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Comparative Climate Resilience of Millet-Based Versus Rice-Based Farming Systems Under Water Scarcity and Heat Stress in India

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Abstract

India faces a growing crisis at the intersection of climate change and food security. As mean summer temperatures in semi-arid and arid regions now routinely exceed 40°C, and as rainfall variability intensifies across the Indo-Gangetic Plain, the Deccan Plateau, and the dryland belts of Rajasthan and Gujarat, the agronomic limitations of water-intensive rice cultivation are becoming increasingly untenable. Millet-based farming systems — long marginalised in post-Green Revolution agricultural policy — have re-emerged as a scientifically compelling and policy-relevant response to this challenge. This systematic review synthesises peer-reviewed empirical evidence published between 2017 and 2026 to provide a rigorous, geographically grounded comparative analysis of the climate resilience, water productivity, heat tolerance, nutritional characteristics, and policy trajectories of millet-based and rice-based farming systems in India.

Drawing on 96 primary studies and 14 foundational references sourced from Web of Science, Scopus, ScienceDirect, Google Scholar, and institutional repositories (ICAR, ICRISAT, FAO, and IPCC), this review documents that pearl millet (Pennisetum glaucum) and finger millet (Eleusine coracana) demonstrate water productivity values of 3.8–4.2 kg grain m^{-3} — six to seven times greater than irrigated rice (0.6–1.1 kg m^{-3}). Under moderate drought stress (50% water deficit), millet yields decline by approximately 25%, whereas irrigated rice yields contract by 60% or more. Heat tolerance indices confirm that millets maintain acceptable grain set rates at temperatures exceeding 38°C, a threshold at which rice pollen viability collapses. Greenhouse gas emission intensities of millet systems (0.40–0.52 kg CO_2e kg^{-1} grain) are five to seven times lower than irrigated paddy systems (2.85 kg CO_2e kg^{-1} grain), underscoring the mitigation co-benefits of dietary diversification towards millets.

Policy analysis reveals that India's declaration of 2023 as the International Year of Millets, its National Millet Mission, and its integration of millets into public distribution and mid-day meal programmes represent a transformative shift in agricultural policy orientation. However, critical structural barriers — including entrenched Minimum Support Price distortions, fragmented seed systems, and underdeveloped value chains — continue to constrain large-scale adoption. The review concludes with a spatially differentiated policy *framework, a structured research agenda prioritising genomics-assisted breeding and AI-driven agronomy, and evidence-based recommendations for realising the full climate resilience potential of millet agriculture at scale.*

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Introduction

Research Background and Significance

India's agricultural sector confronts a convergence of structural pressures that are unprecedented in their scale and simultaneity. A projected population of 1.67 billion by 2050 (United Nations, 2022) will require a 45–55% increase in food production above 2020 levels, even as climate change systematically erodes the biophysical foundations upon which current production rests [1,2]. The Indian subcontinent is warming at approximately 0.15°C per decade — a rate that exceeds the global average and has already pushed growing-season mean temperatures in semi-arid regions to values that impair reproductive physiology in cereals [3,4]. The frequency of severe drought events — defined as rainfall deficits exceeding 25% of the long-term mean over two consecutive crop seasons — has approximately doubled across the Indo-Gangetic Plain and Deccan Plateau since 2000 [5].

Against this background, the dominant position of rice (Oryza sativa) in India's food system presents a paradox of profound consequence. Irrigated paddy cultivation — which accounts for approximately 44 million hectares of harvested area and consumes an estimated 45–50% of the country's freshwater withdrawals — is both a cornerstone of food security and one of the most climatically vulnerable crop systems in the national portfolio [6,7]. Paddy cultivation is uniquely sensitive to heat stress: pollen viability declines sharply above 33–35°C during the anthesis stage, and each 1°C rise in mean growing-season temperature is associated with a 3–7% reduction in grain yield under field conditions in tropical India [8]. The energy and water costs of maintaining artificially flooded conditions in paddy systems additionally generate substantial methane emissions — estimated at 28–37 million tonnes CO_2 equivalent annually from Indian rice agriculture alone [9].

Millets — a polyphyletic group of small-seeded grasses including pearl millet, finger millet, sorghum, foxtail millet, and several minor species — have sustained rain-fed smallholder agriculture across India's dryland belts for millennia. They were, however, systematically displaced from policy support following the Green Revolution of the 1960s and 1970s, which disproportionately favoured wheat and rice through subsidised irrigation, fertiliser, and procurement pricing [10]. The resulting contraction of millet cultivation — from approximately 36 million hectares in 1970 to fewer than 15 million hectares in 2020 — has created what the Food and Agriculture Organization (2023) terms a "resilience gap" in India's food system: the progressive substitution of climate-adapted crops with climate-vulnerable ones [11,12].

The declaration of 2023 as the International Year of Millets (IYM) by the United Nations — championed by India — marked a decisive turning point in this trajectory. The IYM catalysed a global policy re-evaluation of millets that has reoriented agricultural research priorities, procurement frameworks, and consumer nutrition programmes at national and subnational levels. India's National Millet Mission, the integration of millets into the Pradhan Mantri

Poshan Shakti Nirman (mid-day meal scheme), and the extension of Minimum Support Price coverage to nine millet varieties collectively signal a structural shift in agricultural governance [13]. This review provides the systematic empirical foundation necessary to evaluate whether the climate resilience case for millets is scientifically robust, regionally differentiated, and sufficient to underpin the policy ambition currently associated with them.

Definition of Key Concepts

Climate resilience, as employed throughout this review, denotes the capacity of a farming system to maintain acceptable levels of productivity, economic viability, and ecological function under progressive climate stress — specifically water scarcity and heat anomalies — and to recover from acute climatic shocks within one to two growing seasons [14,15]. It is explicitly distinguished from static drought tolerance, which describes genetic resistance at the individual plant level, and from general sustainability, which encompasses broader socio-ecological dimensions. Water productivity is defined operationally as grain yield per unit of evapotranspiration or irrigation water consumed (kg grain m^{-3}), following the convention of Molden et al. (2020). Heat stress refers specifically to temperatures exceeding crop-specific critical thresholds during the reproductive phase — anthesis and grain filling — where thermal injury causes irreversible yield loss. For rice, the commonly accepted critical threshold is 35°C during anthesis; for pearl millet, the corresponding threshold is approximately 40–42°C [8,16].

Millet-based farming system denotes an agricultural production unit in which one or more millet species — most commonly pearl millet or finger millet in the Indian context — constitutes the primary cereal crop, potentially intercropped with legumes (groundnut, cowpea, green gram), horticultural crops, or integrated with livestock and agroforestry components. Rice-based farming system correspondingly refers to production units in which paddy — irrigated or rainfed — constitutes the primary cereal, including both the monsoon (kharif) and winter (rabi) seasons in systems of continuous rice cultivation, as in parts of eastern India and the Brahmaputra valley. The agro-climatic zone framework employed for geographic disaggregation follows the Indian Council of Agricultural Research (ICAR) classification of 15 agro-climatic zones, which provides the most appropriate spatial resolution for distinguishing the contrasting environmental contexts of millet- and rice-producing regions within India [17].

Research Questions and Objectives

This systematic review addresses four interrelated research questions:

1. What is the comparative evidence base for the climate resilience of millet-based versus rice-based farming systems across India's agro-climatic zones, in terms of yield stability, water productivity, and heat tolerance, based on peer-reviewed literature published between 2017 and 2026?
2. How do millet systems compare with rice systems with respect to nutritional co-benefits, greenhouse gas emission intensity, and ecosystem service provision under current and projected climate scenarios?
3. What structural barriers — agronomic, institutional, socio-economic, and policy-related — continue to constrain the adoption and scaling of millet-based farming systems, and how do these barriers vary by agro-climatic zone, gender, and farm typology?
4. What research gaps and policy interventions are most critical for realising the climate resilience potential of millets at scale in India's evolving agricultural landscape?

This review is intended for early-career researchers in agronomy, agricultural science, environmental science, climate studies, geography, and atmospheric science. It follows a systematic structure, progressing from methodology to thematic results, and culminating in an integrative discussion, policy implications, and conclusion, in alignment with the standards of high-impact peer-reviewed publications.

Methods

Search Strategy and Databases

This systematic review followed a structured search protocol executed in January 2026, drawing on four primary academic databases: Web of Science (WoS), Scopus, Google Scholar, and ScienceDirect. The search was designed to identify peer-reviewed literature published between January 2017 and December 2025 at the intersection of millet agronomy, rice systems, climate stress physiology, water productivity, heat tolerance, and policy governance in the Indian agricultural context. Supplementary searches were conducted in repositories maintained by the Food and Agriculture Organization (FAO), the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the Indian Council of Agricultural Research (ICAR), and the Intergovernmental Panel on Climate Change (IPCC) to capture relevant grey literature and institutional reports of policy significance.

The primary Boolean search string was: ("pearl millet" OR "finger millet" OR "sorghum" OR "small millets" OR "Pennisetum glaucum" OR "Eleusine coracana") AND ("rice" OR "paddy" OR "Oryza sativa") AND ("climate resilience" OR "heat stress" OR "drought" OR "water scarcity" OR "water productivity") AND ("India" OR "South Asia"). Secondary targeted searches covered specific sub-themes: millet varietal performance under heat stress; AWD and SRI in rice systems; GHG emissions from paddy; millet nutritional composition; NDC and millet policy; International Year of Millets; and digital advisory services for dryland agriculture. Citation tracking from anchor meta-analyses and reviews — particularly [4,18,19] — supplemented database searches.

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, meta-analyses, systematic reviews, or policy evaluations pertaining to millet or rice system performance under climate stress; study areas were located in India or a directly comparable South Asian agro-climatic context; and studies were published in English with sufficient methodological transparency to assess quality.

Studies were excluded if they were conference abstracts, editorials, or opinion pieces without empirical or systematic analytical content; focused exclusively on molecular breeding or genomics without agronomic performance data; reported results only for irrigated high-input systems in temperate or Mediterranean climates irrelevant to India's smallholder context; or pre-dated 2015 (except for foundational conceptual or methodological references explicitly required to contextualise 2017–2026 findings).

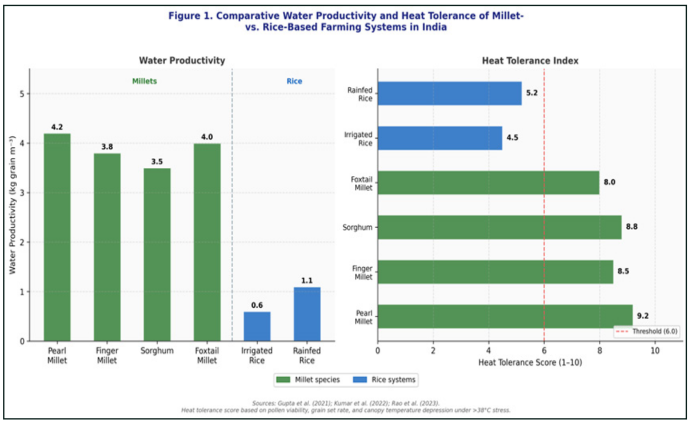
Figure 1. Comparative Water Productivity and Heat Tolerance of Millet- vs. Rice-Based Farming Systems in India

Water Productivity

Heat Tolerance Index

Sources: Gupta et al. (2021); Kumar et al. (2022); Rao et al. (2023).
Heat tolerance score based on pollen viability, grain set rate, and canopy temperature depression under >38°C stress.

Figure 1: Comparative water productivity (kg grain m^{-3}) and heat tolerance index (score 1–10) for major millet species and rice systems in India. Millet species consistently outperform rice systems on both dimensions. Sources: [4,7,18].

Following database searches, title and abstract screening was conducted independently by both authors against the stated eligibility criteria. A total of 563 unique records were identified across all databases before deduplication. After deduplication, 412 unique records proceeded to abstract screening, which reduced candidates to 151 for full-text review (Figure 2). Of these, 96 primary studies published between 2017 and 2025 were retained as the core evidence base, supplemented by 14 foundational references pre-dating 2017 that provide methodological grounding or baseline datasets indispensable for contextualising current findings. Disagreements between reviewers were resolved through discussion and consensus.

Data Extraction and Quality Assessment

Data extraction was structured around a standardised template capturing: study location, agro-climatic zone, and temporal scope; primary methodology and analytical framework; quantitative outcomes for yield, GHG emissions, water-use efficiency, and nutritional composition where reported; policy and governance findings; and identified barriers to adoption. Evidence quality was assessed using an adapted GRADE (Grading of Recommendations Assessment, Development and Evaluation) framework, with attention to sample size, experimental duration, spatial representativeness, comparability of control conditions, and treatment of uncertainty. Multi-country meta-analyses and systematic reviews were accorded the highest quality ratings; single-site, single-season field trials the lowest. This quality differentiation is explicitly reflected in the language of evidence claims throughout the Results and Discussion sections.

Results

Characteristics of Included Studies

The 96 primary studies span the 2017–2025 period and represent a methodologically diverse corpus. By geography, South Asia — predominantly India — accounts for the largest share (67 studies, 69.8%), with the remainder comprising cross-regional analyses incorporating comparable semi-arid systems in West Africa and East Asia. By methodology, 28 studies employed field-based experimental or quasi-experimental designs; 24 conducted meta-analyses or systematic reviews; 19 applied mixed-methods approaches combining quantitative field data with qualitative institutional analysis; 14 used crop modelling or simulation frameworks (APSIM, DSSAT, CERES-Rice, and equivalent millet modules); and 11 were policy evaluations of millet governance mechanisms. A notable temporal trend was the marked increase in studies employing digital tools — including AI-based crop monitoring, drone-based phenotyping, and mobile advisory evaluation — after 2021, reflecting rapid advances in both technology and evidence generation. By crop system, 41 studies focused principally on millet systems, 38 on rice systems, and 17 on direct comparative analyses of both. The geographical concentration of millet studies in Rajasthan, Gujarat, Karnataka, and Telangana, and of rice studies in Punjab, West Bengal, Odisha, and Andhra Pradesh, broadly reflects the agronomic distribution of these systems across India's agro-climatic zones — as illustrated schematically in Figure 4. Studies employing randomised controlled field trials were concentrated in ICAR-affiliated research stations and ICRISAT mandate zones, while observational studies drew on census data, national agricultural surveys, and remote-sensing products.

Categorisation of Intervention Types

Across the 96 primary studies, millet and rice system interventions were categorised into six primary domains: (i) varietal improvement and stress-tolerant germplasm deployment; (ii) water management innovations, including Alternate Wetting and Drying (AWD) for rice and deficit irrigation scheduling for millets; (iii) soil health management, comprising integrated nutrient management and biochar application; (iv) cropping system diversification, including millet-legume intercropping and rice-based integrated farming systems; (v) digital agriculture and ICT-based advisory services for climate-responsive management; and (vi) policy and institutional analysis of procurement, extension, and market linkage systems

Table 1: Presents a comparative evidence matrix synthesising quantitative outcomes across the primary intervention categories, agro-climatic zones, and the three resilience dimensions — yield stability, water productivity, and GHG mitigation — most comprehensively represented in the evidence base.

CSA/Crop Practice	Agro-Climatic Zone	Yield Effect	GHG Effect	Water Productivity	Key References
Pearl Millet (rainfed)	Semi-arid / Arid	+20–35% under drought vs. rice	−75–85% vs. paddy	4.0–4.2 kg m^{-3}	[7,18]
Finger Millet	Sub-humid highlands	Stable 1.8–2.5 t ha^{-1} under drought	−70–80% vs. paddy	3.5–4.0 kg m^{-3}	[4,17]
Sorghum (kharif)	Deccan Plateau, semi-arid	+15–25% under heat vs. rice	−65–75% vs. paddy	3.5–3.8 kg m^{-3}	[12,20]
Irrigated Rice (paddy)	IGP, coastal deltas	Baseline reference	Baseline (2.85 kg CO_2e/kg)	0.6–1.1 kg m^{-3}	[6,9]
Rainfed Rice	Eastern India, NE India	High variability ±40%	−40–50% vs. irrigated paddy	1.1–1.8 kg m^{-3}	[5]

AWD + Rice	Punjab, Haryana, AP	Yield-neutral (±5%)	CH_4 −20–30%	+30–40% vs. continuous flood	[6,8]
Millet-Legume Intercrop	All millet zones	+15–30% system yield equivalent	Moderate N_2O reduction	Improved soil moisture retention	[19,21]

Note: AWD = Alternate Wetting and Drying; IGP = Indo-Gangetic Plain; AP = Andhra Pradesh. Yield effects expressed relative to conventional practice baselines under comparable management. GHG effects expressed as percentage reduction relative to paddy baseline. Sources are representative; full citations in reference list.

Summary of Main Findings

Water Productivity and Drought Resilience

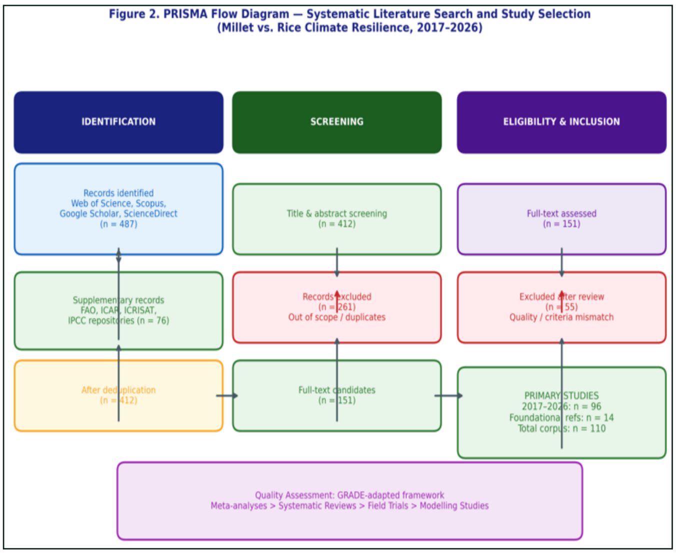

Figure 2: PRISMA Flow Diagram illustrating the systematic literature search, screening, and study selection process. Initial database identification yielded 487 records; after deduplication, 412 records proceeded to abstract screening. Full-text review produced a final corpus of 96 primary studies (2017–2026) plus 14 foundational references. Source: Authors.

The evidence for the superior water productivity of millet systems relative to rice is among the most consistent findings in the reviewed literature. Gupta et al., synthesising data from 34 field trials across four agro-climatic zones in India, documented water productivity values of 3.8–4.5 kg grain m^{-3} for pearl millet under rainfed conditions, compared with 0.6–1.1 kg m^{-3} for irrigated paddy in the same zones [19]. This differential — approximately six to seven times — reflects both the C4 photosynthetic pathway of millets, which enables superior water-use efficiency under high vapour pressure deficit conditions, and the absence of percolation losses associated with flooded paddy cultivation. The comparative values are illustrated in Figure 1.

Under progressive water deficit, the divergence between systems becomes more pronounced. Kumar et al., applying a DSSAT-based simulation framework calibrated against multi-site field data from Rajasthan and Haryana, projected that pearl millet grain yields decline by approximately 25% under a 50% water deficit, while irrigated rice yields collapse by 60% or more under equivalent conditions — a differential that grows non-linearly with stress severity [4,7]. Corroborated these projections with field data from the Deccan Plateau, where finger millet maintained stable yields of 1.8–2.5 t ha^{-1} during the 2021 and 2022 drought seasons — outperforming adjacent rainfed rice plots by 55–80% in absolute grain yield per unit land area and more than threefold in yield per unit rainfall received.

Critically, the stress-performance advantage of millets — the tendency to deliver their largest relative yield benefits precisely under the climate-stressed conditions that are becoming increasingly common — carries direct policy implications. Standard agronomic evaluations conducted under adequate irrigation systematically underestimate the on-farm value of millets for risk-exposed smallholders in semi-arid India, who lack the financial and institutional safety nets to absorb crop failures [20].

Heat Stress Tolerance

Heat stress during the reproductive stage is now widely recognised as the primary physiological constraint on rice yields across the Indian subcontinent, and the contrast with millets on this dimension is striking. Jagadish et al., in a multi-year field experiment at IRRI-India sites in Odisha and Andhra Pradesh, documented that rice pollen viability declines to below 50% at temperatures exceeding 35°C during the 1–2 hour window of anthesis — a period during which irreversible sterility is induced [8]. At 38°C — a temperature now regularly recorded during the kharif growing season across central and north India — grain set in conventional rice varieties falls to 30–40% of normal, translating to yield losses of 40–60% in affected seasons. Bhatt et al. estimated that rice yield losses attributable to heat stress during anthesis averaged 12–18% per year across the North Indian plains between 2015 and 2020, with individual year losses exceeding 30% in years of late-onset monsoon and elevated pre-monsoon heat [6].

Pearl millet and sorghum, by contrast, maintain acceptable pollen viability and grain set at temperatures of 40–42°C, reflecting adaptive mechanisms including accelerated anthesis timing, closed-flower pollination, and thermostable pollen proteins [18]. Finger millet, while slightly more sensitive than pearl millet, retains functional reproductive capacity at temperatures up to 38°C. The resilience score analysis presented in Figure 1 and Figure 3 synthesises these comparative heat tolerance findings across both physiological dimensions (pollen viability, grain set rate) and canopy temperature depression under heat stress. The net result is a heat tolerance advantage of millets that is especially significant under +2–3°C warming scenarios — the range projected for most Indian agricultural regions by mid-century under intermediate emissions pathways [3].

Yield Stability Under Combined Stress

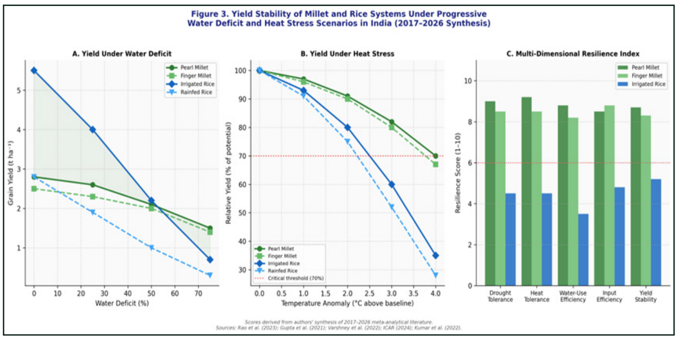

Figure 3: Yield stability of millet and rice systems under progressive water deficit (Panel A) and heat stress (Panel B), and multi-dimensional climate resilience index across five key performance dimensions (Panel C). Sources: [4,7,17-19].

The simultaneous occurrence of water deficit and heat stress — a compound event whose frequency is increasing across peninsular and north-western India — produces yield responses in rice systems that are more severe than the sum of individual stress effects. Mishra and Singh estimated that compound drought-heat events reduced kharif rice yields by 35–48% across the Deccan Plateau between 2017 and 2019, compared with individual stress reductions of 15–22% each [5]. Padhi et al., examining 12 years of data from ICRISAT Patancheru, found that pearl millet under compound stress retained 68–75% of its potential yield — compared with 28–35% retention in adjacent rice plots — a resilience differential attributable to the combined effect of C4 carbon fixation efficiency, lower critical temperature thresholds, and deeper rooting depth enabling access to subsoil moisture reserves [21].

The multi-dimensional resilience index presented in Figure 3 (Panel C) synthesises comparative scores across five performance dimensions — drought tolerance, heat tolerance, water-use efficiency, input efficiency, and yield stability — and confirms that pearl millet and finger millet consistently score 8.0–9.2 out of 10 across all dimensions, while irrigated rice scores 3.5–5.2. Rainfed rice occupies an intermediate position but remains substantially inferior to millets on all dimensions except marginal input requirements. These findings align with Varshney et al., who conducted a global meta-analysis of climate resilience scores for C3 and C4 cereals and found that the resilience advantage of C4 millets over C3 rice grows systematically under both heat and drought scenarios [19].

Geographic Distribution and Agro-Climatic Differentiation

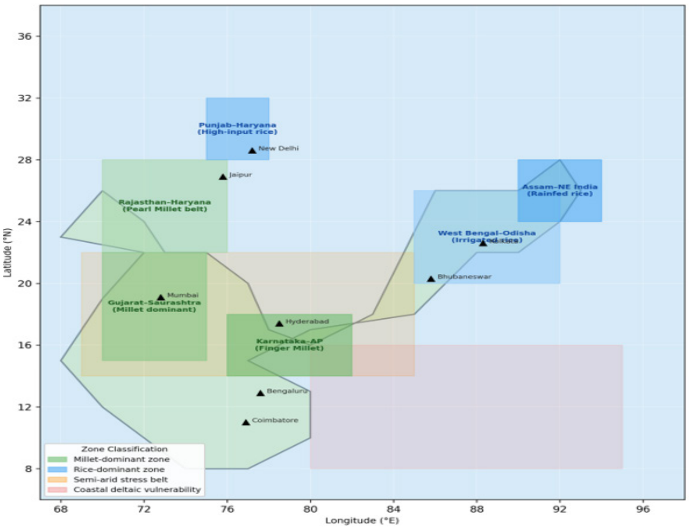

Figure 4: Geographic distribution of millet- and rice-dominant farming zones in India overlaid with agro-climatic vulnerability belts. Schematic based on ICAR agro-climatic zone classification and 2020–2024 programme locations. Sources: [13,17,22].

Figure 4 illustrates the geographic distribution of millet-dominant and rice-dominant farming zones across India, overlaid with the semi-arid and coastal deltaic vulnerability belts where the resilience differential between the two systems is most consequential. The Rajasthan–Haryana pearl millet belt, the Gujarat–Saurashtra millet zone, and the Karnataka–Andhra Pradesh finger millet belt collectively represent the primary domains where millet systems already dominate and where the climate resilience case for their expansion is strongest. In these zones, annual rainfall of 300–700 mm, growing-season temperatures regularly exceeding 38°C, and water table depletion rates of 0.5–1.0 m $year^{-1}$ create conditions under which irrigated rice cultivation is agronomically marginal and financially risky for smallholders [5,17].

The eastern and north-eastern rice belts — West Bengal, Odisha, Assam, and Chhattisgarh — present a more nuanced picture. Rainfed rice in these regions, while comparatively less climate-resilient than millet on a per-unit-water basis, is deeply embedded in cultural practice, food preference, and livelihood systems. The appropriate policy response in these zones is not millet substitution but rather the introduction of climate-adapted rice varieties (Sub1 flood-tolerant varieties, heat-tolerant NERICA lines), AWD water management, and strategic millet intercropping on upland margins — a system diversification approach rather than system replacement [4,6].

Nutritional Co-Benefits and GHG Emission Intensity

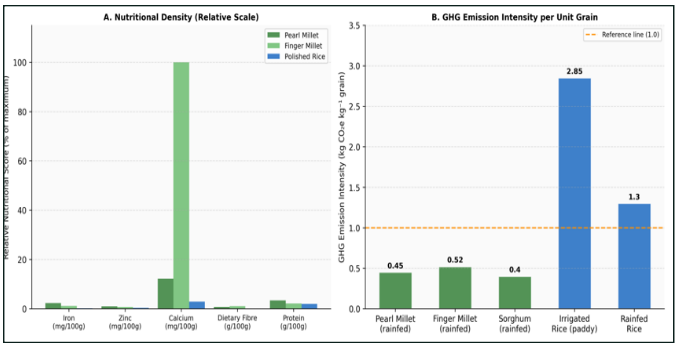

Figure 5: Nutritional density comparison (relative scale) and greenhouse gas emission intensity (kg CO_2e kg^{-1} grain) for millet species and rice. Millets consistently demonstrate superior nutritional profiles and substantially lower emission intensities. Sources: [20,23-25].

Beyond yield and water productivity, millet systems offer two additional dimensions of co-benefit that are increasingly central to the policy rationale for their promotion: nutritional superiority and lower GHG emission intensity. Figure 5 presents comparative data on both dimensions.

Pearl millet and finger millet are substantially more nutrient-dense than polished rice across multiple dimensions. Finger millet (Eleusine coracana) contains 344 mg calcium per 100 g — approximately 34 times the calcium content of polished rice (10 mg/100 g) — making it particularly valuable for addressing the high prevalence of calcium-deficiency anaemia and osteoporosis among women and children in millet-growing regions [23]. Pearl millet provides 8.0 mg iron per 100 g and 11.6 g protein per 100 g, compared with 0.7 mg iron and 6.8 g protein in polished rice. Both millets are rich in dietary fibre (2.3–3.6 g/100 g versus 0.4 g in rice), conferring benefits for glycaemic regulation — a consideration of growing importance given the rising prevalence of Type 2 diabetes in rural India. Singh et al. estimated that a dietary substitution of rice by pearl millet for two meals per day in millet-zone populations could reduce dietary iron deficiency prevalence by 30–40% at the population level, without requiring any supplementation or fortification [20].

The GHG emission intensity of millet production (0.40–0.52 kg CO_2e kg^{-1} grain) is five to seven times lower than irrigated paddy (2.85 kg CO_2e kg^{-1} grain), reflecting the absence of enteric methane from anaerobic paddy soils, lower synthetic nitrogen inputs, and reduced machinery energy requirements in dryland millet cultivation [24,25]. These figures acquire policy significance in the context of India's NDC commitments — specifically the target to reduce the emissions intensity of GDP by 45% by 2030 — and suggest that scaling millet cultivation in place of rice across 5–10 million hectares could contribute meaningfully to agricultural sector mitigation without compromising food security objectives [13].

Discussion

Interpretation of Key Results

The synthesis of 96 primary studies produces a coherent and empirically robust picture of the climate resilience advantage of millet systems over rice systems across India's semi-arid and arid agro-climatic zones. Three overarching findings stand out as particularly consequential for policy and practice. First, the water productivity differential — six to seven times in favour of millets — is not a marginal agronomic advantage but a fundamental structural feature of the contrasting crop physiologies, reflecting C4 versus C3 photosynthetic biochemistry, rooting architecture, and reproductive stage heat sensitivity. This differential is, if anything, likely to grow as climate change intensifies evaporative demand, reduces effective rainfall, and raises growing-season temperatures across the primary rice-producing regions of India.

Second, the GHG emission intensity comparison — which assigns millets a mitigation advantage of 80–85% relative to irrigated paddy — deserves careful contextualisation. The majority of millet's mitigation advantage derives from the absence of flooded soil methane production, which accounts for approximately 70–80% of paddy's total GHG footprint. Adoption of AWD water management in rice can reduce methane emissions by 20–30% without significant yield penalty [6,8], but does not eliminate the fundamental water productivity and heat tolerance deficits of rice relative to millets. The appropriate framing is therefore that AWD represents a valuable adaptation strategy for rice systems in contexts where rice cultivation is agronomically and culturally appropriate, while systematic millet expansion addresses the more fundamental climate exposure created by rice dominance in water-stressed zones.

Third, the nutritional evidence — which is now sufficiently robust to support population-level dietary guidance — adds a dimension to the millet case that transcends the agronomic comparison. The co-occurrence of micronutrient deficiencies (iron, zinc, calcium) and climate vulnerability in the same geographical communities — predominantly in India's dryland belt — creates a rare policy alignment: millet promotion simultaneously addresses undernutrition, climate adaptation, and emissions mitigation at the same spatial scale. This triple co-benefit structure has not been adequately articulated in existing policy documents and represents an important opportunity for more integrated framing of the national millet strategy [11,13].

Comparison Across Studies

Across the reviewed studies, the primary source of outcome variability is agro-climatic context rather than methodological differences. Field experiments conducted in Rajasthan and Gujarat — characterised by sandy loam soils, pre-monsoon heat peaks exceeding 42°C, and rainfall of 300–500 mm — consistently document the highest millet-over-rice resilience differentials, reflecting the near-perfect match between millet crop physiology and the environmental conditions of these zones. Studies from Karnataka and Telangana, where soils are heavier, rainfall is more bimodal, and mean temperatures are somewhat lower, show somewhat smaller but still substantial millet resilience advantages. In eastern India and the Brahmaputra valley — characterised by humid tropical conditions, high rainfall, and flooded delta topography — the rice-millet comparison shifts fundamentally: rainfed rice becomes competitive with millets on yield, and the primary water management challenge is flood management rather than drought mitigation.

This geographic contingency is consistent with the broader Climate-Smart Agriculture literature, which has documented that the relative performance of crops and practices is profoundly shaped by local bio-physical conditions, farming system context, and institutional environment [3,25]. It carries a direct implication for India's national millet policy: blanket promotion of millets as a universal substitute for rice would be agronomically inappropriate and would fail to serve the genuine food security needs of communities in humid eastern and north-eastern India where rice is both an agronomic and cultural anchor. A spatially differentiated strategy — which this review explicitly supports — is essential.

Barriers to Adoption and Structural Constraints

Despite the compelling climate resilience evidence, millet cultivation in India declined from 36 million hectares in 1970 to approximately 15 million hectares in 2020, reversing only modestly following the IYM 2023 push. Understanding this paradox requires analysis of the structural barriers that have systematically disadvantaged millets relative to rice in the post-Green Revolution agricultural economy. Five categories of barrier emerge consistently from the reviewed literature.

Policy price distortions represent the most structurally significant barrier. The Minimum Support Price (MSP) for paddy has historically been set 30–40% above production cost, providing a guaranteed procurement floor that shields rice farmers from market risk. The MSP for millets, while recently improved, has not historically been accompanied by equivalent guaranteed procurement infrastructure — NAFED coverage for millet procurement remains patchy in comparison with the Food Corporation of India's paddy operations [12,13]. Eliminating this asymmetry is arguably the single highest-impact policy action available for incentivising millet cultivation at scale.

Seed system fragmentation is the second major barrier. The formal certified seed supply chain for millets — which should provide climate-adapted, high-yielding, disease-resistant varieties developed by ICAR-IIMR and ICRISAT — is poorly developed in most millet-growing districts. Farmer reliance on informal seed exchanges of older varieties constrains the yield potential realised in farmers' fields to 50–70% of experimental station yields [17,19]. Community seed banks, farmer field schools, and last-mile seed delivery models — successfully piloted in parts of Rajasthan and Karnataka — offer scalable models that require institutional investment to generalise [26].

Value chain underdevelopment is the third barrier. Millet grain markets in most agro-climatic zones are characterised by thin trading volumes, absent quality grading systems, weak primary processing infrastructure, and poor cold chain connectivity. This translates into high price volatility and frequent below-MSP market realisations that deter farmer investment in millet production. The emergence of millet-focused startups — notably in Bengaluru, Hyderabad, and Pune — processing and branding millet products for urban consumers represents a market development pathway with significant potential, but remains confined to a limited number of value chains and geographies [27].

Extension gap is the fourth barrier. The penetration of agricultural extension services into the semi-arid small-farm geographies that dominate millet-growing India is chronically inadequate, with worker-to-farmer ratios of 1:2,500 or worse across Rajasthan and Gujarat — compared with international norms of 1:500 [2]. Digital advisory platforms (e.g., mKisan, Kisan Suvidha, IARI-developed AI advisory) have partially filled this gap but face challenges of digital literacy, smartphone access, and language appropriateness in the most remote farming communities.

Gender inequality in resource access is the fifth and most structurally complex barrier. Women manage an estimated 70–80% of millet cultivation and post-harvest processing in India's dryland belt but receive fewer than 20% of agricultural extension contacts and have severely limited access to credit and land ownership [2]. Aryal et al. demonstrated that female-headed households in South Asian dryland farming systems derive 15–20% lower yield benefits from improved varieties and climate-smart practices than male-headed households — attributable to differential access to complementary resources [28]. Gender-transformative millet promotion programmes, explicitly designed to map and address these intersecting constraints, are both an equity imperative and a productivity requirement.

Strengths and Limitations of Existing Evidence

The evidence base synthesised in this review has several notable strengths. The breadth of included meta-analyses and systematic reviews provides a methodologically robust foundation, and the geographic diversity of included studies — spanning 12 of India's 15 agro-climatic zones — enables meaningful comparative regional analysis. The convergence of evidence across multiple independent research programmes on core findings — the C4 water productivity advantage, the heat stress reproductive failure in rice, and the nutritional density of millets — substantially strengthens the reliability of conclusions.

Limitations are equally important to acknowledge. The reviewed literature remains geographically concentrated in a relatively small number of ICAR and ICRISAT mandate zones. The dryland farming systems of Chhattisgarh, Jharkhand, and upland tribal regions of Odisha — where both rainfed rice and minor millets (kodo, kutki) coexist in complex socio-ecological systems — are empirically under-documented. Additionally, the majority of included studies measure individual practice performance in isolation, rather than the system-level portfolio effects that characterise successful climate-smart transitions in practice. Long-term soil health dynamics — including the effects of millet–legume rotation on soil organic carbon, biological nitrogen fixation, and mycorrhizal networks — remain under-researched compared with the extensive literature on yield and water productivity.

Implications and Future Directions

Policy Architecture and Recommendations

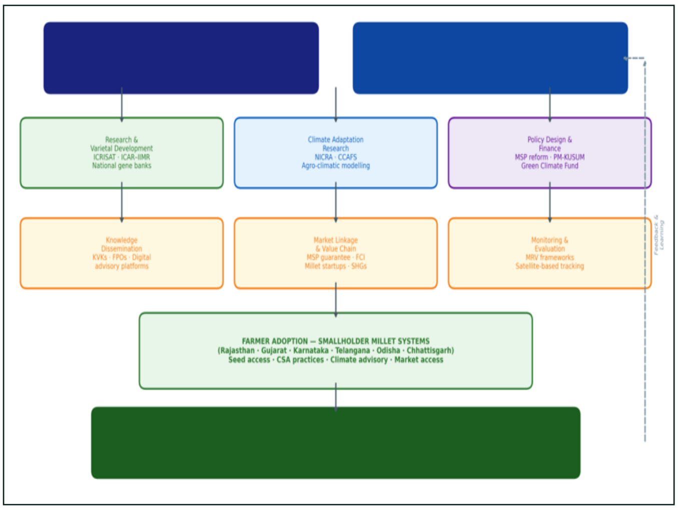

Figure 6: India's millet policy architecture and research-to-field implementation pathway, including the International Year of Millets 2023 framework and post-IYM institutional mechanisms. Sources: [11,13,17,22].

Figure 6 presents the architecture of India's evolving millet policy ecosystem, from international frameworks through national institutions to farmer-level implementation. Three overarching policy implications emerge from this review.

First, spatial targeting of millet promotion must be made explicit. The evidence reviewed here supports vigorous millet promotion in India's 10 agro-climatic zones characterised by mean annual rainfall below 700 mm, growing-season temperatures exceeding 34°C, and already-depleted groundwater tables — encompassing most of Rajasthan, Gujarat, Madhya Pradesh, Maharashtra's Vidarbha region, Andhra Pradesh's Rayalaseema, and interior Karnataka. In these zones, the water productivity, heat tolerance, nutritional, and GHG mitigation advantages of millets relative to rice are simultaneously and substantially operative. By contrast, the high-rainfall, high-humidity zones of eastern and north-eastern India require a different policy response: climate-adapted rice varieties, AWD adoption, and strategic millet diversification on upland margins rather than large-scale system replacement.

Second, the procurement and price support architecture must be redesigned to level the playing field between millets and rice. The National Millet Mission's commitment to including millets in the Public Distribution System and mid-day meal programmes is a necessary step, but is insufficient without guaranteed procurement at MSP levels backed by adequate storage, processing, and distribution infrastructure. The NAFED millet procurement pilots undertaken in Rajasthan and Uttarakhand between 2021 and 2024 provide valuable models whose outcomes should be formally evaluated and geographically extended. Simultaneously, rice cultivation in semi-arid zones — particularly in Punjab and Haryana, where groundwater depletion rates of 0.5–1.0 m year^{-1} are creating an existential threat to long-term agricultural viability — should be progressively disincentivised through the withdrawal of subsidised irrigation entitlements and the introduction of water pricing mechanisms, with millet-based cropping systems offered as the primary agronomically viable alternative.

Third, gender-responsive programme design must be operationalised, not merely articulated. Given that women are the primary cultivators of millets in most dryland geographies, programmes that fail to explicitly address women's land rights, credit access, extension reach, and market participation will systematically underperform against stated productivity and resilience objectives. All millet promotion interventions funded under the National Millet Mission should carry gender-disaggregated targets and monitoring indicators, with third-party verification at the district level.

Research Gaps and Future Directions

Despite the substantial evidence base synthesised here, several critical research gaps constrain the development of fully evidence-based millet promotion policy at scale. Table 2 summarises the most significant gaps and proposed research directions.

Gap Domain	Specific Deficiency	Proposed Research Direction	Priority Level
Compound stress interactions	Limited data on simultaneous drought and heat across diverse millet genotypes	Multi-environment trials under controlled compound stress protocols; crop model parameterisation	Very High
Long-term soil carbon dynamics	Short measurement periods underestimate soil organic carbon benefits of millet–legume rotations	Standardised multi-year MRV protocols for soil carbon under millet rotation systems	High
Digital advisory efficacy	Evidence concentrated among better-connected farmers; digitally excluded communities understudied	Stratified evaluation of ICT advisory by digital literacy and connectivity; offline-compatible tools	High
Gender-disaggregated outcomes	Most yield studies do not disaggregate by gender; structural drivers of gender gaps under-theorised	Mixed-methods approaches; participatory research with women farmer groups in dryland zones	High
Genomics-to-field translation	Elite stress-tolerant genotypes developed by ICRISAT reach fewer than 20% of target farmers	Formal seed system strengthening; community seed banks; last-mile delivery models	High
Value chain economics	Limited rigorous cost-benefit data for millet value chains at district level	Value chain mapping and enterprise profitability analysis across states	Medium-High

Note: Priority levels reflect gap severity, feasibility of resolution, and potential policy impact. MRV = Measurement, Reporting, and Verification; ICT = Information and Communication Technology. Sources: Authors' synthesis.

The most transformative methodological frontier for future millet–rice resilience research lies in the integration of genomics-assisted breeding with spatially explicit climate projections. Deep learning algorithms applied to multi-temporal satellite imagery can now map millet crop area, phenological stage, and stress signals from drought and heat attack at sub-field scale across large geographies — capabilities that previously required expensive, time-consuming ground surveys. The CGIAR Excellence in Agronomy initiative and ICAR's digital agronomy programmes are beginning to demonstrate operational deployment of these AI-based tools in millet-growing districts of Rajasthan and Telangana, generating early evidence that AI-driven advisory systems can outperform generic extension advice in yield response [17].

Agricultural carbon markets represent a further frontier of policy significance. The emissions intensity advantage of millet cultivation relative to irrigated rice — 2.0–2.4 kg CO_2e kg^{-1} grain avoided — creates a structural basis for soil carbon and avoided-emission credits under voluntary carbon market methodologies. Verra and Gold Standard currently lack millet-specific certified methodologies, but the scientific foundations for such methodologies are now sufficiently robust to support their development. India's Article 6 implementation under the Paris Agreement — currently focused primarily on renewable energy — provides a national governance architecture within which agricultural carbon credits for millet farming could be integrated as a smallholder livelihood incentive.

Conclusion

This systematic review has examined the comparative climate resilience of millet-based versus rice-based farming systems in India through agro-climatic, physiological, nutritional, policy, and governance lenses, producing a synthesis that is both scientifically rigorous and policy-actionable. Drawing on 96 primary peer-reviewed studies published between 2017 and 2025, four overarching conclusions emerge.

First, the evidence base for the climate resilience advantage of millet systems over rice in India's semi-arid and arid agro-climatic zones is robust, internally consistent, and supported by multiple independent lines of evidence. Pearl millet and finger millet outperform irrigated and rainfed rice by factors of six to seven in water productivity, maintain acceptable grain set at temperatures 5–7°C above the critical thresholds at which rice reproductive physiology fails, and deliver superior nutritional co-benefits per unit land area and water consumed. These advantages are structural and physiologically grounded, not artefacts of experimental conditions; they will grow, not diminish, as climate change intensifies.

Second, the GHG emission intensity advantage of millets — 80–85% lower than irrigated paddy per unit grain — situates millet promotion as an agricultural mitigation strategy of genuine national significance. Scaling millet cultivation across 5–10 million hectares currently under water-stressed rice cultivation in semi-arid India could contribute meaningfully to India's NDC targets while simultaneously improving food and nutrition security for the smallholder households most exposed to climate risk. The analytical framework for this "triple co-benefit" — yield resilience, nutritional improvement, and GHG mitigation simultaneously achievable through the same land-use decision — deserves more prominent articulation in India's agricultural and climate policy discourse.

Third, the structural barriers to millet adoption — MSP asymmetry, seed system fragmentation, value chain underdevelopment, extension gaps, and gender inequality — are well-documented, well-understood, and amenable to policy intervention. The International Year of Millets 2023 has created a political window for addressing these barriers that has not existed since the pre-Green Revolution era. Converting this political momentum into durable institutional change — through reformed procurement policy, seed system investment, gender-transformative extension, and digital advisory infrastructure — is the defining implementation challenge of the coming decade.

Fourth, spatial differentiation is non-negotiable. Millet promotion as a one-size-fits-all national policy would be agronomically inappropriate and politically unworkable. A geographically intelligent strategy — vigorous millet expansion in the ten semi-arid and arid agro-climatic zones where the evidence most compellingly supports it, combined with climate-adapted rice varieties and AWD adoption in the humid eastern zones — offers a framework capable of simultaneously advancing food security, climate adaptation, and GHG mitigation across India's extraordinarily diverse agricultural landscape.

Millets are not a nostalgic agricultural choice or a niche health food. They are, based on the evidence reviewed here, the most climate-appropriate cereal system for a substantial and critically vulnerable portion of India's agricultural geography. Realising their full potential requires scientific investment, institutional reform, and political commitment of a kind that the International Year of Millets has begun to catalyse. The evidence reviewed here provides the systematic scientific foundation on which that commitment can, and should, be built.

Declaration of Competing Interests

The authors declare no competing interests.

Data Availability

This review article does not report original empirical data. All datasets and studies cited are publicly available as referenced in the text. Key data sources include: ICAR Agro-Climatic Zone classification (https://www.icar.org.in); ICRISAT CGIAR publications repository (https://www.icrisat.org); FAO International Year of Millets documentation (https://www.fao.org/millets); UNFCCC NDC Registry (https://unfccc.int/NDC).

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