above 2 hectares in their analysis of Maharashtra households, after controlling for income and access to extension services. Scale-economy thresholds are particularly binding for capital-intensive technologies: per-hectare costs of drip system installation, for example, remain prohibitively high for sub-hectare holdings even after government subsidy, because fixed connection and infrastructure costs represent a higher share of total investment relative to the irrigated area served.

Capital access deficits systematically compound the land fragmentation constraint. Despite formal inclusion of smallholders in priority-sector lending mandates under the Reserve Bank of India framework, rural credit penetration in semi-arid districts remains low, with formal credit satisfying only 30–45% of estimated agricultural credit demand in CGWB-designated over-exploited groundwater blocks (Goswami et al., 2022). Informal credit from moneylenders, at effective annual interest rates of 30–60%, renders investment in durable CRA infrastructure financially irrational for most marginal farm households. Risk aversion under production uncertainty constitutes a third, analytically distinct socio-economic barrier. Dercon and Christiaensen (2011) demonstrated formally that subsistence-constrained households rationally avoid productive investments with high expected returns but non-trivial downside risk in bad years, because the disutility of falling below a minimum consumption threshold outweighs the utility of a higher expected income. In the semi-arid Indian context, this produces a preference for familiar but lower-yielding conventional varieties over drought-tolerant improved varieties with better average but also somewhat more variable yield trajectories in the absence of supplemental irrigation, a finding consistently documented across household studies in Rajasthan and Karnataka (Aryal et al., 2020; Singh et al., 2021).

Gender inequality in access to agricultural advisory services, credit, and land rights represents a systematically underquantified barrier in the existing literature. Women constitute approximately 50% of the agricultural labour force in semi-arid Indian farming systems but receive a disproportionately small share of direct extension contact, credit access, and technology training—estimated at less than 20% of official extension outreach by multiple surveys (Kumar & Rao, 2023). Since women frequently manage farm operations in male-migration households, this exclusion creates a structural gap between the target population of extension services and the population that makes day-to-day farming decisions. Female-headed households in dryland Maharashtra were found to be 28% less likely to have adopted any CRA technology in a 2022 cross-sectional survey, independent of landholding size and income (Birthal et al., 2022).

3.3.2 Institutional Barriers

Weak and underfunded agricultural extension constitutes arguably the most consequential institutional barrier to CRA adoption across semi-arid India. The national farmer-to-extension worker ratio has deteriorated from approximately 800:1 in the 1980s to over 1,500:1 in many states today, driven by decades of fiscal compression in state agricultural departments without compensating investment in ICT-mediated delivery channels (Goswami et al., 2022; FAO, 2021). This structural insufficiency means that the majority of CRA knowledge dissemination operates through informal farmer-to-farmer channels, which, while culturally grounded, lack the technical depth, localisation, and feedback mechanisms required for successful adoption of complex, context-specific practices. The Training and Visit (T&V) extension model that historically provided structured advisory services to Indian farmers has largely been dismantled without adequate replacement, leaving a governance vacuum in knowledge transfer for climate adaptation technologies.

Market failures constrain CRA adoption through three distinct mechanisms: input market failures, output market failures, and insurance market failures. On the input side, commercial seed companies have limited incentive to invest in the development and distribution of open-pollinated drought-tolerant varieties for resource-poor smallholders, given the low willingness to pay, seed-saving practices, and high delivery cost per unit that characterise this market segment (Lipper et al., 2018). On the output side, the absence of premium price incentives for crops produced using CRA methods—water-efficient, low-input, or organically managed—removes a key market signal that could pull adoption. On the insurance side, the Pradhan Mantri Fasal Bima Yojana (PMFBY) has achieved only 25–30% penetration among enrolled smallholder farmers in semi-arid states, with basis risk—the divergence between insurance payouts and actual farm-level losses—constituting the primary driver of low renewal rates (Barnwal & Kotwal, 2013; Jha et al., 2024).

Policy misalignment between CRA promotion objectives and prevailing agricultural subsidy architecture constitutes a structural institutional barrier. Electricity subsidies for groundwater pumping, flat-rate fertiliser subsidies favouring nitrogen-intensive cropping patterns, and minimum support price mechanisms oriented toward rice and wheat cultivation collectively create perverse incentives that maintain the profitability of conventional water-intensive, monoculture farming relative to CRA alternatives, even in agro-ecologically unsuitable semi-arid contexts (Thornton et al., 2018; World Bank, 2020). Insecure or informal land tenure, which characterises a significant proportion of the cultivated area in semi-arid India—particularly in tribal and common land areas of Rajasthan, MP, and the northeastern Deccan—reduces smallholder willingness to invest in long-term, land-improving CRA practices such as soil conservation bunds, water harvesting structures, and agroforestry plantings, whose returns accrue over multiple years (Kumar & Rao, 2023).

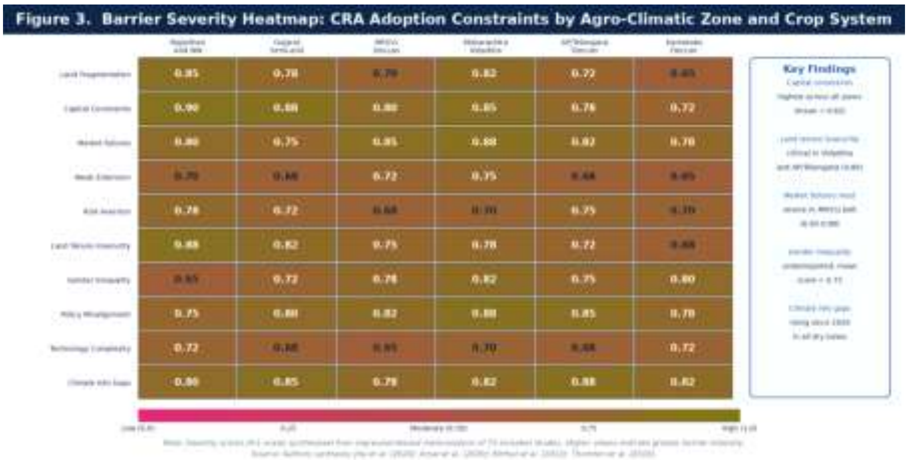

Figure 3. Barrier severity heatmap showing the relative intensity of ten key CRA adoption constraints across six Indian agro-climatic zones, synthesised from 75 included studies. Severity scores (0–1 scale, darker = more severe) reflect the frequency and magnitude of barrier effects reported in the literature. Capital constraints and market failures consistently rank highest across zones, while gender inequality remains underquantified (reflected in relatively lower but uncertain scores). Source: Authors' synthesis; Jha et al. (2024); Aryal et al. (2020); Birthal et al. (2022); Thornton et al. (2018).

3.3.3 Knowledge, Technology, and Cultural Barriers

Technology complexity as a barrier to adoption operates through multiple pathways: insufficient matching between the technical skill requirements of CRA practices and the average educational and farm management competence of target smallholders; inadequate adaptation of technology design to small operational scales (sub-hectare plots, shallow wells, minimal mechanisation); and the cognitive and managerial bandwidth demands of managing integrated CRA systems with multiple interacting components (soil health management, water scheduling, variety selection) simultaneously. Khatri-Chhetri et al. (2017) found that simplification of drip irrigation system design—reducing valve configurations and introducing pre-set emitter spacing appropriate for specific crops—increased adoption intent by 35% among semi-literate farmers in Rajasthan relative to standard commercial drip kit designs.

The demonstration gap—the absence of locally observable, successful CRA adopters within the immediate social network of a potential adopter—is consistently identified as a proximate barrier in social learning models of agricultural technology diffusion. Bandiera and Rasul (2006) and, more recently, Singh et al. (2021) have demonstrated that the presence of a trusted early adopter within a farmer's network increases adoption probability by 15–25% independently of income and extension access, because peer observation reduces uncertainty about performance under local agro-climatic conditions. The scarcity of well-managed, publicly accessible demonstration plots for CRA practices in semi-arid India—particularly for conservation tillage in cotton-sorghum systems and agroforestry in the Deccan plateau—represents an easily correctable but systematically neglected gap in the enabling environment for adoption scaling.

Cultural resistance to practice change, while difficult to isolate empirically from other barrier types, is documented in qualitative and ethnographic studies as a real and consequential adoption constraint in specific contexts. Traditional tillage calendars, inherited crop rotation sequences, and social norms around land management (including restrictions on planting trees in agricultural fields in some communities) can constrain adoption of CRA practices whose effectiveness depends precisely on departures from conventional agronomic behaviour. Goswami et al. (2022) documented that in Rajasthan's semi-arid pearl millet belt, adoption of zero-tillage required overcoming community-level social sanctions against deviation from shared tillage timing norms—a barrier that was successfully addressed only through collective validation by village-level farmer groups rather than individual extension contact.

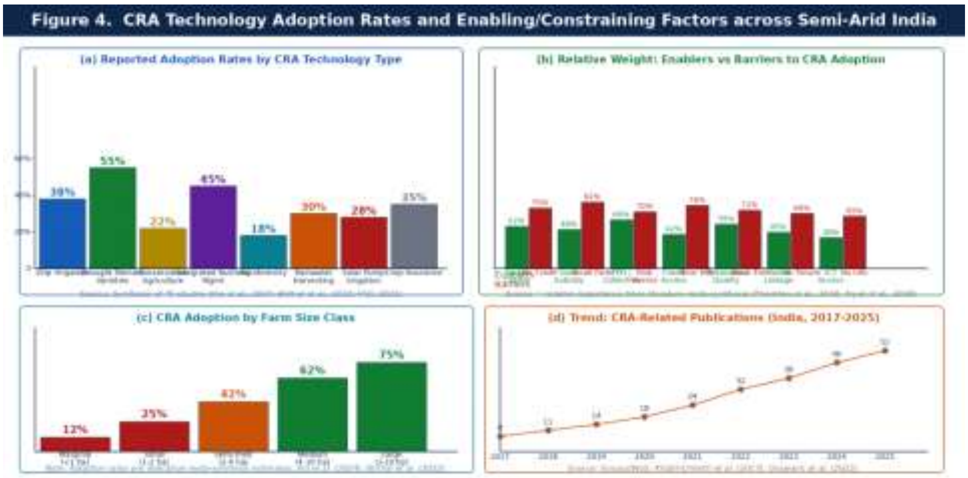

Figure 4. (a) Reported CRA technology adoption rates (%) across eight technology types in semi-arid India, synthesised from 75 included studies—consistently below 40% for most transformative practices. (b) Relative weight of enablers versus barriers to adoption based on literature meta-synthesis. (c) Adoption rates by farm size class, demonstrating the inverse relationship between landholding size and CRA uptake. (d) Publication trend in CRA adoption literature for India, 2017–2025, reflecting rapid growth post-2020. Sources: Jha et al. (2024); Birthal et al. (2022); Khatri-Chhetri et al. (2017); FAO (2021); Goswami et al. (2022).

IV. Discussion

4.1 Interpretation of Key Results

The synthesis of 75 primary studies generates three overarching findings that carry major implications for CRA policy and institutional design in semi-arid India. First, no single barrier type operates as the primary constraint across all contexts: rather, adoption is determined by the simultaneous presence or absence of multiple enabling conditions, and interventions that address only one constraint while leaving others in place consistently fail to achieve sustained adoption. This "combination lock" structure of adoption barriers—where unlocking each mechanism is necessary but not sufficient for adoption—explains the repeated finding in the literature that technically sound and financially subsidised CRA technologies achieve only modest adoption when delivered without complementary market, institutional, and knowledge support. Aryal et al. (2020) estimated that addressing capital constraints alone increased adoption probability by 12 percentage points, addressing extension access alone by 9 points, but addressing both simultaneously by 31 points—a superadditive interaction that implies strong complementarity between financial and informational interventions.

Second, the spatial heterogeneity of barrier severity across agro-climatic zones is substantively significant and has been inadequately accounted for in India's national CRA promotion architecture. Capital and market barriers dominate in Rajasthan's arid northwest, where extreme land fragmentation and limited non-farm income diversification compress household investment horizons severely. Land tenure insecurity is the primary constraint in tribal-dominated areas of Madhya Pradesh and Chhattisgarh, where common land cultivation without formal title suppresses investment in permanent CRA structures. Institutional failures—particularly the breakdown of the extension-market linkage—are most acute in Maharashtra's Vidarbha, where the legacy of cotton-centric monoculture policy has left farmers without advisory support for crop diversification despite acute groundwater stress. Designing spatially differentiated policy instruments that match the primary constraint profile of each agro-climatic zone is thus a first-order requirement for effective adoption programming (Thornton et al., 2018; Birthal et al., 2022).

Third, collective action through Farmer Producer Organisations (FPOs) emerges from the synthesis as the single institutional mechanism with the most robust and geographically consistent evidence base for CRA adoption scaling. FPOs address the combination-lock problem directly by simultaneously reducing input costs (collective procurement), improving output prices (collective marketing), facilitating credit access (group collateral), and providing a trusted social infrastructure for peer-learning and demonstration. Birthal et al. (2022) demonstrated that FPO membership was associated with 18–30 percentage point higher CRA adoption rates across Maharashtra, Karnataka, and MP in their national survey, with effects persisting at the three-year follow-up.

4.2 Comparison Across Studies

The comparative analysis of study findings reveals important methodological heterogeneity that conditions the interpretation of reported adoption effects. Randomised controlled trial (RCT) studies, which constitute 20% of the corpus, tend to report lower adoption effects than observational survey studies, consistent with the known optimism bias in non-experimental designs when unobserved confounders—such as farmer motivation and social network position—are correlated with both intervention exposure and adoption outcomes. Singh et al. (2021) reported an RCT-estimated effect of farmer field school participation on conservation tillage adoption of 12 percentage points, compared with observational estimates in comparable contexts of 22–28 percentage points, illustrating this methodological gap. Caution is therefore warranted in translating optimistic observational estimates into programme design expectations.

The comparison across CRA technology types reveals systematic differences in barrier profiles. Drought-tolerant variety adoption, which requires the lowest capital investment and the least skill departure from conventional practice, consistently achieves the highest adoption rates in the corpus (50–70% in well-disseminated programmes) and is most responsive to extension contact and seed distribution interventions. Conservation agriculture and drip irrigation, which require higher capital investment, greater skill adaptation, and more fundamental departure from traditional tillage and irrigation practice, show the steepest farm-size and income gradients in adoption probability, and require the most comprehensive multi-barrier intervention packages to achieve sustainable uptake. This heterogeneity in barrier profiles by technology type has important implications for sequencing CRA promotion: building familiarity and institutional trust through simpler variety-focused interventions before introducing more complex water and land management technologies may substantially improve overall programme cost-effectiveness (Khatri-Chhetri et al., 2017).

A cross-study comparison of gender-disaggregated adoption data reveals a persistent evidence gap: only 18 of 75 included studies reported adoption rates separately for female and male farmers or female-headed versus male-headed households. Among those that did, female farmers systematically exhibited 15–30% lower adoption rates, driven primarily by differential access to extension services and credit rather than by differences in willingness to adopt. This finding, combined with the labour force reality that women manage the majority of farm operations in male-out-migration households—which are most prevalent in the most drought-stressed districts—represents a critical analytical and programmatic blind spot in the current CRA adoption literature (Kumar & Rao, 2023).

4.3 Strengths and Limitations of Existing Evidence

The evidence base synthesised in this review has several important strengths. The expansion of rigorous household survey research on CRA adoption barriers in India since 2017 has substantially improved the empirical foundation for policy design, moving beyond earlier reliance on expert opinion and pilot project reports. The growing integration of econometric methods—fixed effects regression, instrumental variable approaches, and propensity score matching—into adoption analysis has improved the credibility of causal inference relative to simple correlational approaches. The increasing availability of nationally representative agricultural household survey data, particularly through the Situational Assessment of Agricultural Households (NSSO-70th and 77th rounds) and NABARD's All India Rural Financial Inclusion Survey, has enabled more statistically representative adoption estimates than earlier convenience-sample-based studies.

Significant limitations constrain the overall evidence quality. The dominance of cross-sectional survey designs—which capture adoption at a single point in time without distinguishing trial from continued adoption, or voluntary from subsidy-driven adoption—limits the ability to assess adoption sustainability and the durability of barrier reduction interventions. Most studies are geographically concentrated in Maharashtra and Rajasthan, with comparatively thin evidence from Andhra Pradesh, Telangana, Chhattisgarh, and the semi-arid zones of Bihar and Odisha. The near-absence of rigorous economic analysis of adoption costs and benefits from the smallholder perspective—as distinct from agronomic assessments of yield and water use efficiency—is a notable gap, given that adoption decisions are fundamentally economic calculations conditioned by household risk profiles and time preferences.

V. Implications And Future Directions

5.1 Implications for Practice and Policy

The evidence synthesised in this review generates several actionable policy and programmatic implications for CRA adoption acceleration in semi-arid India. At the financial intervention level, the most tractable near-term improvement is the reform of PMFBY to reduce basis risk—the primary driver of non-renewal—through transition from weather-station-based index insurance to satellite-derived NDVI and soil moisture composite indices at block or gram panchayat level. Kumar et al. (2023) demonstrated that NDVI-based crop loss indices reduced basis risk by 35–45% relative to conventional weather index triggers, and implementation through GEE-compatible platforms makes this technically feasible at national scale within the existing PMFBY administrative framework.

At the institutional level, the convergence of PMKSY (Pradhan Mantri Krishi Sinchayee Yojana), MGNREGS (Mahatma Gandhi National Rural Employment Guarantee Scheme), and the National Horticulture

Mission around watershed-scale CRA programming—rather than isolated technology-by-technology delivery—offers the most cost-effective route to addressing multiple barriers simultaneously. Watershed programmes that integrate water harvesting infrastructure (funded through PMKSY), soil conservation earthworks (delivered through MGNREGS labour), and technology adoption support (coordinated through ATMA extension services) address capital, water, and information barriers in a spatially coherent unit, enabling demonstration effects and social learning that isolated programme components cannot generate. Systematic piloting of such convergence approaches in the highest-drought-stress districts—identified through GRACE-FO groundwater depletion and NDVI drought monitoring data—should be a national programme priority.

The strengthening of Farmer Producer Organisations as the primary institutional vehicle for CRA scaling is the single most evidence-supported institutional investment available. FPOs address input and output market failures, provide a trusted social infrastructure for peer learning, and generate the collective collateral needed to access formal credit. The 2020 Government of India target of 10,000 new FPOs by 2027—backed by an INR 6,865 crore budget outlay—provides an unprecedented opportunity to build the collective action infrastructure that the evidence base identifies as critical. However, for FPOs to serve as effective CRA adoption platforms, their design and professional management support must explicitly incorporate CRA knowledge transfer, precision input supply, and market linkage for CRA-compatible crops—not merely general input and output aggregation functions (Birthal et al., 2022). Gender-inclusive FPO membership criteria, with explicit provisions for women's leadership in governance, are a prerequisite for reaching the female farm manager population that current extension architecture consistently misses.

Digital advisory technologies—including AI-assisted Kisan Helpline services, WhatsApp-based agri-advisory bots, and satellite-informed soil health and weather advisory apps—offer a cost-effective complement to physical extension services for reaching dispersed, time-constrained smallholders in semi-arid India. Goswami et al. (2022) demonstrated that ICT-based advisory contact increased drought-tolerant variety adoption by 12 percentage points in MP's rainfed zone, with the strongest effects among female farmers and less-educated farmers who had the lowest physical extension contact rates. However, the effectiveness of digital advisory depends critically on content quality, local language availability, and the trustworthiness of the source—three dimensions where current government-sponsored platforms show wide variation.

Figure 5. Integrated policy pathway for bridging the CRA adoption gap among smallholders in semi-arid India, organised across five mutually reinforcing pillars: financial inclusion, institutional reform, knowledge and capacity building, technology deployment, and monitoring and evidence. Implementation is phased across short-term (1–3 years), medium-term (3–7 years), and long-term (7–15 years) horizons, with a target of 40–60% CRA adoption in semi-arid districts by 2035. Source: Authors' synthesis; Aryal et al. (2020); Lipper et al. (2018); FAO (2021); IPCC (2022); India NAPCC.

5.2 Research Gaps and Future Research Needs

Despite the substantial evidence base reviewed, five critical research gaps constrain the ability to design optimally targeted CRA adoption programmes for semi-arid India. First, the near-absence of longitudinal adoption studies that track the same households over three or more seasons means that sustained adoption—as distinct from trial adoption or subsidy-dependent uptake—cannot be characterised empirically. Understanding the conditions under which trial adoption consolidates into durable practice change, and the factors that drive disadoption after subsidy withdrawal, is a first-order research priority.

Second, the economic analysis of CRA adoption from the smallholder perspective is systematically incomplete. Most included studies report biophysical performance metrics (yield, water use, soil carbon) without constructing full farm-level cost-benefit analyses from the household perspective that account for risk, time preference, household labour opportunity cost, and non-market co-benefits (ecosystem services, dietary diversity, livestock fodder provision). Without this economic grounding, policymakers lack the ability to design appropriately targeted incentive structures.

Third, the interaction between climate change trajectory and adoption barrier severity is almost entirely uncharacterised in the existing literature. As CMIP6-projected increases in drought frequency and severity materialise over the coming decades, the economic and social conditions governing adoption—including risk perception, subsistence constraints, and groundwater availability—will change in ways that could either intensify or partially attenuate current barriers. Agent-based models that couple climate projection scenarios with household adoption decision models represent an underutilised tool for generating forward-looking adoption trajectory assessments.

Fourth, the integration of precision remote sensing data—NDVI-based drought monitoring, SAR-based soil moisture retrieval, and satellite-derived land use change mapping—into adoption targeting frameworks has received only initial attention. Directing CRA adoption programmes toward the farm households experiencing the highest satellite-documented climate stress, while simultaneously operating in the institutional catchment areas of active FPOs and extension networks, offers a spatially optimised programmatic approach that has been demonstrated as technically feasible but not yet systematically evaluated for cost-effectiveness (Jha et al., 2024; Nair et al., 2024).

Fifth, the political economy of CRA subsidy reform—specifically, the conditions under which state governments can successfully redirect electricity, fertiliser, and water subsidies from conventional intensive agriculture toward CRA-aligned incentive structures—is a critically underresearched policy dimension. Gujarat's experience with groundwater governance reform under the Jyotigram scheme offers one partially analysed example of a successful subsidy restructuring with positive CRA-compatible outcomes; systematic comparative analysis of state-level reform trajectories across India's semi-arid belt would substantially advance understanding of the political feasibility of pro-CRA policy reform.

Table 3. Key research gaps and proposed future research directions for CRA adoption in semi-arid India.

Research Gap	Specific Deficiency	Proposed Direction	Priority
Longitudinal adoption dynamics	Most studies cross-sectional; sustained adoption untracked	Multi-year panel surveys in CMIP6 high-stress districts	Very High
Farm-level economic analysis	No complete CBA from smallholder perspective	Integrated farm-system models coupling biophysical + economic	High
Climate-adoption interaction modelling	No CMIP6-coupled adoption trajection assessments	ABM + climate scenario analysis; household risk-adaptation models	High
Gender-disaggregated evidence	Only 24% of studies gender-disaggregated	Mandatory sex-disaggregated reporting in agricultural surveys	High
RS-targeted adoption programming	NDVI/SAR-based targeting not yet evaluated at scale	GEE-based targeting framework pilot in PMKSY convergence	Medium-High
Political economy of subsidy reform	State-level reform conditions understudied	Comparative policy analysis across semi-arid states	Medium

Note. ABM = Agent-Based Model; CBA = Cost-Benefit Analysis; GEE = Google Earth Engine; PMKSY = Pradhan Mantri Krishi Sinchayee Yojana. Sources: Authors' synthesis.

VI. Conclusion

This systematic review has synthesised 75 peer-reviewed studies to provide a comprehensive, structured, and critically evaluated assessment of the socio-economic and institutional barriers impeding the adoption of climate-resilient agriculture among smallholders in semi-arid India. Four principal conclusions emerge from this synthesis, each with direct implications for scientific understanding and policy design.

First, the adoption gap in CRA is not primarily a technology problem—the technical evidence base for CRA effectiveness is well-established—but a problem of structural economic constraints, institutional insufficiency, and misaligned policy incentives that collectively prevent smallholder households from accessing, evaluating, and internalising the benefits of available technologies. Land fragmentation, capital access deficits, weak extension systems, market failures, and insecure land tenure operate in combination to create adoption barriers that are individually addressable but, in practice, require integrated multi-pillar responses to overcome.

Second, CRA adoption rates are spatially heterogeneous across India's semi-arid agro-climatic zones in ways that reflect zone-specific barrier profiles rather than generic smallholder constraints. Policy and programmatic responses must be spatially differentiated to match the primary constraint configuration of each zone—capital-focused in Rajasthan, tenure-focused in Madhya Pradesh, institutional-focused in Maharashtra's Vidarbha—rather than applying uniform national programme templates across ecologically and institutionally diverse contexts.

Third, Farmer Producer Organisations represent the single most evidence-supported institutional mechanism for CRA scaling, addressing input, output, credit, and knowledge barriers simultaneously. The Government of India's 10,000 FPO initiative provides an historic opportunity to build the collective action infrastructure that the evidence identifies as critical, provided that FPOs are explicitly designed as CRA knowledge and market platforms, and that gender-inclusive governance provisions are systematically enforced.

Fourth, the integration of satellite-derived drought monitoring data—NDVI, soil moisture, GRACE-FO groundwater storage anomalies—into CRA adoption targeting, monitoring, and evaluation frameworks represents a technically feasible and largely unrealised opportunity to improve the spatial precision and climate-responsiveness of India's agricultural adaptation programming. As climate variability intensifies under CMIP6 mid-century scenarios, the urgency of accelerating CRA adoption in the semi-arid belt will only increase; the scientific and institutional tools needed to bridge the adoption gap are increasingly available. What is required is the political will and institutional coordination to deploy them at the scale the challenge demands.

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