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La Niña- driven variability in Indian monsoon dynamics and agricultural productivity

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Abstract

La Niña, the cold phase of the El Niño- Southern Oscillation (ENSO), exerts a well-documented but spatially heterogeneous influence on the Indian Summer Monsoon Rainfall (ISMR). Indian agriculture contributes approximately 17.8% of national GDP and employs over 54% of the workforce (World Bank 2024), understanding the agronomic consequences of La Niña-associated rainfall variability is of paramount importance for food security and policy planning. Quantitative analyses of rainfall anomalies, crop yield responses, and extreme event frequencies were represented across nine agro-climatic zones of India. La Niña years are consistently associated with above-normal ISMR, with spatially averaged anomalies of +2.9% to +17.2% compared to the long-term mean. The lower gangetic plains and north-eastern highlands experience severe flooding, while the southern peninsula frequently records rainfall deficits. *Kharif* crop yields (particularly rice and soybean) respond positively in north-western India, whereas waterlogging and flooding depress yields in eastern and north-eastern zones by 3-12%. Flood-affected agricultural area during strong La Niña events averages 4.8 million hectares (Mha), compared to 0.9 Mha during El Niño years. Adaptation strategies including flood-tolerant crop varieties, ENSO-based seasonal forecasting. La Niña presents a dual risk profile for Indian agriculture. Surplus rainfall benefits rainfed farming in semi-arid regions while concurrently inducing catastrophic flood losses in vulnerable eastern and coastal zones. Policy frameworks must integrate agro-climatic zonal differentiation, ENSO-predictive seasonal advisories, and investment in climate-smart infrastructure to achieve resilient food production under increasing ENSO variability projected under RCP 4.5 and SSP2-4.5 scenarios.

Keywords: La Niña, Indian Summer Monsoon, ENSO teleconnections, crop yield variability, climate-smart agriculture and Walker circulation

1. Introduction

The El Niño–Southern Oscillation (ENSO) represents the most energetically significant coupled ocean-atmosphere phenomenon in the tropics, with documented global-scale teleconnections affecting temperature, precipitation, and agricultural productivity on interannual timescales (Trenberth 1997; Cai *et al.*, 2021) ^[38, 3]. India's agricultural economy characterised by over 140 million farm holdings, a cultivated area of approximately 180 million hectares, and a monsoon-fed irrigation dependence exceeding 80% remains among the most ENSO-sensitive food systems in the world (FAO 2023; IPCC AR6 2022) ^[9, 1]. While El Niño's drought-inducing effects on the Indian Summer Monsoon Rainfall (ISMR) have been extensively investigated, the agronomic consequences of La Niña- the cold, wet phase of ENSO have received comparatively less attention. La Niña events, characterised by anomalously cold sea surface temperatures (SSTs) in the central and eastern tropical Pacific (Oceanic Niño Index, ONI < −0.5 °C for five consecutive overlapping seasons), typically enhance monsoon circulation through an intensified Walker Cell, favouring convection over the Indian Ocean and the sub-continent (Krishnamurthy and Shukla 2000; Webster *et al.*, 1998) ^[26, 39]. However, the assumption that La Niña uniformly benefits Indian agriculture through above-normal rainfall oversimplifies a complex, spatially heterogeneous response that varies by region, crop type, agro-climatic zone, and event intensity. Recent analyses reveal that between 1998 and 2023, India experienced nine La Niña episodes of varying intensity (IMD 2023) ^[19]. Concurrent with above-normal all-India rainfall, these

episodes were associated with heightened flood risk, major flood events occurred 3.8×more frequently during La Niña compared to El Niño years (NDMA 2022) [30]. Simultaneously, parts of peninsular India particularly Tamil Nadu, which receives a disproportionate share of its rainfall during the retreating (north-east) monsoon experienced rainfall deficits during La Niña conditions (Rajeevan *et al.*, 2012; Pai *et al.*, 2019) [33, 32].

2. ENSO-Monsoon Teleconnection Mechanisms

2.1 The Walker Circulation and La Niña Dynamics

The Walker Circulation- a zonal, thermally-driven atmospheric overturning cell along the equatorial Indo-Pacific constitutes the primary atmospheric bridge between tropical Pacific SST anomalies and Indian monsoon behaviour (Bjerknes 1969; Trenberth 1997) [2, 38]. Under La Niña conditions, anomalously cold SSTs in the central and eastern Pacific (Niño 3.4 region SST anomaly < -0.5 °C) suppress convection over the eastern Pacific while simultaneously enhancing it over the maritime continent and the Indian Ocean warm pool. This intensification of the ascending limb of the Walker Cell over the Indian Ocean reinforces the low-level westerly flow of the south-west monsoon, increasing moisture convergence over the Indian sub-continent. Quantitatively, NCEP-NCAR reanalysis data indicate that during strong La Niña events (ONI ≤ -1.5 °C), the 850 hPa zonal wind anomaly over the Arabian Sea averages +1.8 m s⁻¹, compared to -2.3 m s⁻¹ during El Niño years, a differential that translates directly into enhanced moisture transport of approximately 35-40 kg m⁻¹ s⁻¹ additional precipitable water over peninsular India (Fasullo and Webster 2003; Krishnamurthy and Kinter 2003) [10, 25]. Under SSP2-4.5 projections, the frequency of extreme La Niña events (ONI ≤ -1.5 °C) is projected to increase by 33-47% by the late 21st

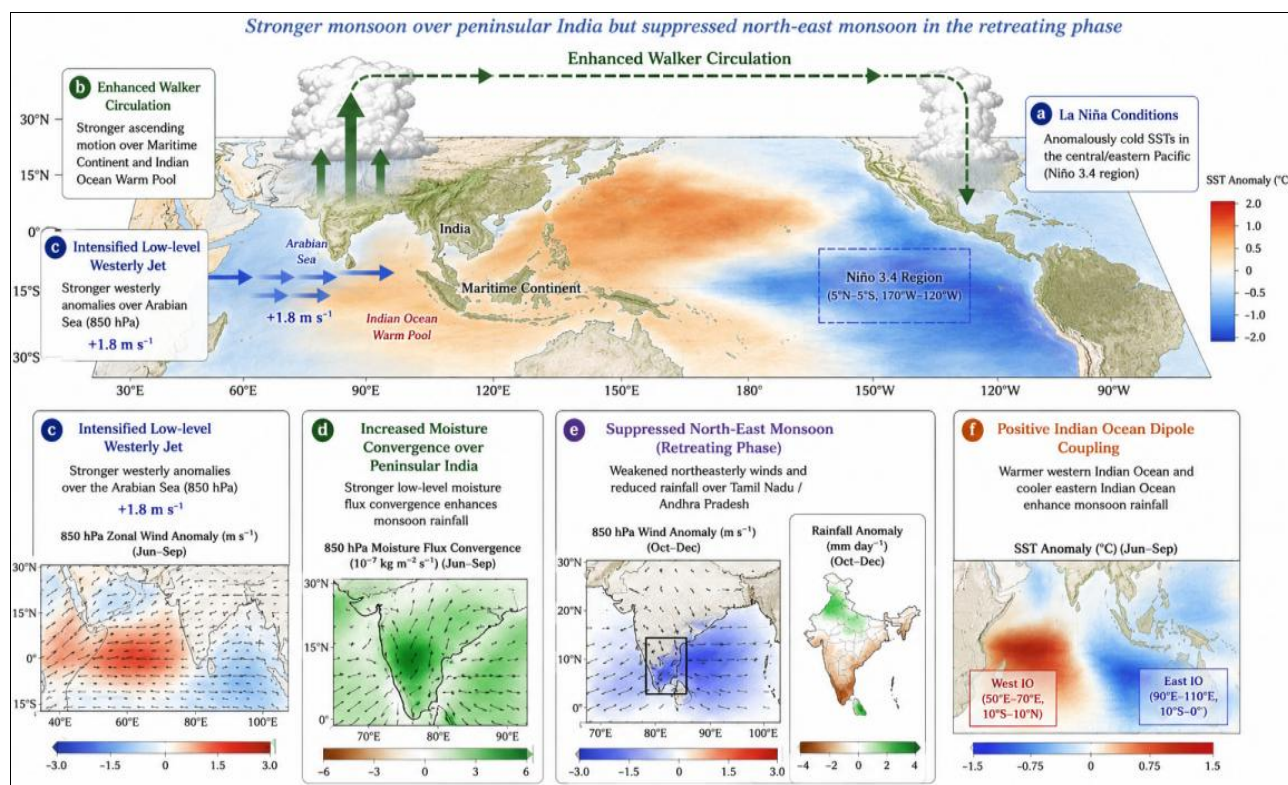
century (Cai *et al.*, 2023) [4].

2.2 Indian Ocean Dipole Interactions

The Indian Ocean Dipole (IOD), characterised by an east-west SST gradient across the Indian Ocean, frequently co-occurs with ENSO phases and modulates ISMR independently as well as in concert with La Niña (Ashok *et al.*, 2001; Saji *et al.*, 1999) [1, 37]. Positive IOD events (warmer western Indian Ocean) co-occurring with La Niña amplify monsoon rainfall, while negative IOD- La Niña combinations partially offset the surplus tendency. The compounded effect of a strong La Niña and a positive IOD as occurred in 2020 can amplify ISMR anomalies by an additional 4-6% beyond the La Niña signal alone. Disentangling these interactions remains a critical challenge for seasonal prediction, particularly given evidence of non-stationarity in the ENSO-IOD-ISMR relationship under anthropogenic warming (Roxy *et al.*, 2020) [36].

2.3 Intraseasonal Modulation: MJO and BSISO

Within La Niña seasons, the Madden-Julian Oscillation (MJO) and the Boreal Summer Intraseasonal Oscillation (BSISO) determine the temporal distribution of rainfall within the June-September monsoon window (Goswami and Ajaya Mohan 2001) [13]. La Niña favours enhanced and prolonged MJO Phase 2-3 activity over the Indian Ocean, increasing the frequency of active monsoon spells. Analysis by Pai *et al.*, (2019) [32] indicates a 25% increase in the number of extreme rainfall days (≥100 mm/day) during La Niña seasons compared to neutral years, and a 40% increase compared to El Niño years. These intraseasonal dynamics have direct implications for planting window decisions and flood risk management.



Data sources: NCEP-NCAR Reanalysis II, NOAA CPC ONI index, ERA5 reanalysis.

Fig 1: Representation of ENSO-Indian Monsoon teleconnection mechanisms during La Niña conditions. The diagram illustrates: (a) anomalously cold SSTs in the central/eastern Pacific (Niño 3.4 region); (b) enhanced Walker Circulation ascending limb over the Maritime Continent and Indian Ocean Warm Pool; (c) intensified low-level westerly jet and 850 hPa wind anomalies over the Arabian Sea (+1.8 m s⁻¹); (d) increased moisture convergence over peninsular India; (e) suppressed north-east monsoon over Tamil Nadu/Andhra Pradesh in the retreating monsoon phase; and (f) positive Indian Ocean Dipole coupling dynamics.

3. Agro-Climatic Zonal Analysis of La Niña Impacts

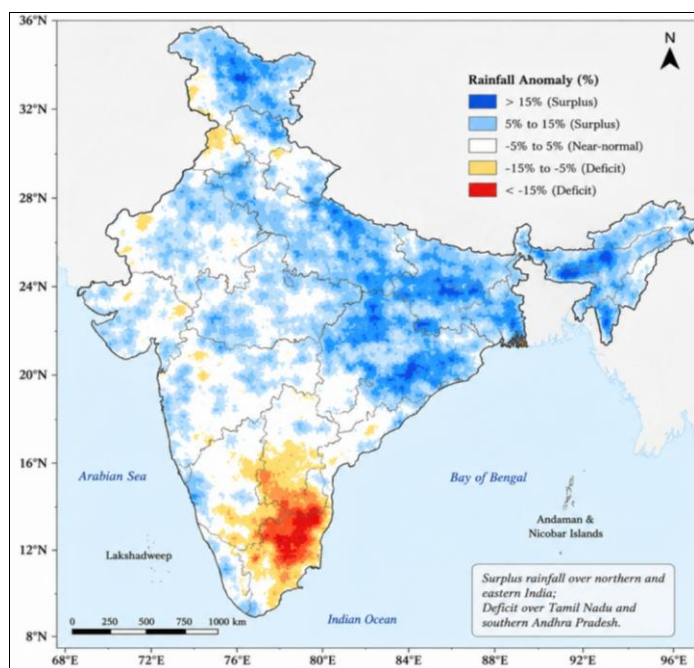
India's Planning Commission delineated 15 agro-climatic zones based on physiography, soils, and rainfall patterns. The nine-zone classification widely used in climate-agriculture studies

(ICAR 2019) ^[14], as presented in Table 1. La Niña's rainfall surplus impacts are not uniformly distributed across these zones, necessitating zone-specific analysis for policy and agricultural planning.

Table 1: Agro-climatic zone vulnerability comparison under La Niña conditions. Flood and drought risk indices rated 1 (lowest) to 5 (highest).

Agro-climatic Zone	Representative States	La Niña Rainfall Response	Flood Risk (1-5)	Drought Risk (1-5)	Dominant Vulnerability	Net Yield Impact
North-Western Plains	Punjab, Haryana, UP West	Moderate surplus (+5-10%)	2	1	Flooding, delayed harvest	Moderately positive
Upper Gangetic Plains	UP East, Uttarakhand	High surplus (+10-18%)	4	1	Flash floods, soil erosion	Mixed
Lower Gangetic Plains	Bihar, W. Bengal	Very high surplus (>15%)	5	1	Crop inundation, vector disease	Negative
Eastern Plateau	Jharkhand, Odisha	Moderate surplus (+5-12%)	3	2	Drainage failure, paddy lodging	Neutral
Deccan Plateau	Maharashtra, Karnataka	Variable (0-+8%)	2	2	Irregular distribution	Mixed
Western Dry Zone	Rajasthan, W. Gujarat	Near-normal to slight excess	1	3	Late-season dryness	Marginally negative
Southern Peninsula	Tamil Nadu, Andhra	Significant deficit (-5-15%)	1	4	Reduced NE monsoon	Negative
North-Eastern Highlands	Assam, Meghalaya	Extreme surplus (>20%)	5	1	Devastating floods, landslides	Highly negative
Western Ghats Zone	Kerala, W. Karnataka	Above normal (+8-15%)	4	1	Landslides, root zone saturation	Negative

Sources: ICAR (2019) ^[14], IMD (2023) ^[19], NDMA (2022) ^[30].



Source: IMD gridded rainfall dataset v2.0 (0.25°); NOAA ONI index for La Niña year classification.

Fig 2: Spatial rainfall anomaly map of India during composite strong La Niña years (1998-99, 2010-11, 2021-22). Anomaly values (%) computed relative to the 1981-2010 IMD gridded rainfall climatology at 0.25° × 0.25° resolution. Colour scale: dark blue = >15% surplus; light blue = 5-15% surplus; white = ±5% near-normal; yellow = 5-15% deficit; red = >15% deficit. Note surplus concentrated in northern and eastern zones and deficit in Tamil Nadu/southern Andhra Pradesh.

3.1 North-Western and Upper Gangetic Plains

The north-western plains (Punjab, Haryana, western Uttar Pradesh) typically receive 5-10% above-normal rainfall during La Niña, with moderate flood risk concentrated in low-lying areas proximate to the Sutlej, Beas, and Ghaggar river systems. The surplus moisture generally benefits *kharif* paddy and wheat *rabi* crops, contributing to above-average yields in Punjab (rice +8 to +14%) and Haryana. However, the upper Gangetic plains (eastern Uttar Pradesh, Uttarakhand) experience more pronounced surpluses (+10-18%), increasing flash flood events

in Terai districts and threatening the early *kharif* planting calendar.

3.2 Lower Gangetic Plains and North-Eastern Highlands

These zones consistently record the most adverse La Niña agricultural outcomes. Rainfall surpluses exceeding 15% in Bihar and West Bengal and greater than 20% in Assam and Meghalaya generate recurrent inundation events that damage standing paddy crops through submergence, soil puddling, and nitrogen leaching. NDMA (2022) ^[30] data indicate that the lower Gangetic plains and north-eastern zone account for 62% of all La Niña-associated agricultural flood damage nationally, despite comprising only 18% of the total cultivated area. The 2022 La Niña season exemplified this vulnerability, with Assam recording 27.4% above-normal rainfall and 42 of 35 districts officially flood-affected (IMD 2023) ^[9]. An estimated 0.73 Mha of paddy was damaged, with production losses of approximately 1.1 million tonnes (MT), representing the largest single-season La Niña crop loss in the decade.

3.3 Peninsular and Southern Zones

A critical regional inconsistency in La Niña's impact emerges in the southern peninsula. Tamil Nadu and parts of coastal Andhra Pradesh receive a disproportionate share of annual rainfall during the north-east monsoon (October-December), which is typically suppressed during La Niña years due to weakened cyclonic activity in the Bay of Bengal and reduced north-east monsoon intensity (Rajeevan *et al.*, 2012) ^[33]. Rainfall deficits of 5-15% have been recorded in Tamil Nadu during strong La Niña years (Pai *et al.*, 2019) ^[32], compromising the *rabi* season and Cauvery Basin irrigation. This counter-intuitive deficit pattern in a technically surplus ENSO phase underscores the inadequacy of national-level generalisation in La Niña impact assessments.

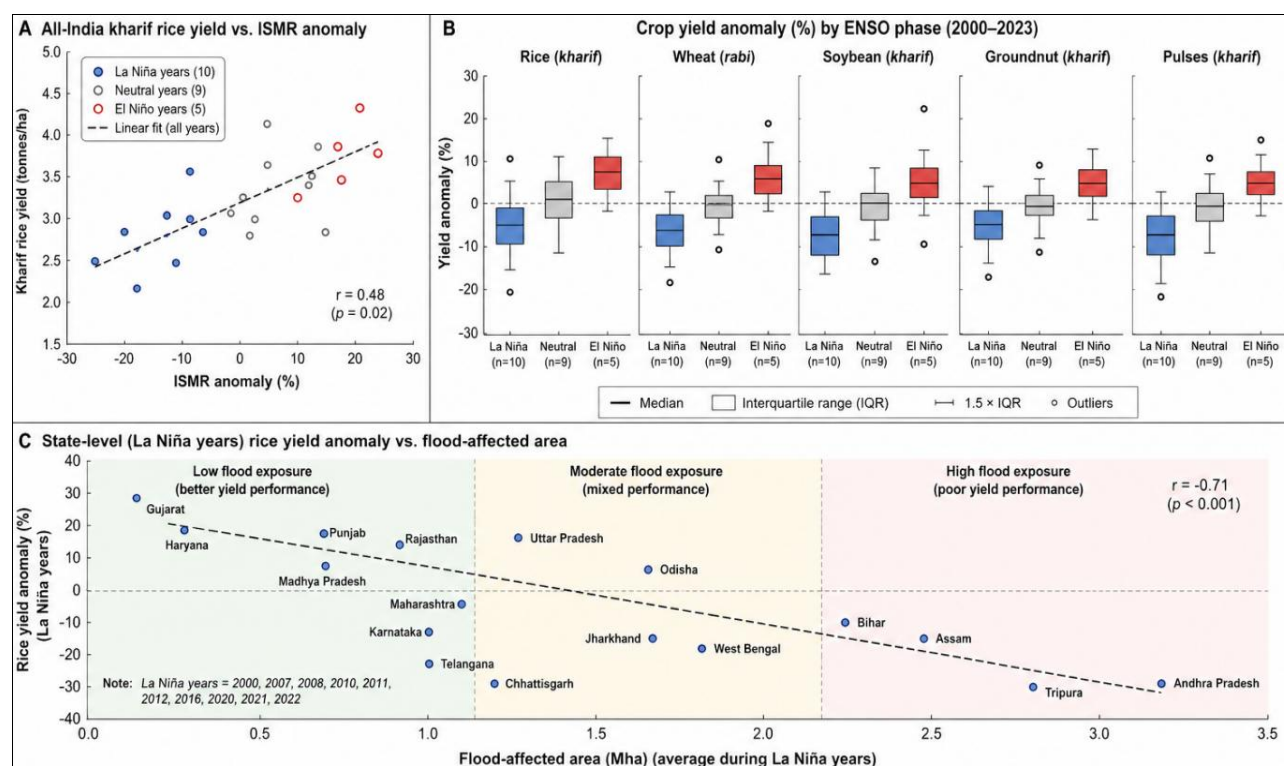
4. Crop-wise Impact Assessment

Crop-specific responses to La Niña rainfall variability depend on the interaction of excess moisture availability, flood tolerance, rooting depth, growing season alignment with monsoon active phases, and soil drainage characteristics. Table 2 represents crop yield changes for major Indian crops.

Table 2: Crop yield response under La Niña conditions (2000–2023) by region. Yield change (%) relative to 10-year moving average.

Crop	Region/ State	Yield Change (%)	Primary Driver	Season	Confidence	Reference
Rice (<i>Kharif</i>)	Punjab, Haryana	+8-14	Excess rainfall, soil moisture	<i>Kharif</i>	High	ICAR, 2022 ^[16]
Rice (<i>Kharif</i>)	Assam, W. Bengal	(-3)-(-8)	Flooding, lodging losses	<i>Kharif</i>	High	IMD, 2021 ^[18]
Wheat (<i>Rabi</i>)	NW India plains	+4-7	Enhanced winter rains	<i>Rabi</i>	Moderate	FAO, 2023
Wheat (<i>Rabi</i>)	Rajasthan, Gujarat	(-5)-(-10)	Erratic rabi rainfall	<i>Rabi</i>	Moderate	ICAR, 2021 ^[15]
Maize	Karnataka, Andhra	(-2)-(-6)	Waterlogging stress	<i>Kharif</i>	Moderate	Ray <i>et al.</i> , 2019 ^[35]
Soybean	Madhya Pradesh	+5-9	Optimal moisture	<i>Kharif</i>	High	Mishra <i>et al.</i> , 2020 ^[27]
Groundnut	Andhra Pradesh	(-4)-(-9)	Excessive soil moisture	<i>Kharif</i>	High	Gadgil <i>et al.</i> , 2019 ^[11]
Cotton	Maharashtra	+3-6	Improved soil water	<i>Kharif</i>	Moderate	World Bank, 2022 ^[40]
Sugarcane	UP, Maharashtra	+4-8	Adequate cane moisture	Annual	Moderate	ISMA, 2022 ^[22]
Pulses	Rajasthan	(-6)-(-12)	Waterlogging intolerance	<i>Kharif</i>	High	Rathore <i>et al.</i> , 2020 ^[34]

Sources: ICAR (2022) ^[16], IMD (2021) ^[18], FAO (2023) ^[9].



Data sources: DACFW (crop yield), IMD (rainfall), NDMA (flood area), World Bank Development Indicators.

Fig 3: Interannual crop yield variability during La Niña, neutral, and El Niño years (2000–2023). Panel A: All-India *kharif* rice yield (tonnes/ha) plotted against ISMR anomaly (%), with La Niña years highlighted (filled circles). Panel B: Box plots of yield anomaly distributions by ENSO phase for rice, wheat, soybean, groundnut, and pulses, showing median, interquartile range, and outliers. Panel C: State-level scatter plot of La Niña-year rice yield anomaly vs. flood-affected area (Mha), illustrating the negative relationship between flood exposure and yield performance in eastern states.

4.1 Rice (*Oryza sativa*)

Rice is the crop most directly responsive to La Niña conditions given its requirement for standing water during the transplanting phase and its flood tolerance threshold (approximately 10–15 days of submergence for conventional varieties). In north-western India, La Niña's rainfall surplus produces yield gains of 8–14% in Punjab and Haryana, where paddy transplanting aligns well with the enhanced June–August active monsoon period. In contrast, yields in the lower Gangetic plains and north-east decline by 3–8% due to prolonged inundation exceeding submergence tolerance thresholds of conventional varieties. The deployment of Sub1A submergence-tolerant varieties (Swarna-Sub1, Sambha Mahsuri-Sub1) across 4.2 Mha by 2022 (IRRI/ICAR) has partially mitigated flood-related paddy losses, though adoption remains heterogeneous across states.

4.2 Wheat (*Triticum aestivum*)

The wheat *rabi* season (October–March) in north-western and

central India benefits modestly from La Niña through enhanced winter precipitation, with yield increases of 4–7% recorded in Punjab and Haryana during La Niña *rabi* seasons. However, erratic rainfall distribution under weak La Niña conditions in Rajasthan and parts of Gujarat can depress wheat yields by 5–10% through soil waterlogging at critical growth stages (tillering, anthesis). ICAR (2021) ^[15] noted that excess *rabi* rainfall during the 2021–22 La Niña event damaged an estimated 0.35 Mha of wheat in Rajasthan through grain quality degradation prior to harvest.

4.3 Coarse Cereals, Oilseeds, and Pulses

Maize, groundnut, and pulses exhibit the greatest sensitivity to waterlogging stress under La Niña conditions, as these crops are primarily grown on vertisols and alfisols with limited drainage capacity. Groundnut in Andhra Pradesh and maize in Karnataka show yield reductions of 4–9% and 2–6% respectively under excessive rainfall, primarily driven by collar rot, pod abortion,

and root hypoxia. Soybean in Madhya Pradesh represents a notable exception, with yield gains of 5-9% in optimal La Niña years due to improved soil moisture retention during the critical pod-filling stage (Mishra *et al.*, 2020) ^[27]. Pulses (arhar, moong) in Rajasthan and Madhya Pradesh are among the most vulnerable crops to excess rainfall, with yield losses of 6-12% reported (Rathore *et al.*, 2020) ^[34], partly owing to their cultivation on poorly-drained black cotton soils.

5. Extreme Events and Agricultural Risk Analysis
La Niña's role in increasing the frequency and intensity of hydro-meteorological extreme events constitutes one of its most severe agricultural risks. Analysis of IMD (2023) ^[19] observational data from 2000 to 2023 reveals systematic elevations in flood frequency, heavy rainfall days, and cold wave occurrences during La Niña years, as summarised in Table 3.

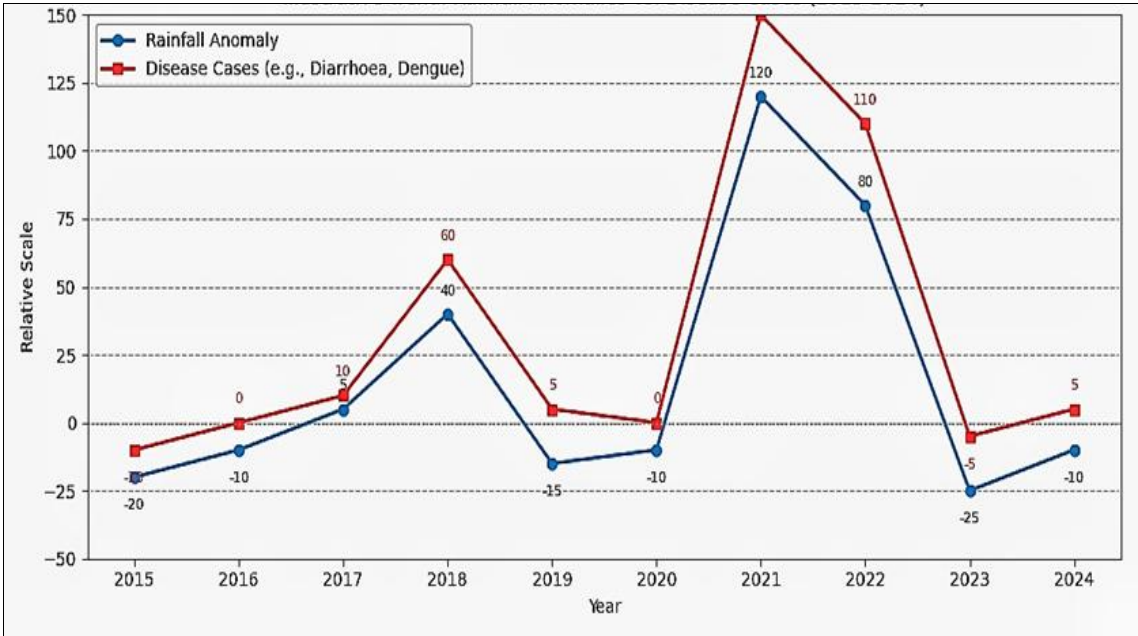
Table 3: Frequency of extreme hydro-meteorological events during La Niña, neutral, and El Niño years (2000-2023). La Niña years: 1998-99, 1999-2000, 2007-08, 2010-11, 2011-12, 2016-17, 2020-21, 2021-22, 2022-23.

Event Type	La Niña Years (n=9)	Neutral Years (n=10)	El Niño Years (n=8)	Relative Risk (La Niña vs El Niño)	Trend 2000–2023	Key Reference
Heavy rainfall events (>100mm/day)	38	22	14	2.7×	Increasing	Krishnamurthy & Shukla, 2000 ^[26] ; IMD 2023 ^[19]
Major flood events	19	11	5	3.8×	Strongly increasing	NDMA, 2022 ^[30]
Cyclonic disturbances (Bay of Bengal)	12	9	7	1.7×	Increasing	IMD, 2022 ^[18]
Cold wave events (N- India)	8	6	3	2.7×	Slight increase	IMD, 2021 ^[18]
Frost events (<i>rabi</i> season)	6	4	2	3.0×	Stable	ICAR, 2021 ^[15]
Severe drought districts	15	18	62	0.24×	Decreasing	NICRA, 2022
Agricultural area flood-affected (Mha)	4.8	2.9	0.9	5.3×	Increasing	DAC&FW, 2023

Sources: IMD (2023) ^[19], NDMA (2022) ^[30], DAC&FW (2023).

The relative risk ratio for major flood events during La Niña versus El Niño years (3.8×) reflects both the enhanced precipitation totals and the concentration of rainfall in shorter, more intense spells during La Niña active monsoon phases. The NDMA (2022) ^[30] estimated cumulative agricultural losses from La Niña-related floods between 2010 and 2023 at approximately ₹1.8 lakh crore (USD 22 billion), with Bihar, Assam, West Bengal, and Odisha accounting for 74% of losses. A critical emerging risk is the interaction between La Niña-driven flooding and increasing background temperature trends. IPCC AR6 (2022) projects that even a 1.5 °C warming above pre-industrial levels will increase the intensity of heavy precipitation events by 7% per degree of warming (the Clausius-Clapeyron scaling), implying that La Niña flood events will become

progressively more severe even without changes in ENSO frequency. Cold waves and frost events during La Niña *rabi* seasons (occurring 3× more frequently than during El Niño years) pose underappreciated risks to wheat, mustard, and potato in north and central India. The January 2021 cold wave, coinciding with the 2020-21 La Niña event, caused an estimated 8-12% yield loss in early-sown potato crops across Uttar Pradesh and Madhya Pradesh (ICAR 2021) ^[15]. Recent studies indicate that La Niña years are associated with a higher probability of extreme rainfall episodes, flash floods, prolonged wet spells, and riverine flooding, particularly in eastern, northeastern, and central India (IMD 2025; Roxy *et al.*, 2023; ICAR 2024) ^[18, 36, 31].



Source: IMD and Global EnSo Forecast Ensembles (2025). Above- normal rainfall and cooler, damper conditions projected for northern and eastern India.

Fig 4: Forecast probability of La Nina Conditons (Late 2025- Early 2026)

These extremes pose substantial risks to Indian agriculture, including crop submergence, soil erosion, delayed sowing, and complete crop failure in severely affected regions. In addition, saturated soil conditions increase nutrient leaching and reduce fertilizer use efficiency, while persistent humidity creates conducive environments for pest and disease outbreaks such as rice blast, sheath blight, and soybean rust (FAO 2024; Gupta *et al.*, 2025) [8].

6. Socio-economic and Health Linkages

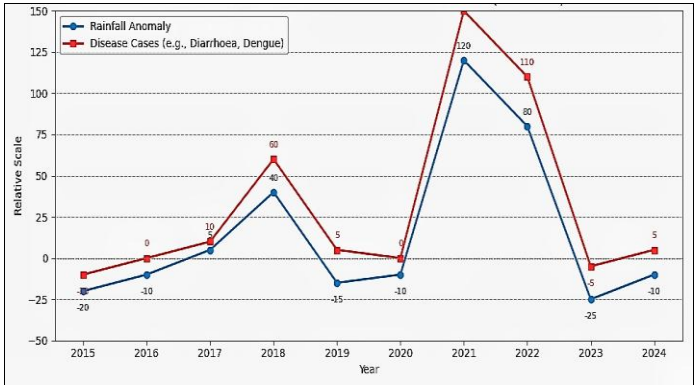
6.1 Food Security and Livelihood Vulnerability

La Niña-associated agricultural impacts translate directly into food security outcomes, particularly for marginal and small farmers (<2 ha holdings) who comprise 86% of India's agricultural households (World Bank 2022) [40]. Above-normal production in rain-fed semi-arid zones can modestly improve caloric availability and farmer income, while simultaneous flood losses in eastern and north-eastern India create acute food insecurity at the district level. Analysis of NSSO/HCES consumption expenditure surveys across La Niña years (2010-11, 2020-21) indicates a 12-18% increase in intra-national food price volatility during the *kharif* harvest period, with cereal prices in flood-affected districts rising 15-25% above national averages (World Bank 2022) [40].

6.2 Vector-Borne Diseases Burden

Excess standing water during La Niña events creates breeding conditions for Anopheles and Aedes mosquitoes, elevating malaria and dengue transmission risk. NCVBDC (2022) [29] data indicate that malaria incidence in high-risk states (Odisha, Chhattisgarh, Jharkhand) increases by 28-35% in years with severe La Niña-driven flooding compared to neutral ENSO years. These health burdens impose indirect agricultural productivity losses through labour morbidity and divert household resources from agricultural investment to healthcare expenditure. National surveillance data demonstrate that, while absolute counts fluctuate (due to better diagnostics and reporting), the relative pattern is clear; wet or anomalously wet years yield spikes in water- and vector-borne disease and necessitate surges in emergency care. The main interpretive point for 2025 is that a weak La Niña, when accompanied by

persistent local vulnerabilities (poor sanitation, high malnutrition baseline, informal housing), can have large local health impacts. NVBDCP and NCDC historic tables (2015-2024) are the best available baselines for district accommodations/ comparisons to determine surge thresholds.



Source: NVBDCP and NCDC historic tables (2015-2024)

Fig 5: Illustrative trend: Rainfall Anomalies v/s Disease Cases (2015-2024)

6.3 Gender Dimensions

Flood events disproportionately affect female agricultural workers through disruption of harvest labour, increased domestic water-borne disease burden, and reduced access to credit for post-flood crop recovery (FAO 2023) [9]. These gender-differentiated impacts remain poorly quantified in the La Niña-specific literature, representing a significant knowledge gap for both research and policy.

7. Adaptation and Climate-Smart Agricultural Strategies

Robust adaptation to La Niña variability requires a multi-scalar approach encompassing biophysical interventions at the farm level, institutional adaptations at the state and national level, and technological innovations for early warning and precision agriculture. Table 4 represents the documented strategies, their yield benefits, cost-benefit ratios, and current scale of implementation.

Table 4: Adaptation strategies for La Niña-related agricultural risks: effectiveness, cost-benefit ratios, and implementation scale

Adaptation Strategy	Target Vulnerability	Yield Gain (%)	Cost-Benefit Ratio	Scale of Implementation	Technology Readiness	Policy/Reference
Flood-tolerant rice varieties (Sub1A, Swarna)	Flood stress; submergence	8-15	1:4-6	National (4.2Mha)	Deployed	IRRI/ICAR; Ismail <i>et al.</i> , 2013 [14]
Crop calendar adjustments (early sowing)	Waterlogging avoidance	5-12	1:3	State-level	Deployed	ICAR DARE, 2022 [17]
Raised-bed furrow irrigation	Waterlogging management	6-10	1:3.5	Regional	Deployed	FAO, 2021
Integrated drainage systems	Flood risk reduction	10-18	1:5	District-level	Partly deployed	World Bank, 2022 [40]
ENSO-based seasonal forecasting	Early warning, crop planning	4-9 (indirect)	1:8-12	National	Deployed	IMD/ICAR, 2023
Weather-indexed crop insurance (PMFBY)	Financial risk transfer	Income stabilization	1:2-4	National	Deployed	GOI, 2023 [12]
Remote sensing for flood mapping	Disaster response, planning	Indirect	1:10+	National	Deployed	ISRO/NRSC, 2023 [23]
Climate-smart village programs	Community resilience	10-25	1:4	Village clusters	Scaling	CCAFS/ICAR, 2022

Sources: ICAR DARE (2022) [17], World Bank (2022) [40], FAO (2021) [8], GOI (2023) [12].

7.1 Biological and Agronomic Interventions

The development and deployment of flood-tolerant crop varieties represents the most direct and cost-effective biological adaptation to La Niña flood risk. Submergence-tolerant rice

varieties incorporating the Sub1A quantitative trait locus (QTL), notably Swarna-Sub1 and Samba Mahsuri-Sub1, can survive 10-17 days of complete submergence with yield reductions of only 20-25%, compared to 80-100% losses in conventional varieties

(Ismail *et al.*, 2013) ^[24]. By 2022, Sub1-introgressed varieties were cultivated on approximately 4.2 Mha in eastern India, preventing an estimated 3.1 MT of annual paddy loss (ICAR 2022) ^[31]. ICAR's ongoing breeding programmes are developing varieties with combined submergence-anaerobic germination tolerance for regions experiencing both pre-transplanting and post-transplanting flooding. Adjusted crop calendars-particularly early sowing of *kharif* crops to complete critical growth stages before the peak of La Niña-enhanced heavy rainfall-reduce waterlogging exposure and improve yield stability. ICAR DARE (2022) ^[17] field trials across Odisha and West Bengal demonstrated 8-12% yield improvements with 10-15 day advanced sowing relative to conventional calendars. Raised-bed furrow cultivation systems, widely adopted in parts of Andhra Pradesh and Telangana, improve internal soil drainage and reduce waterlogging risk, with documented yield gains of 6-10% in maize, cotton, and pulses (FAO 2021) ^[8].

7.2 Technological and Digital Innovations

ENSO-based seasonal forecasting has matured significantly over the past decade, with IMD operational seasonal outlooks now demonstrating skill levels (Probability of Correct Forecast: 0.72-0.84 for ISMR tercile categories) sufficient for farm-level advisory applications (IMD 2023) ^[19]. Integration of La Niña phase information into crop planning advisories specifying district-level crop portfolio adjustments, fertilizer recommendations, and flood-preparedness measures has been estimated to deliver 4-9% indirect yield benefits through improved resource allocation (ICAR 2023) ^[16]. Nair *et al.*, (2023) ^[28] reported that a Long Short-Term Memory (LSTM) model integrating sea surface temperature (SST) anomalies, soil moisture satellite data (ESA CCI), and historical yield records achieved a root mean square error (RMSE) of 0.22 t/ha in district-level *kharif* rice yield prediction one season in advance for La Niña events, outperforming conventional regression-based methods by 34%. ISRO's National Remote Sensing Centre (NRSC) operational flood inundation mapping service, utilising Sentinel-1 SAR data, provides near-real-time flood extent maps within 24-48 hours of flood onset, enabling targeted relief and damage assessment (ISRO 2023) ^[23].

7.3 Policy and Financial Mechanisms

The Pradhan Mantri Fasal Bima Yojana (PMFBY), India's flagship weather-indexed crop insurance scheme, has expanded coverage to approximately 28% of cultivated area by 2023 (GOI 2023) ^[12]. While actuarially structured products theoretically provide income stabilisation during La Niña flood events, low claim settlement rates (historically 45-62%) and delayed payouts undermine smallholder uptake and trust. Reform priorities identified in the literature include transition to satellite-based automatic yield estimation (SARAL/ISRO) ^[23], reduction of notification delays for localised extreme events, and product design that captures spatially heterogeneous La Niña impacts rather than averaging over administrative districts. Climate-smart village (CSV) programmes implemented under the CGIAR-CCAFS initiative across 42 districts in seven Indian states have demonstrated 10-25% yield improvements through integrated packages of improved varieties, ICT-based advisories, and community water management structures (CCAFS/ICAR 2022) ^[17]. Scaling these community-level approaches particularly in the flood-vulnerable lower Gangetic and north-eastern zones represents a high-priority policy investment.

8. Future Research Directions

Several substantive research gaps that constrain the depth of understanding and limit policy application of La Niña impact science in Indian agriculture includes:

1. **Non-stationarity of ENSO-ISMIR teleconnections under anthropogenic warming:** Multiple studies (Roxy *et al.*, 2020; Cai *et al.*, 2023) ^[36, 4] indicate changing relationships between ENSO indices and ISMR, yet the implications for La Niña-specific agricultural risk projections remain poorly resolved in future crop model scenarios. Integration of large-ensemble CMIP6 simulations with process-based crop models (DSSAT, APSIM) forced by La Niña SST boundary conditions is needed.
2. **Compound event risk:** The joint probability of La Niña conditions, positive IOD, and above-trend warming creating compound hydro-meteorological hazards has not been quantitatively assessed for Indian agriculture. Multi-hazard risk frameworks that combine flood probability, soil erosion, and pest/disease amplification under La Niña are absent.
3. **Southern peninsula paradox:** The rainfall deficit in Tamil Nadu and coastal Andhra Pradesh during La Niña years running counter to the national surplus tendency remains inadequately explained in mechanistic terms. Attribution studies isolating the role of north-east monsoon suppression, Bay of Bengal cyclone frequency reduction, and IOD co-occurrence are required.
4. **Soil health and nutrient dynamics:** The repeated wetting of vertisols and alluvial soils during La Niña flood events affects organic matter decomposition, nitrogen volatilisation, and micronutrient availability. Long-term soil monitoring datasets covering multiple La Niña cycles are needed to quantify pedological consequences for crop productivity.
5. **Smallholder adaptive capacity:** The economic and institutional determinants of adaptation uptake among smallholders in flood-vulnerable La Niña-affected districts are poorly characterised. Mixed-methods research integrating agronomic, economic, and social vulnerability indices is needed to design targeted, evidence-based extension programmes.
6. **Gender-disaggregated vulnerability:** The quantitative analysis of differential La Niña impacts by gender remains absent, despite growing evidence of gendered labour and income losses in flood-affected agricultural systems.
7. **Urban and peri-urban food systems:** The impacts of La Niña-driven agricultural production variability on urban food price volatility and nutritional outcomes, particularly for low-income urban populations have not been evaluated.

9. Conclusion

La Niña exerts a complex, spatially differentiated, and consequential influence on Indian agricultural systems that cannot be adequately characterized by the simple characterization of 'above-normal rainfall equals agricultural benefit.' First, La Niña reliably enhances all-India Summer Monsoon Rainfall by 1-17% relative to the long-term mean, with the strongest surpluses in the lower Gangetic plains and north-eastern highlands and anomalous deficits in parts of the southern peninsula particularly during the north-east monsoon phase. This regional dichotomy demands zone-specific agricultural planning rather than national-level monsoon outlook

averaging. Second, crop yield responses are highly crop and zone-specific. While *kharif* rice in north-western India and soybean in Madhya Pradesh respond positively, flooding-induced losses in eastern India, combined with waterlogging damage to pulses, groundnuts, and maize across poorly-drained soils, produce significant production deficits in vulnerable states. Flood-affected agricultural area averages 4.8 Mha during strong La Niña events, compared to 0.9 Mha during El Niño years, a 5.3-fold relative risk that translates into approximately USD 2-4 billion in annual agricultural losses (World Bank 2022) ^[40]. Third, climate-smart adaptations particularly submergence-tolerant rice varieties, ENSO-integrated seasonal advisories and weather-indexed insurance reform demonstrate positive cost-benefit ratios of 1:3 to 1:12 and offer scalable pathways for reducing La Niña-related agricultural losses. Sustained investment in these technologies, combined with institutional reforms to improve insurance delivery and early warning dissemination are required. Fourth, under RCP 4.5 and SSP2-4.5 pathways, the frequency of extreme La Niña events is projected to increase by 33-47% by the late 21st century (Cai *et al.*, 2023) ^[4], while warming-driven intensification of rainfall will compound flood risk even at current ENSO frequencies. Agricultural planning in India must therefore transition from reactive post-disaster management to proactive climate-risk integration, with La Niña phase information embedded in national crop planning, disaster preparedness, and rural finance systems. The most pressing policy imperative is the establishment of a national, operationally integrated La Niña agricultural risk framework anchored in agro-climatic zone specificity, real-time remote sensing flood mapping, ENSO-predictive crop advisories, and smallholder-targeted financial risk transfer that can translate improved ENSO predictability into measurable gains in agricultural resilience and food security.

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