frontiers in Climate

TYPE Original Research
PUBLISHED 11 March 2026
DOI 10.3389/fclim.2026.1768137

OPEN ACCESS

EDITED BY
Anusorn Cherdthong,
Khon Kaen University, Thailand

REVIEWED BY
Ramadas Sendhil,
Pondicherry University, India
Fehim Wani,
Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, India

*CORRESPONDENCE
Ashok Kumar Balhara
✉ balharaak@gmail.com

†These authors have contributed equally to this work and share first authorship

RECEIVED 15 December 2025
REVISED 19 February 2026
ACCEPTED 23 February 2026
PUBLISHED 11 March 2026

CITATION
Aiswarya S, Makarabbi G, Balhara S, Boora A, Phulia SK, Kumar S, Kumar S, Hooda E, Singh M and Balhara AK (2026) Household-level climate vulnerability of buffalo-rearing communities in northern and western India: a composite index approach.
Front. Clim. 8:1768137.
doi: 10.3389/fclim.2026.1768137

Household-level climate vulnerability of buffalo-rearing communities in northern and western India: a composite index approach

S. Aiswarya[1†], Gururaj Makarabbi[1†], Sunesh Balhara[2], Ashok Boora[3], S. K. Phulia[4], Sanjay Kumar[3], Sanjay Kumar[5], Ekta Hooda[2], Mala Singh[6] and Ashok Kumar Balhara[4]*

[1]Transfer of Technology Unit, ICAR-Central Institute for Research on Buffaloes, Hisar, Haryana, India, [2]Agricultural Knowledge Management Unit, ICAR-Central Institute for Research on Buffaloes, Hisar, Haryana, India, [3]Animal Genetics and Breeding Division, ICAR-Central Institute for Research on Buffaloes, Hisar, Haryana, India, [4]Animal Physiology and Reproduction Division, ICAR-Central Institute for Research on Buffaloes, Hisar, Haryana, India, [5]Department of Animal Nutrition, Bihar Animal Sciences University (BASU), Patna, Bihar, India, [6]Department of Veterinary Physiology and Biochemistry, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

Buffalo husbandry is central to the livelihoods of millions of smallholder farmers in northern and western India, providing both economic security and nutritional sustenance. Climate variability and extreme weather events, however, increasingly threaten buffalo productivity and household resilience, particularly among resource-poor farmers with limited access to veterinary and extension services. This study employed a composite index framework to assess the vulnerability of 720 buffalo-rearing households across six states Uttar Pradesh, Bihar, Rajasthan, Gujarat, Punjab, and Haryana by integrating indicators of exposure, sensitivity, and adaptive capacity. The Buffalo rearing Households Vulnerability Index (B-HVI) was constructed using 41 indicators classified under these three dimensions, with Shannon's entropy-based objective weighting. Results revealed substantial inter- and intra-state disparities. Haryana (B-HVI = 0.595) and Punjab (B-HVI = 0.488), characterized by high adaptive capacity (AC = 0.886 and AC = 0.745, respectively), structured extension support, and strong market linkages, exhibited the lowest vulnerability. Conversely, Bihar (B-HVI = 0.801) and Rajasthan (B-HVI = 0.799) showed the highest vulnerability due to low adaptive capacity (ACI = 0.208 and ACI = 0.618, respectively) and high sensitivity (SI = 0.789 and SI = 0.657). One-way ANOVA confirmed significant differences in mean B-HVI across states ($F = 30.08$, $p < 0.001$), and Tukey's *post-hoc* test delineated two distinct groups: Haryana and Punjab with relatively lower vulnerability, versus Bihar, Rajasthan, Gujarat, and Uttar Pradesh with substantially higher vulnerability. Strengthening adaptive capacity through improved veterinary services, extension networks, and resource access is critical for reducing vulnerability in Bihar and Rajasthan, while consolidating resilience in Haryana and Punjab. The study highlights the urgency of state-specific, climate-resilient strategies to safeguard buffalo husbandry and rural livelihoods.

KEYWORDS
adaptive capacity, buffalo, climate vulnerability, exposure, sensitivity

Introduction

Buffalo husbandry is integral to India's livestock economy and rural livelihoods, with approximately 109.85 million buffaloes representing 56.8% of the world's population (Department of Fisheries, Animal Husbandry and Dairying (DAHD), 2024; 20th Livestock Census Report, 2019). These animals contribute more than 100 million tonnes of milk annually, accounting for roughly 45% of the national milk output—amounting to an estimated economic value of US $17.0 billion, and approximately 7–8 per cent of agricultural GDP. Beyond high milk yield and butterfat, Indian buffaloes exhibit remarkable resilience to thermal stress, stronger immunity to endemic parasitic infections, and comparative tolerance to hemoprotozoan diseases (Muner et al., 2025). Despite their central economic and biological importance, buffalo production systems remain underrepresented in climate vulnerability research compared to cattle-dominated systems, particularly in empirical household-level analyses.

India recognizes 21 buffalo breeds distributed across zones: Northern (Murrah, Nili-Ravi, Gojri), Western (Jaffarabadi, Mehsana, Surti, Banni), Central (Bhadawari, Chhattisgarhi, Nagpuri, Marathwadi, Pandharpuri), Eastern (Chilika, Kalahandi, Manda, Luit & Manah), and Southern [Toda, Bargur, Dharwadi; Makarabbi et al., 2025; National Bureau of Animal Genetic Resources (NBAGR), 2025]. This diversity reflects buffalo's adaptive variation across climates and systems. Among these, the Murrah breed, predominantly reared in Haryana and Punjab, is widely valued for productivity, fat content, and adaptability across environments, making it a primary dairy livestock for small holders and organized farms alike (Tyagi, 2018). However, systematic evidence on how breed-specific management interacts with climatic stressors at the household level remains fragmented and poorly quantified. Buffalo husbandry in India is predominantly a smallholder enterprise, with more than 70 million households engaged, and women performing the majority (~ 85%) of dairy activities (Lowder et al., 2025; Vijayalakshmy et al., 2023), indicating strong links to women's empowerment, nutrition, and inclusive livelihoods in line with SDG 1 (No Poverty), SDG 2 (Zero Hunger), and SDG 5 (Gender Equality; Aiswarya et al., 2025). Yet, women's central role in routine buffalo management is rarely incorporated into vulnerability metrics, resulting in limited understanding of gender-differentiated exposure, sensitivity, and adaptive responses.

Despite high importance, buffalo-rearing households remain highly vulnerable to climate variability and change (Ape et al., 2025). Of various factors, heat waves, erratic rainfall, and drought, which reduce feed and water availability, depress milk yield and elevate disease risks and input costs (Savsani et al., 2015). Thermal stress reduces feed intake, disrupts reproductive cycles, and increases susceptibility to metabolic disorders, while erratic rainfall and extreme events exacerbate fodder scarcity, water shortages, and exposure to infectious diseases (Shekhar et al., 2025). Resource-poor households, particularly those in semi-arid and flood-prone regions, are disproportionately affected due to limited adaptive capacity, poor access to veterinary services, insufficient market linkages, and low financial resilience (Kropff et al., 2023). These interacting stressors highlights the need for an integrated framework that captures biological, climatic, and socio-economic dimensions simultaneously, rather than in isolation.

Previous vulnerability assessments in livestock often emphasize macro trends, regional climate projections, or single species-specific production metrics (Behere et al., 2025; Singh et al., 2025; Blasiak et al., 2017; Maiti et al., 2014) with limited micro level quantification of household exposure, sensitivity, and adaptive capacity in integrated buffalo production systems. Composite vulnerability frameworks such as those proposed by Hahn et al. (2009), Deressa et al. (2009), and Brooks et al. (2005) have demonstrated the analytical strength of integrating multidimensional indicators into index-based approaches, and recent empirical applications have extended such frameworks to agriculture and livestock systems using entropy-based or weighted aggregation techniques. However, much of this work remains concentrated on crop systems or cattle-dominated contexts, with relatively limited application to buffalo-based production systems, particularly at the household scale. Few studies have integrated veterinary access, feeding practices, climate-adaptive management, and household socio-economic factors into comprehensive vulnerability assessments, limiting ability to design targeted interventions (Maiti et al., 2014; Blasiak et al., 2017; Behere et al., 2025; Singh et al., 2025). Moreover, prior studies have rarely incorporated experimentally validated animal-level health indicators such as hematological and biochemical parameters within composite vulnerability indices, thereby overlooking physiological dimensions of sensitivity that are critical under climate stress. These limitations in the literature directly inform the present research questions, which seek to (i) operationalize a multidimensional composite vulnerability index tailored to buffalo-rearing households, and (ii) examine how inter- and intra-state variations in socio-economic, institutional, and animal-level factors shape climate vulnerability across contrasting agro-climatic regions. This reveals a critical research gap in translating climate risk into actionable, household-scale evidence for buffalo-based systems across contrasting agro-climatic regions. Addressing these gaps, the present study applies a household-level composite index for climate vulnerability of buffalo-rearing households in northern and western India, integrating exposure (climatic stressors such as temperature extremes, drought, and rainfall variability), sensitivity (herd health, milk yield, reproductive efficiency), and adaptive capacity (physical, human, financial, social and natural capitals), to reveal regional disparities and intervention entry points. By combining environmental, biological, and socio-economic dimensions into a single framework, the design enables identification of most-at-risk households and prioritization of adaptation pathways suited to local production ecologies. This integrated approach represents a methodological advancement over existing studies by operationalizing vulnerability at the household scale using empirically observed animal-level and institutional indicators and by employing an objective entropy-based weighting procedure to minimize subjectivity in composite index construction. The present study has two aims: build a composite index to measure climate vulnerability of buffalo-keeping households in selected northern and western Indian states, and compare vulnerability within and across states using socio-economic, institutional, and animal level factors. It tests two hypotheses: inter-state differences are significant (H_1), and intra-state differences are significant and driven by these factors (H_2). Using household data and veterinary indicators, it maps vulnerability patterns and points to risks and practical adaptation options for policy and programs, especially for resource -poor households, with benefits for food security, livelihoods, and climate -resilient livestock management. The specific objectives of the present study are:

(i) to construct a household-level composite index to quantify climate vulnerability of buffalo-keeping households.

(ii) to examine inter-state differences in climate vulnerability among buffalo-rearing households across selected northern and western Indian states;

The study's contribution lies in generating policy-relevant evidence to support region-specific, gender-responsive, and climate-adaptive interventions for strengthening resilience in buffalo-based livelihoods.

Materials and methods

Locale of study

The study was conducted during 2018–2021 across six major buffalo-rearing states of India, namely Uttar Pradesh, Bihar, Rajasthan, Gujarat, Punjab, and Haryana, capturing diverse agro-ecological settings and buffalo genetic resources (Figure 1). In Uttar Pradesh, the villages named Chhabriya, Chandna, and Jhitkari in Sardna Tehsil of Meerut District were selected; these lie in the fertile Upper Gangetic Plains characterized by alluvial soils, intensive agriculture, and a subtropical climate with hot summers, monsoon rainfall, and cool winters, where Murrah and Bhadawari buffaloes are predominantly reared (Lata, 2019). In Bihar, the study villages named Dhatraul, Roh, and Budhauli of Nawada District represent the eastern Indo-Gangetic Plains with a humid subtropical monsoon climate, recurrent flooding, and resource-constrained farming systems, where Murrah, Bhadawari and non-descript buffaloes serve as vital sources of both milk and draft power (Pant et al., 2024). The Rajasthan sites, villages namely Kherad, Bhainson ka Namla, and Tulsiyon ka Namla in Chatpur Tehsil of Udaipur District—fall within the semi-arid tract characterized by undulating terrain, erratic rainfall, and feed scarcity, where Murrah, Mehsana and local non-descript buffaloes are reared for their resilience and adaptability (Williams, 2015). In Gujarat, the villages named Erandawali, Bhirdiyara, Sethwad, and Hodka of Kutch District represent the arid and drought-prone breeding tract of the Banni buffalo, which thrives under extensive grazing, night feeding, and extreme temperatures, sustaining pastoral livelihoods in a water-scarce environment (Kaliravana and Rao, 2024). The Punjab study area, comprising the villages named Jhall and Saluwal of Nabha Tehsil in Patiala District, is located in the agriculturally advanced north-western plains with fertile soils, assured irrigation, and a semi-arid to sub-humid climate, where commercial dairy farming is dominated by the high-yielding Nili Ravi and Murrah breeds (Singh and Singh, 2025). In Haryana, the selected villages named Kharar Alipur, Khoka, Kharkari, and Nayana of Hisar District represent the native breeding tract of the Murrah buffalo, often termed the "black gold" of India for its global reputation in dairy productivity where buffalo husbandry is deeply embedded in both the rural economy and cultural fabric under a semi-arid climate with extreme seasonal variations (Manjunath, 2023). Collectively, the six study states span production environments from humid plains to arid deserts and encompass key genetic resources—Murrah, Bhadawari, Mehsana, Banni, and non-descript types providing a comprehensive basis to examine household- level vulnerabilities and adaptive capacities under climatic and socio-economic stressors.

Sampling

A multi-stage random sampling strategy was implemented to obtain a representative household sample across major buffalo-rearing belts in northern and western India. In the primary stage, six states namely Uttar Pradesh, Bihar, Rajasthan, Gujarat, Punjab, and Haryana were purposively selected because they together account for a substantial proportion of India's buffalo population and represent the country's most important buffalo production regions. The buffalo population (in million) across the selected states is as follows: Uttar Pradesh (11.07 million), Rajasthan (4.43 million), Bihar (2.95 million), Gujarat (2.63 million), Haryana (1.42 million), and Punjab (1.16 million), as reported in the 20th Livestock Census [Department of Animal Husbandry and Dairying (DAHD), 2019]. Uttar Pradesh and Bihar contribute the largest buffalo populations in in northern and eastern India respectively, dominated by non-descript and riverine buffaloes under smallholder systems, while Punjab and Haryana are the native tract of the Murrah and Nili-Ravi breeds, characterized by high-input, high-productivity dairy systems. Rajasthan represents arid and semi-arid production ecologies with breeds such as Bhadawari and non-descript buffaloes adapted to heat and water stress, whereas Gujarat represents western production systems with Bunni, Jaffarabadi, Mehsana, and Surti breeds, known for adaptability to diverse climatic and management conditions. The selection of these states thus ensured representation of major indigenous buffalo breeds, contrasting production systems, and wide agro-climatic gradients relevant to climate vulnerability assessment. In the secondary stage, one district was randomly selected within each state from districts with significant buffalo populations to ensure adequate representation of buffalo-rearing households while minimizing location-specific bias. In the tertiary stage, villages were randomly drawn from each selected district to capture intra-district heterogeneity in ecological conditions and production practices. In the ultimate stage, households were randomly selected within each village based on predefined inclusion criteria to ensure that all respondents were active buffalo rearers rather than general livestock-owning farmers. Only households maintaining a minimum herd size of three buffaloes and possessing at least 10 years of continuous experience in buffalo rearing were included in the sample, thereby ensuring adequate exposure to climatic variability and sufficient engagement in buffalo-based livelihood activities. A uniform sample size of 120 households per state was adopted, resulting in a total sample of 720 households ($n = 720$). Equal allocation was deliberately chosen to ensure balanced representation and comparable statistical power across states for constructing composite vulnerability indices and testing inter- and intra-state differences.

Data collection

Primary data were collected to operationalize the three Intergovernmental Panel on Climate Change (IPCC) vulnerability pillars *viz.* exposure, sensitivity, and adaptive capacity at the household level. Animal blood samples were collected during field visits and health camps to derive hemato-biochemical profiles, enabling direct measurement of physiological sensitivity to climatic stressors. A structured interview schedule was developed and pre-tested with 23 respondents in a non-sampling area, and then refined for clarity, relevance, and contextual appropriateness before administration. The schedule captured household demographics, socio-economic

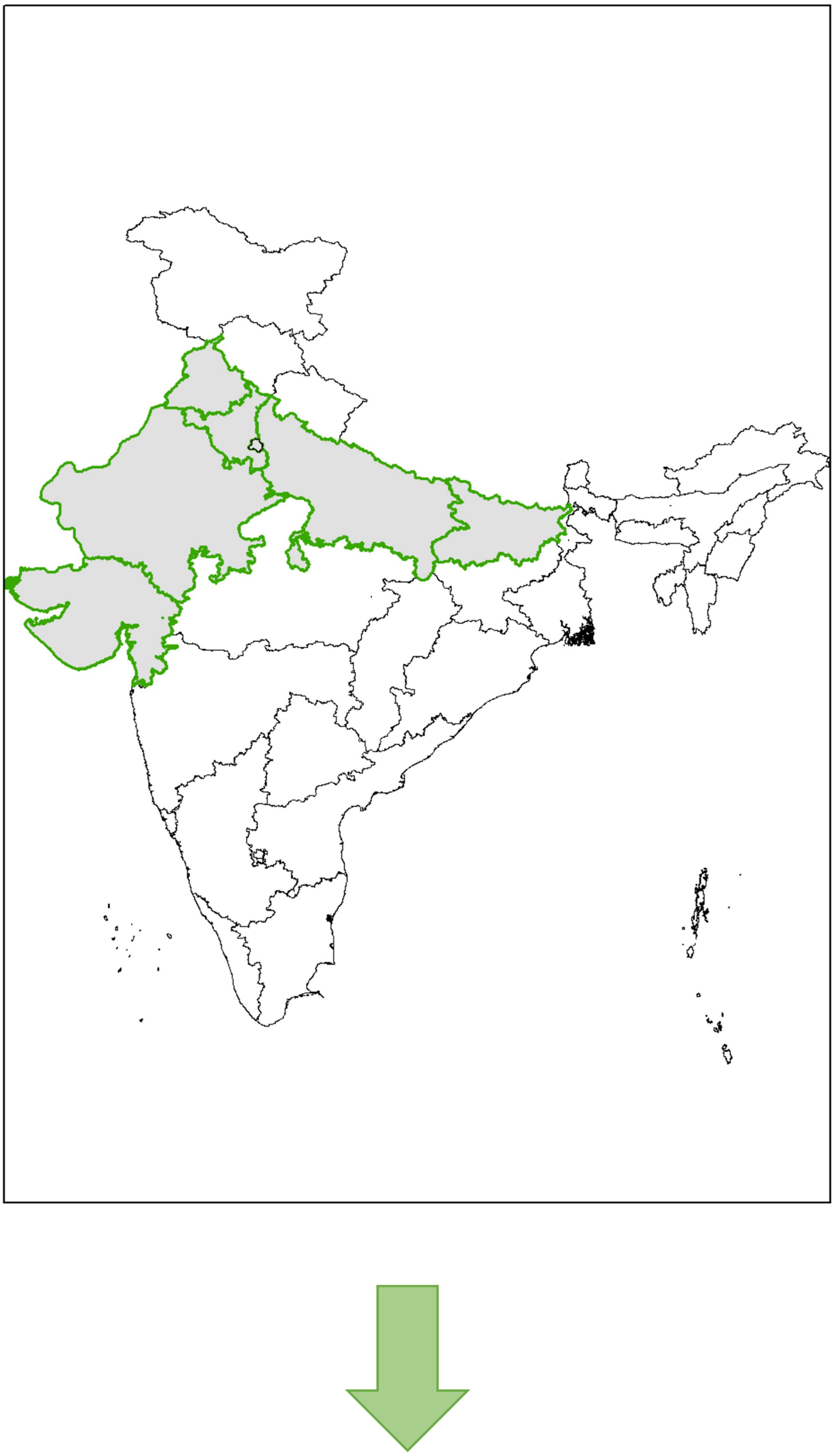

FIGURE 1 (Continued)

attributes, veterinary and extension access, management practices, and indicators related to adaptive capacity, exposure perceptions, and sensitivity. Data collection modalities included household surveys, animal health check-up camps, focus group discussions, and door-to-door blood sampling, ensuring triangulation across self-reports, clinical examinations, and experimental measurements.

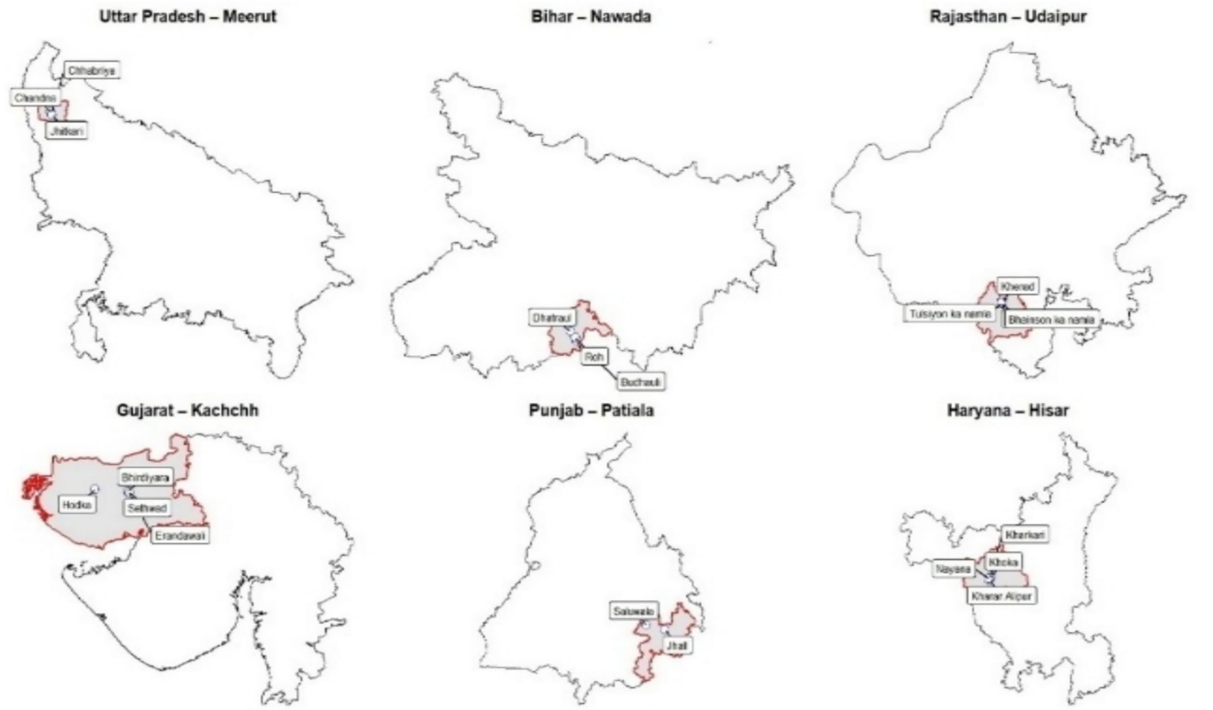

FIGURE 1
Locale of study.

Data analysis

Selection of indicators and development of buffalo household vulnerability index (B-HVI)

Household-level climate change vulnerability among buffalo-rearing households was quantified through the development of a composite, weighted index grounded in the IPCC vulnerability framework (Solomon et al., 2007), wherein vulnerability is conceptualized as a function of exposure, sensitivity, and adaptive capacity. A total of 41 indicators were selected based on an extensive review of IPCC guidelines, climate vulnerability literature, and buffalo production system–specific empirical studies. These indicators were carefully chosen to ensure contextual relevance, measurability, theoretical justification, and representation of socio-economic, institutional, climatic, and animal health dimensions affecting buffalo-rearing households (Table 1). The selected indicators were organized into three major dimensions. The Adaptive Capacity Index (ACI) comprised 20 indicators, capturing five livelihood capital domains viz. Human, Social, Physical, Natural, and Financial capital. The Exposure Index (EI) included 6 climatological stress indicators, reflecting household-reported climatic experiences and location-specific temperature and precipitation extremes. The Sensitivity Index (SI) consisted of 15 animal health and production indicators, grounded in experimental records, reproductive performance measures, disease prevalence, feeding adequacy, and physiological health parameters. Based on these dimensions, a composite index termed the Buffalo Household Vulnerability Index (B-HVI) was developed to quantify household-level vulnerability specific to buffalo-based production systems.

Normalization of indicators

For weighting and normalization, both subjective and objective approaches are widely documented in the literature, and their selection can substantially influence composite index outcomes (OECD, 2008; Nardo et al., 2005). Normalization is particularly critical when indicators differ in scale, measurement units, and direction of influence, as inappropriate transformation may distort inter-indicator comparability and aggregation results (OECD, 2008; Mazziotta and Pareto, 2016). Range (min–max) normalization is commonly applied in vulnerability and sustainability index construction due to its interpretability and preservation of relative dispersion, although it may be sensitive to extreme values (Nardo et al., 2005).

Entropy-based objective weighting

With respect to weighting, subjective approaches such as the Analytic Hierarchy Process (AHP) incorporate expert judgment and facilitate structured multi-criteria decision-making (Saaty, 1982; Saaty, 2008). However, AHP may introduce normative bias and inconsistency depending on expert perception and pairwise comparison reliability (Ishizaka and Labib, 2009). Statistical approaches such as Principal Component Analysis (PCA) generate data-driven weights based on variance structure and correlation patterns, and are advantageous for dimensionality reduction and minimizing arbitrariness (Jolliffe, 2025; Filmer and Pritchett, 2001). Nevertheless, PCA-derived weights may be unstable across datasets, sensitive to multicollinearity, and difficult to interpret in policy-oriented vulnerability assessments (Saltelli, 2007). In the present study, the Shannon Entropy method was adopted as an objective weighting technique because it assigns weights based on the inherent information divergence of indicators, thereby reducing

TABLE 1 Indicators, operational definitions, and measurement methods adopted for assessing buffalo-rearing household vulnerability to climate change.

Dimension	Indicator	Operational definition	Measurement / Unit	Justification with key references	Relationship with vulnerability
Adaptive capacity (ACI)	Family Education Status	Educational attainment of household members contributing to adoption of climate-resilient practices	Sum of household members' education divided by household size	Education enhances awareness, information access, and adoption of climate-resilient practices (Deressa et al., 2009; Below et al., 2012)	–
	Dependency Ratio	Ratio of dependents to working-age household members	Ratio (dependents / working-age members)	Higher dependency increases economic pressure and reduces investment capacity for adaptation (Hahn et al., 2009; Brooks et al., 2005).	+
	Trainings in 5 years	Exposure to formal livestock training	Number of trainings attended by household members (head or any member)	Training improves adaptive skills and uptake of climate-resilient technologies (Thornton et al., 2018).	–
	Experience in Buffalo Rearing	Experience of household in buffalo rearing in years	Years	Experience improves coping strategies and risk perception under climate stress (Nhemachena and Hassan, 2007).	–
	Age of Household Head	Chronological age of household head in years	Years	Age may increase experience but reduce flexibility in adopting new technologies (Deressa et al., 2009)	+
	Level of Community Participation	Participation in community decision-making processes	Ordinal scale 1–5; 5 = more active and 1 = no participation	Social capital enhances collective action and climate resilience (Adger, 2003).	–
	Level of Conflict	Household/community-level conflict perception	Ordinal scale 1–5; 5 = more conflict and 1 = no conflict	Conflict erodes social capital and weakens adaptive capacity (Adger and Hodbod, 2014).	+
	Level of Extension Contact	Contact with formal extension agencies	Frequency of interaction with agencies (Veterinary Officer, KVK); Ordinal scale 1–5; 5 = Very high interaction and 1 = no contact	Extension services improve access to veterinary care and climate advisories (Ragasa et al., 2016).	–
	Climate-induced Migration	Migration of household members due to climate-related stress	Ordinal scale 1–5; 5 = Very high and 1 = no contact scale	Climate-induced migration reflects livelihood stress and reduced adaptive capacity (Black et al., 2011).	+
	Farmer-to-Farmer Extension	Peer-to-peer knowledge transfer	Ordinal scale 1–5 scale; higher = more frequent knowledge exchange; 5 = Very high interaction and 1 = no contact	Informal networks facilitate diffusion of locally adapted practices (Bandiera and Rasul, 2006).	–
	Modern Equipments	Modern tools/equipment for livestock production	Count of equipment possessed by household	Equipment improves efficiency and buffers climatic stress (Herrero et al., 2015).	–
	Animal Sheds Ratio	Adequacy of housing for livestock	Ratio of animals to shed capacity	Inadequate housing increases heat stress and disease exposure (Aggarwal and Upadhyay, 2012a).	+
	Climate Resilient Technology Adoption	Adoption of cost-saving climate-resilient technologies	Count of technologies adopted	Adoption reduces sensitivity to heat and water stress (Thornton et al., 2018).	–

(Continued)

TABLE 1 (Continued)

Dimension	Indicator	Operational definition	Measurement / Unit	Justification with key references	Relationship with vulnerability
	Livestock Water Facility	Availability of water for animals	Ordinal scale 1–5 1; 5 = Water fully available and 1 = severe shortage	Water access is critical for thermoregulation and productivity (Nardone et al., 2010).	–
	Geographical Location	Suitability of farm location for livestock	Ordinal Scale 1–5; 5 = Highly suitable and 1 = Highly unsuitable	Favorable location reduces climate vulnerability (Heltberg and Bonch-Osmolovskiy, 2011)	–
	Farm Ownership	Ownership of livestock farm	Area in ha	Ownership improves investment security and long-term adaptation (Brooks et al., 2005).	–
	Herd Productivity Ratio	Productivity of livestock herd	Ratio of milk yield / benchmark yield	Higher productivity provides financial buffers against climate shocks (Hahn et al., 2009).	–
	Formal Credit Ratio	Proportion of credit accessed from formal sources	Ratio	Formal credit supports adaptive investments and risk management (Deressa et al., 2009).	–
	Value Addition Intensity	Extent of value addition to farm products	Ratio	Value addition diversifies income and reduces vulnerability (Birthal et al., 2014).	–
	Livestock Insurance Coverage	Coverage of animals under insurance	% of herd insured	Insurance mitigates financial losses from climate-induced mortality (Binswanger-Mkhize, 2012).	–
Exposure (EI)	Days >40 °C	Frequency of extreme hot days in a year	Number of days exceeding 40 °C (plains) / 30 °C (hills)	High temperatures increase heat stress and productivity loss (Nardone et al., 2010).	+
	Warm Nights	Nights with high minimum temperatures in a year	Number of nights where min temp ≥ threshold and temp departure ≥5°C	Warm nights prevent recovery from heat stress (Legg, 2021).	+
	Days <10 °C	Frequency of extreme cold days in a year	Number of days per year with min temp <10 °C	Cold stress affects immunity and metabolism (Sejian et al., 2015).	+
	Heat Waves / Cold Spells	Extreme temperature events in a year	Number of events per year	Frequency of extremes captures climate variability (Perkins et al., 2012).	+
	Extreme Climatic Events	Occurrence of floods, storms, hail, heavy rains in a year	Number of events per year	Extreme events cause sudden livestock and asset losses (IPCC, 2014).	+
	Annual Precipitation (mm)	Rainfall received per year	mm per year	Excess rainfall elevates livestock vulnerability (Thornton et al., 2007)	+

(Continued)

TABLE 1 (Continued)

Dimension	Indicator	Operational definition	Measurement / Unit	Justification with key references	Relationship with vulnerability
Sensitivity (SI)	Digestible Ration Component	Proportion of digestible nutrients in feed	% of total ration (feed + fodder)	Higher digestibility reduces climate vulnerability (Moyo and Nsahlai, 2021)	–
	Ration Balancing	Adequacy of diet for animal nutrition	Ordinal Scale 1–5 5 = Highly adequate and 1 = Highly inadequate	Balanced rations reduce metabolic stress under heat load (Aggarwal and Upadhyay, 2012b).	–
	Mineral Deficiency	Degree of mineral deficiency in ration	Ordinal Scale 1–5; 5 = Highly adequate and 1 = Highly inadequate	Mineral imbalance increases disease and reproductive failure (Sejian et al., 2015).	+
	Soil Quality	Soil fertility for fodder / grazing	Ordinal Scale 1–5; 5 = Highly suitable and 1 = Highly suitable	Soil quality affects fodder availability and animal nutrition (Thornton et al., 2018).	–
	Blood Hematology Score	Health status based on hematology	Ordinal Scale 1–5; 5 = Highly adequate and 1 = Highly inadequate	Reflects immune competence and stress response (Sejian et al., 2015).	–
	Blood Biochemistry Score	Health status based on biochemistry	Ordinal Scale 1–5; 5 = Highly adequate and 1 = Highly inadequate	Indicates metabolic stress and disease susceptibility (Nardone et al., 2010).	–
	Age at First Calving	Age of primiparous animals at first calving	Months	Delayed AFC indicates poor reproductive efficiency (Hansen, 2004).	+
	Return to Estrus	Days between calving and resumption of estrus	Days	Longer intervals reflect stress and reduced reproductive performance (Sejian et al., 2015).	+
	Milk Persistency	Consistency of milk yield during lactation	Ordinal Scale 1–5; 5 = Highly persistent and 1 = Not at all persistent	Higher persistency buffers income shocks under climate stress (Thornton et al., 2014).	–
	Calving Interval	Interval between successive calvings	Months	Longer intervals reduce lifetime productivity (Hansen, 2004).	+
	Mastitis Prevalence	% of animals affected by mastitis	% of herd	Mastitis increases under heat stress and poor hygiene (Nardone et al., 2010).	+
	FMD & HS Prevalence	% of animals affected by FMD / HS	% of herd	Disease outbreaks increase sensitivity under climatic stress (IPCC, 2014).	+
	Parasitic Infestation	% of animals affected by parasites	% of herd	Climate variability increases parasite burden (Thornton et al., 2018).	+
	Milk Fever Prevalence	% of animals affected by milk fever	% of herd	Metabolic disorders increase vulnerability under stress (Upadhyay et al., 2009).	+
	Pest/Fly Control	Measures to reduce pest/fly attack	Ordinal Scale 1–5; 5 = Excellent measures and 1 = No measures	Effective control reduces disease transmission and stress (Sejian et al., 2015).	–

TABLE 2 Socio-economic characteristic of the household.

State	Standard animal units			Average household size (No.)	Average education of HH head (Years)	% households accessing formal credit	% households with extension contact
	Milch buffaloes	Heifer	Calves				
Haryana	6.89	1.11	0.45	5.2	10.8	72	78
Punjab	6.35	1.03	0.45	5	11.2	75	82
Uttar Pradesh	4.59	0.95	0.41	6.1	8.1	46	51
Gujarat	5.12	0.62	0.42	5.6	8.9	58	60
Rajasthan	4.76	0.62	0.38	6.4	7.2	42	47
Bihar	2.58	0.69	0.23	6.8	5.4	29	33

subjectivity while retaining indicator-specific discriminatory power (Shannon, 1948; Trivedi and Dubey, 2025). Entropy weighting is particularly suitable in multi-attribute decision-making contexts where experimental or preference-based weighting is not feasible and where the objective is to allow the data structure itself to determine relative importance. The steps followed to obtain objective weights of the indicators were as follows:

(i) The raw data were first normalized to eliminate the bias of measurement units and scales. A normalized decision matrix was thus obtained:

$$\gamma_{ij} = \frac{x_{ij}}{\sum_{j=1}^{m} x_{ij}}$$

where, i = 1, 2, 3,... n.

(ii) Entropy (h_i) was calculated as:

$$h_i = -h_0 \sum_{j=1}^{m} \gamma_{ij} \ln \gamma_{ij}$$

where h_o is the entropy constant and is equal to $(\ln m)^{-1}$ and γ_{ij}. ln γ_{ij} is defined as 0 if $\gamma_{ij} = 0$.

(iii) The degree of diversification (d_i) was then computed as:

$$d_i = 1 - h_i$$

(iv) Finally, the objective weights (w_i) were derived as:

$$w_i = \frac{d_i}{\sum_{i=1}^{n} d_i}$$

(v) The final index values were obtained by multiplying the range-normalized values with the corresponding entropy-derived weights:

$$f_i = y_i w_i$$

where: $i = 1, 2, \ldots, n$ denotes indicators,
$j = 1, 2, \ldots, m$ denotes households,
γ_{ij} is the proportion of the ith indicator for the jth household in the normalized decision matrix,
m is the total number of households,
$h_0 = (\ln m)^{-1}$ is the entropy constant,
h_i is the entropy value of indicator i,
d_i is the degree of diversification, and.
w_i is the entropy-derived weight of indicator i.

TABLE 3 Entropy-derived weights of adaptive capacity indicators for buffalo-rearing households.

Indicator	Weight
Family education status	0.05342
Trainings in 5 years	0.06218
Experience in buffalo rearing	0.04785
Age of household head	0.04126
Community participation	0.05639
Conflict	0.05277
Extension contact	0.06371
Farmer-to-farmer extension	0.05192
Formal credit ratio	0.04826
Value addition intensity	0.04351
Livestock insurance coverage	0.04688
Modern equipment	0.04567
Animal sheds ratio	0.04493
Climate resilient tech adoption	0.06084
Livestock water facility	0.05912
Geographical location	0.04975
Farm ownership	0.03724
Herd productivity ratio	0.06648
Climate-induced migration	0.04656

TABLE 4 Entropy-derived weights of exposure indicators for buffalo-rearing households.

Indicator	Weight
Days > 40 °C	0.19842
Heat waves / cold spells	0.18265
Extreme climatic events	0.16853
Warm nights	0.16027
Annual precipitation (mm)	0.14936
Days < 10 °C	0.14077

TABLE 5 Entropy-derived weights of sensitivity indicators for buffalo-rearing households.

Indicator	Weight
Digestible ration component	0.07984
Ration balancing	0.07162
Mineral deficiency	0.06725
Soil quality	0.05731
Blood hematology score	0.05982
Blood biochemistry score	0.06047
Age at first calving	0.06538
Return to estrus	0.06273
Milk persistency	0.07011
Calving interval	0.06345
Mastitis prevalence	0.09042
FMD & HS prevalence	0.09218
Parasitic infestation	0.08674
Milk fever prevalence	0.08591
Pest/fly control	0.07778

TABLE 6 Entropy-derived weights of vulnerability dimensions for buffalo-rearing households.

Parameter	Weight
Adaptive capacity	0.52846
Exposure	0.31182
Sensitivity	0.15972

Construction of sub-indices and composite B-HVI

The weighted indicators were aggregated to construct sub-indices, which were further combined into the Adaptive Capacity Index (ACI), Exposure Index (EI), and Sensitivity Index (SI). The overall Vulnerability Index (B-HVI) for buffalo-rearing households was then derived using the IPCC formula:

$$VI = \left(Exposure + Sensitivity \right) - Adaptive\ Capacity$$

Classification of vulnerability levels

The computed B-HVI values were stratified using the cumulative cube root frequency method (Dalenius and Hodges, 1957) to classify households into three *categories* i.e., *low*, medium, and high vulnerability. This approach was selected because it provides a statistically balanced and distribution-sensitive classification, particularly suitable for moderately skewed composite index data. Unlike arbitrary percentile cut-offs or equal-interval classification, the cube root frequency method reduces the influence of extreme values and ensures more stable group differentiation in vulnerability studies (Hahn et al., 2009).

Statistical analysis

A one-way Analysis of Variance (ANOVA) was employed to examine differences in mean Vulnerability Index (B-HVI) scores across states. Prior to analysis, the assumptions of normality and homogeneity of variance were assessed using Shapiro–Wilk tests, Q–Q plot diagnostics, and Levene's test, respectively. Upon satisfying these assumptions, ANOVA was deemed appropriate for comparing group means. Tukey's Honest Significant Difference (HSD) *post-hoc* test was subsequently conducted to identify pairwise differences while controlling for Type I error under multiple comparisons. All data were coded and analyzed using MS Excel and the statistical software R (version 4.5.1; Posit team, 2025).

Results

The socio-economic profile of the buffalo-rearing households (Table 2) marked inter-state variation. Households in Haryana and Punjab exhibited relatively larger buffalo holdings in standard animal units, with higher numbers of milch buffaloes, heifers, and calves, coupled with smaller household sizes and substantially higher human capital indicators. These states recorded the highest average years of education of household heads and the greatest access to formal credit and extension services, reflecting stronger institutional integration and commercial orientation of buffalo production systems. In contrast, Bihar showed the lowest standard animal units across all categories, larger household sizes, limited educational attainment, and the weakest access to formal credit and extension support, indicating predominantly subsistence-oriented buffalo rearing with constrained adaptive capacity. Uttar Pradesh, Gujarat, and Rajasthan occupied an intermediate position, characterized by moderate herd sizes, household size, and educational levels, along with partial access to institutional services. Overall, the observed gradients in herd composition, education, and institutional access underscore substantial disparities in socio-economic endowments across states, with important implications for differential adaptive capacity and climate vulnerability among buffalo-rearing households.

Entropy weights of indicators and indices

The vulnerability of buffalo-rearing households was quantified using a composite Buffalo Households Vulnerability Index (B-HVI), constructed from three dimensions: adaptive capacity, exposure, and sensitivity. The relative importance of indicators within each dimension was determined using the entropy weighting method to ensure an objective measure of contribution to household vulnerability.

Within the adaptive capacity dimension (Table 3), indicators reflecting herd productivity, knowledge, and engagement in extension activities emerged as the most influential. Specifically, Herd Productivity Ratio (0.066), Extension Contact (0.064), and Trainings in the past 5 years (0.062) had the highest weights. Other notable indicators included Community Participation (0.056), Family Education Status (0.053), and Conflict (0.053), whereas Farm Ownership (0.037) and Age of Household Head (0.041) contributed relatively less. These findings highlight the central role of livestock performance, technical knowledge, and community engagement in determining adaptive capacity among buffalo-rearing households.

For the exposure dimension (Table 4), climatic extremes represented the dominant threat. Days exceeding 40 °C (0.198), Heat Waves/Cold Spells (0.183), and Extreme Climatic Events (0.169) contributed the most, followed by Warm Nights (0.160). Annual

TABLE 7 State-wise adaptive capacity, exposure, sensitivity, and composite vulnerability index of buffalo-rearing households ($n = 720$).

State	ACI	Rank	EI	Rank	SI	Rank	B-HVI	Rank
Haryana	0.886	I	0.734	III	0.298	V	0.595	V
Punjab	0.745	II	0.652	IV	0.312	IV	0.488	VI
Rajasthan	0.618	III	0.801	II	0.657	II	0.799	II
Gujarat	0.532	IV	0.886	I	0.286	VI	0.722	III
UP	0.431	V	0.594	V	0.733	III	0.658	IV
Bihar	0.208	VI	0.194	VI	0.789	I	0.801	I
Pooled sample	0.52	—	0.593	—	0.345	—	0.690	—

Precipitation (0.149) and Days below 10 °C (0.141) had comparatively lower contributions. These results indicate that high-temperature events are the most critical drivers of environmental exposure affecting buffalo-rearing households.

Within the sensitivity dimension (Table 5), animal health and nutritional parameters were predominant. FMD & HS prevalence (0.092), Mastitis prevalence (0.090), and Parasitic infestation (0.087) emerged as the most significant indicators, followed by Milk Fever prevalence (0.086) and Digestible Ration Component (0.080). Lower weights were observed for Soil Quality (0.057) and Blood Hematology Score (0.060), reflecting their moderate influence on household vulnerability.

The aggregation of dimensions into the B-HVI (Table 6) revealed that adaptive capacity contributed the largest share (0.528), followed by exposure (0.312) and sensitivity (0.160). This highlights that strengthening adaptive capacity—through improved herd productivity, technical knowledge, and extension support—can substantially mitigate vulnerability among buffalo-rearing households.

Status of adaptive capacity, exposure, sensitivity, and vulnerability index

Inter-state disparities were evident in adaptive capacity, exposure, sensitivity, and the composite vulnerability index (Table 7; Figures 2, 3). Haryana exhibited the highest adaptive capacity (ACI = 0.886), reflecting relatively strong institutional, infrastructural, and livelihood support systems. Punjab (ACI = 0.745) and Rajasthan (ACI = 0.618) followed, while Gujarat (ACI = 0.532) remained below the regional mean. Uttar Pradesh (ACI = 0.431) and Bihar (ACI = 0.208) recorded the lowest adaptive capacities, highlighting systemic limitations in their ability to respond effectively to external stressors. The pooled mean adaptive capacity (ACI = 0.520) indicated a moderate level of resilience across the study region. Climatic Exposure was most pronounced in Gujarat (EI = 0.886) and Rajasthan (EI = 0.801). Haryana (EI = 0.734) and Punjab (EI = 0.652) reflected intermediate exposure, while Uttar Pradesh (EI = 0.594) and Bihar (EI = 0.194) were relatively less exposed. The average exposure score (EI = 0.593) suggests that most states face moderate-to-high external pressures. For the Sensitivity index, Bihar (SI = 0.789) was the highest, followed by Uttar Pradesh (SI = 0.733) and Rajasthan (SI = 0.657). In contrast, Punjab (SI = 0.312), Haryana (SI = 0.298), and Gujarat (SI = 0.286) demonstrated lower levels of inherent sensitivity. The pooled sensitivity score (SI = 0.345) reflects relatively low-to-moderate susceptibility overall. The composite B-HVI integrating adaptive capacity, exposure, and sensitivity, revealed Bihar (B-HVI = 0.801) and Rajasthan (B-HVI = 0.799) as the most vulnerable states, followed by Gujarat (B-HVI = 0.722) and Uttar Pradesh (B-HVI = 0.658). Punjab (B-HVI = 0.488) and Haryana (B-HVI = 0.595) demonstrated comparatively lower vulnerability levels. The pooled B-HVI value was 0.690, indicating an overall high level of vulnerability in the study region. The results point to a clear stratification: Bihar and Rajasthan show highest vulnerability driven by low adaptive capacity and heightened sensitivity; Punjab and Haryana show lower vulnerability with stronger adaptive mechanisms despite moderate exposure; Gujarat and Uttar Pradesh fall in the intermediate range, where elevated exposure interacts with moderate adaptive capacity and sensitivity.

Distribution of vulnerability categories of buffalo-rearing households

Households were classified into vulnerability categories based on their B-HVI: low (B-HVI $\leq$ 0.50), medium (0.51–0.70), and high (B-HVI > 0.70; Table 8). Only 11.81% of households fell into the low vulnerability category, while nearly half (45.83%) fell into the medium range. A considerable share (42.36%) were classified as highly vulnerable, indicating systemic limitations in coping and adaptive capacities. Haryana performed comparatively better, with 16.67% low, 66.67% medium and 16.66% high group. Punjab showed 29.17% low, 58.33% medium, and 12.50% high—the least vulnerable profile among states. Bihar emerged as the most vulnerable with 79.17% high, and none in the low category. Uttar Pradesh showed substantial vulnerability with 20.83% high despite 66.67% medium. Rajasthan and Gujarat also reflected predominance of high vulnerability at 66.66 and 58.34%, respectively with only 4.17% (Rajasthan) and 8.33% (Gujarat) in the low category. Overall, Punjab and Haryana exhibited relatively lower vulnerability due to higher shares in low and medium categories, whereas Bihar, Rajasthan, and Gujarat were concentrated in the high group; Uttar Pradesh occupied an intermediate position skewed toward the medium class.

Inter-state differences in vulnerability index of buffalo-rearing households

The one-way ANOVA confirmed a statistically significant difference in mean Vulnerability Index (B-HVI) across the six states under study ($F = 30.08$, $p < 0.001$; Table 9).

Because ANOVA does not identify which pairs differ, Tukey's *post-hoc* test was applied for pairwise comparisons (Table 10). Out of the 15 comparisons, 8 showed statistically significant differences. Rajasthan differed significantly from Punjab ($p < 0.001$) and Haryana ($p < 0.001$), indicating higher vulnerability in Rajasthan. Gujarat and Uttar Pradesh also differed from Punjab ($p < 0.001$ each) and from Haryana ($p < 0.001$ and $p = 0.011$, respectively). Bihar showed the strongest contrast, with higher mean B-HVI than both Punjab and

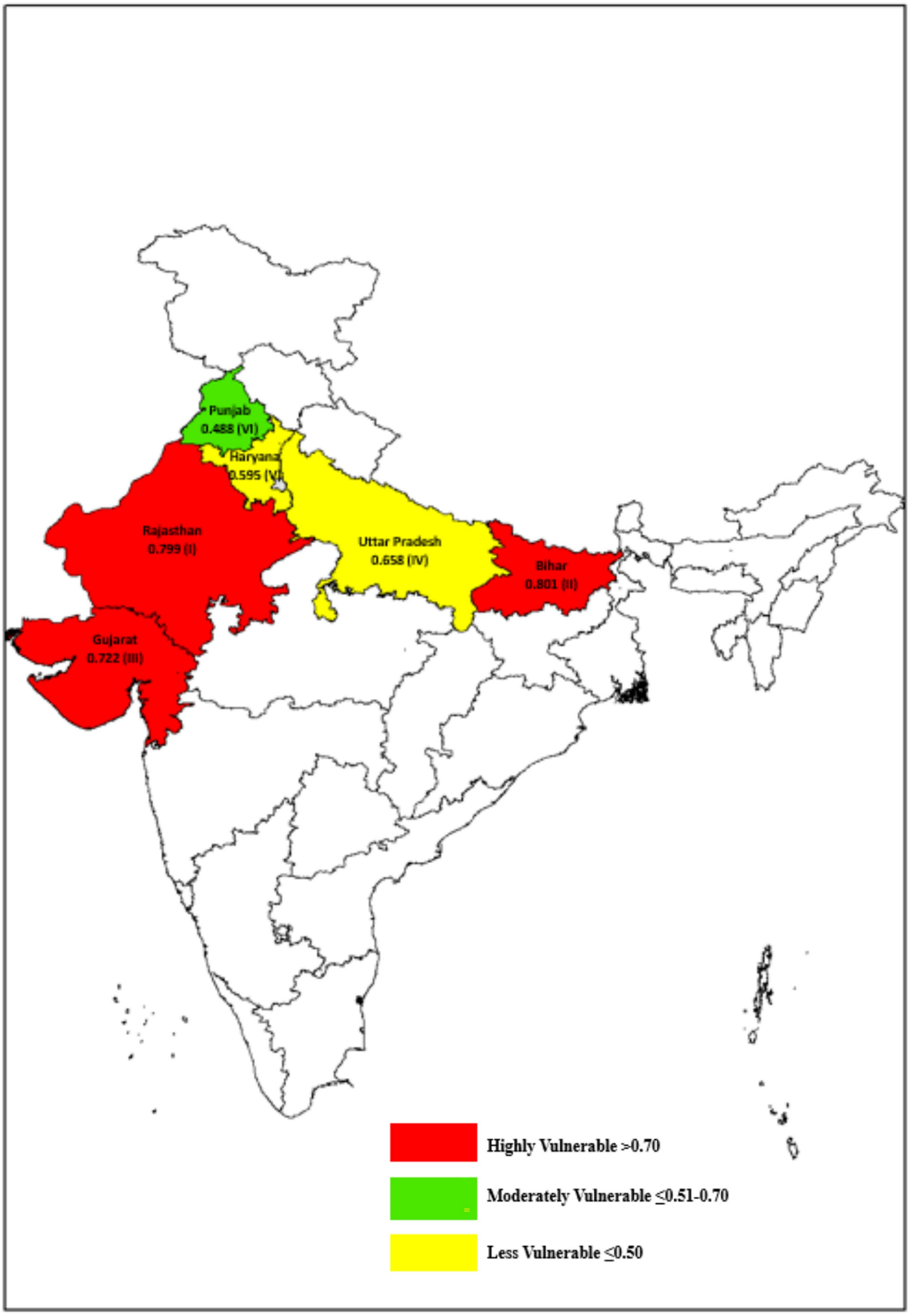

FIGURE 2
Spatial representation of the buffalo households vulnerability index across states.

Haryana ($p < 0.001$). In contrast, pairwise comparisons among Rajasthan, Gujarat, Uttar Pradesh, and Bihar were not statistically different, suggesting broadly similar high vulnerability among these states. The Haryana- Punjab difference was not significant ($p = 0.365$), indicating comparable vulnerability levels between these relatively resilient states. Overall, the *post-hoc* analysis delineates two groups: Punjab and Haryana, with lower mean B-HVI, and Bihar, Rajasthan, Gujarat, and Uttar Pradesh, with substantially higher vulnerability.

Discussion

The present study provides one of the first integrated micro-level examinations of climate change vulnerability among buffalo-rearing households in northern and western India using a composite index framework. The analysis, incorporating household-level information on adaptive capacity, exposure, and sensitivity and triangulated with epidemiological parameters, offers a more precise picture of regional

TABLE 8 State-wise household-level classification of buffalo rearing households' vulnerability index ($n = 720$).

State	Low vulnerability (≤0.50) (f)	%	Medium vulnerability (0.51–0.70) (f)	%	High vulnerability (>0.70) (f)	%
Haryana	20	16.67	80	66.67	20	16.66
Punjab	35	29.17	70	58.33	15	12.5
Rajasthan	5	4.17	35	29.17	80	66.66
Gujarat	10	8.33	40	33.33	70	58.34
UP	15	12.5	80	66.67	25	20.83
Bihar	0	0	25	20.83	95	79.17
Pooled sample	85	11.81	330	45.83	305	42.36

TABLE 9 One-way ANOVA for differences in buffalo-rearing household vulnerability across states ($n = 720$).

Source of variation	DF	Sum of squares	Mean square	F value	*p*-value
State	5	0.614	0.123	30.08	<2e−16 ***
Residuals	714	2.924	0.0041	-	-
Total	719	3.538	-	-	-

Statistical significance levels are denoted as: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. Non-significant differences are reported without asterisks.

TABLE 10 Tukey's *post-hoc* test for pairwise comparisons of state-wise mean B-HVI ($n = 720$).

Between states	Difference	*p*-value (adjusted)
Haryana-Punjab	0.107	0.365
Rajasthan-Punjab	0.311	< 0.001***
Gujarat-Punjab	0.234	< 0.001***
Uttar Pradesh-Punjab	0.17	< 0.001***
Bihar-Punjab	0.313	< 0.001***
Rajasthan-Haryana	0.204	< 0.001***
Gujarat-Haryana	0.127	< 0.001***
Uttar Pradesh-Haryana	0.063	<0.05**
Bihar-Haryana	0.206	< 0.001***
Gujarat-Rajasthan	−0.077	0.565
Uttar Pradesh -Rajasthan	−0.141	0.498
Bihar-Rajasthan	0.002	0.208
Uttar Pradesh-Gujarat	−0.064	0.611
Bihar-Gujarat	0.079	0.628
Bihar-Uttar Pradesh	0.143	0.554

Statistical significance levels are denoted as: ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$. Non-significant differences are reported without asterisks.

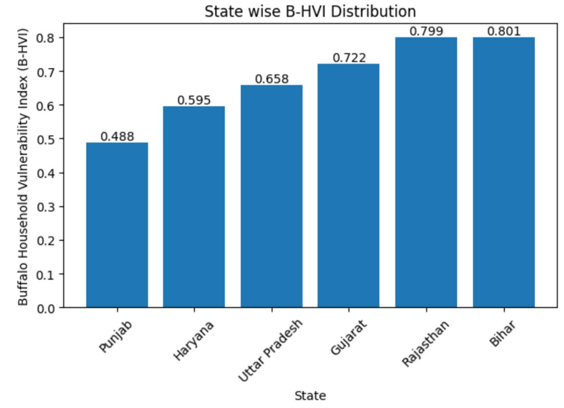

FIGURE 3
State-wise distribution of buffalo household vulnerability index (B-HVI).

disparities than conventional macro-level vulnerability assessments. This methodological approach identifies intra-state differences in livelihood resilience otherwise masked in district- or state-level averages. The results indicate that while climatic exposure is a common stressor across states, the magnitude of vulnerability is mediated by household-level adaptive capacities and livestock management practices.

Haryana and Punjab emerged as the leading states in terms of adaptive capacity, with scores of 0.886 and 0.745, respectively. Their reputation as dairy-progressive states reflect the central role of buffaloes in household economies and the commercialization of dairying (Gupta, 2025). High literacy and education levels facilitate uptake of scientific husbandry practices (Aiswarya et al., 2025). Larger herd sizes and stronger integration with milk markets help buffer climatic shocks (Guja and Bedeke, 2025). Veterinary and extension infrastructures are critical determinant: Punjab maintains one veterinarian per 1,729 cattle units and Haryana 1: 3,434—both among the most favorable ratios—ensuring timely preventive and curative services (Pashudhanpraharee, 2025). Routine vaccination campaigns against major infectious diseases such as foot-and-mouth disease and haemorrhagic septicaemia, coupled with deworming and prophylaxis against parasitic infestations are systematically implemented (Madhulatha, 2023). Extension systems sustain high farmer awareness via trainings, exposure visits, demonstration farms, and dissemination of farm literature on clean milk production, mastitis control, ration balancing, reproductive management, and biosecurity (Makarabbi et al., 2025; Madhulatha, 2023; Pandey, 2022). These supports translate into proactive herd management, minimizing disease outbreaks and sustaining productivity under climatic stress (Aliyu et al., 2025). Cooperative dairies and organized milk collection further enhance resilience through assured markets, standardized pricing, and veterinary advisory access (Singla and Singh, 2024).

Despite these strengths, inter-state contrasts are notable. Haryana ranked first in adaptive capacity, but experienced higher exposure (EI = 0.734) than Punjab (EI = 0.652). Semi-arid tracts of south-western Haryana face heat waves and water scarcity, complicating buffalo husbandry (Chauhan et al., 2022). Households employ targeted adaptation: foggers, sprinklers, fans, shades, and improved water management to reduce heat load and ensure supply (Bal et al., 2025), complimented by green fodder supplementation, ration balancing, and mineral mixtures, and timely veterinary interventions. Punjab showed slightly higher sensitivity (SI = 0.312), linked to mastitis, parasitism, and reproductive disorders exacerbated by intensification. Its robustness lies in institutional support and the widespread preventive practices, which buffer disease-related sensitivity. Thus, while both states are relatively less vulnerable overall, Haryana demonstrates resilience under higher exposure, whereas Punjab leverages strong institutions to offset higher sensitivity.

Rajasthan and Gujarat represent contrasting vulnerability profiles within arid and semi-arid agro-ecologies. Rajasthan recorded the second-highest vulnerability index (B-HVI = 0.799), primarily due to high exposure (EI = 0.801) and sensitivity (SI = 0.657). Recurrent heat waves, sandstorms, and erratic rainfall constrain feed and fodder availability (Chhabra and Arora, 2024). Despite a large buffalo population, adaptive capacity (ACI = 0.618) is curtailed by lower levels of education, weak extension linkages, and inadequate farm infrastructure (Kanwal et al., 2022). Veterinary density is a key bottleneck: Rajasthan has one veterinarian per 7,691 cattle units, around five times worse than Punjab limits timely herd health management (Pashudhanpraharee, 2025). Prolonged calving intervals, higher mastitis and foot-and-mouth prevalence, and nutritional deficiencies heighten sensitivity. Investments to strengthen adaptive capacity, expand veterinary coverage, and raise farmer education are essential to reduce vulnerability.

Gujarat illustrates that even under extreme exposure conditions (EI = 0.886, highest), vulnerability can be moderated when sensitivity is contained and adaptive mechanisms are strengthened. With modest adaptive capacity (ACI = 0.532) but the lowest sensitivity (SI = 0.286), Gujarat benefits from cooperative-based veterinary and extension infrastructure led by AMUL (Nidhishree et al., 2025). Although veterinary density is weaker (1:5,998 cattle units) than in the progressive north–west, village milk societies facilitate ration balancing, collective management, and access to veterinary interventions (Panchal et al., 2025). Farmer-to-farmer networks and organized dairy marketing provide income stability and market assurance (Biradar et al., 2025). Nonetheless, overall vulnerability remains medium (B-HVI = 0.722), indicating a need to strengthen adaptive capacity through farmer education, climate information services, and expansion of veterinary coverage.

Uttar Pradesh (UP) and Bihar emphasize the impact of sensitivity and weak adaptive capacity on vulnerability. UP exhibited moderate exposure (EI = 0.594) but very high sensitivity (SI = 0.733), yielding B-HVI = 0.658. Bihar was the most vulnerable (B-HVI = 0.801) with extremely low adaptive capacity (ACI = 0.208) coincides with high sensitivity (SI = 0.789). Veterinary coverage is a critical explanatory: UP has one veterinarian per 8,211 cattle units, and Bihar 1:7,275 both worse than the national average of 1:4,616 (Pashudhanpraharee, 2025)—constraining timely animal health services. Weak extension penetration compounds challenges; reliance on ethno-medicinary practices or informal networks is common (Dutta et al., 2021), yet inadequate for reproductive inefficiencies, mastitis, or mineral deficiencies that require scientific care (Ayoola et al., 2025). Nutritional imbalances, mineral deficiencies, parasitic infestations, and reproductive problems (such as delayed age at first calving and prolonged calving intervals) intensify sensitivity (Fadlalla, 2022). Awareness of ration balancing, clean milk production, and biosecurity measures is relatively low, and limited organized marketing reduces incentives to upgrade practices (Singh et al., 2020). Consequently, vulnerability remains high, with nearly 80% of Bihar's households in the high-vulnerability category.

Overall, vulnerability among buffalo-rearing households is shaped not by exposure alone but by interplay of sensitivity and adaptive capacity, with veterinary infrastructure as a critical determinant. Punjab and Haryana, with relatively favorable cattle-to-veterinarian ratios (1:1,729 and 1:3,434), show how robust institutions mitigate climatic stress. In contrast, Bihar, Uttar Pradesh, and Rajasthan, with higher ratios (1:7,275, 1:8,211, and 1:7,691, respectively)—illustrate how limited coverage amplifies sensitivity and constrains adaptation. Gujarat demonstrates that cooperative innovations can partly compensate for modest veterinary density (1: 5,998) by moderating sensitivity (Pashudhanpraharee, 2025). Strengthening veterinary manpower, integrating preventive herd health with climate advisories, and embedding ration-balancing practices via cooperative or digital platforms could substantially enhance adaptive capacity.

Policy implications

Given the socioeconomic and climate-induced vulnerability of buffalo-rearing households, improving livelihood sustainability requires multi-level interventions. While extension, cooperative dairies, and veterinary networks exist, reach is uneven in UP, Bihar, Rajasthan, and Gujarat. Based on study findings, the following measures are suggested to enhance climatic resilience of buffalo households with economic sustainability:

(1) Strengthening veterinary and extension infrastructure:
The state-wise cattle-to-veterinarian ratios reveal critical gaps in Bihar (1:7,275), Uttar Pradesh (1:8,211), and Rajasthan (1:7,691), which are substantially less favorable than the national average (1:4,616; Pashudhanpraharee, 2025). Targeted recruitment and deployment of mobile units, and telemedicine, can reduce biological sensitivity and improve disease management. Scaling grassroots extension—through Krishi Vigyan Kendras (KVKs), Agricultural Technology Management Agency (ATMA), and dairy cooperatives—will facilitate adoption of climate-resilient practices in feeding, breeding, and health management.

(2) Promoting livelihood diversification within dairy systems:
In high-vulnerable states, encourage allied activities such as fodder cultivation, small-scale processing (cheese, ghee, or

curd), and livestock-based agri-tourism. Prioritize subsidies for fodder seeds, feed storage infrastructure, and small processing units in high exposure and high-sensitivity regions.

(3) Market access and commercialization support:
Establish cooperative milk collection centers, link rural producers to urban markets, and support digital platforms for assured outlets and fair pricing. State-supported buy-back arrangements can stabilize incomes and incentivize improved husbandry.

(4) Climate-resilient buffalo husbandry interventions:
Promote heat-tolerant genotypes, water-efficient management, improved housing design, and optimized feeding schedules during heat waves or droughts, especially in Rajasthan and Gujarat. Training should integrate indigenous knowledge with scientific guidance to improve uptake.

(5) Community-based capacity building and cooperative structures:
Strengthen FPOs, cooperatives, and commodity groups to enhance bargaining power and access to credit, inputs, and climate information. Enable KVKs and ATMA with dedicated funds for intensive programs on sustainable buffalo management, fodder conservation, disease prevention, and biodiversity-friendly practices.

(6) Integrated monitoring and policy coordination:
Establish a robust monitoring framework (with ICAR and dairy research institutes) to track herd health, milk yield, veterinary coverage, and climate risks. Real-time data can guide adaptive resource allocation. Cross-departmental integration will ensure holistic interventions and long-term sustainability.

Conclusion

Development planning traditionally aims to improve rural livelihoods and reduce vulnerability of resource-dependent communities. Macro-level estimation often masks intra-state disparities; a household-level, sustainable livelihood perspective captures multiple dimensions of resources, adaptive capacity, and exposure. This study estimates household-level vulnerability across northern and western India and shows that Haryana and Punjab, followed by Gujarat, are comparatively better off, whereas Bihar, UP, and Rajasthan face higher vulnerability due to low adaptive capacity, high sensitivity, and limited veterinary and market access. The Composite Buffalo Vulnerability Index can support monitoring and prioritization. Veterinary coverage, extension contacts, market access, and diversification are critical for resilience. Without targeted, community-based, region-specific strategies, smallholder buffalo farmers in high-risk states will continue to face income instability, disease risks, and climate stress. Integrating ICAR, KVKs, cooperative dairies, state veterinary departments, and community organizations is necessary for participatory planning and adoption of adaptive, climate-resilient management. Such coordination is essential for long-term livelihood sustainability and resource conservation.

Limitations of the study

While the present study provides a comprehensive micro-level assessment of vulnerability among buffalo-rearing households across northern and western India, several limitations must be acknowledged:

- The study is cross-sectional and perception-based, particularly for meteorological exposure, relying on farmers' reports rather than high-resolution instrumental data, which may introduce recall bias or subjective bias.
- Detailed financial records, precise animal health histories, and high-resolution climate variability metrics, could not be fully incorporated, potentially affecting the granularity.
- Intra-village heterogeneity in networks, resource access, and cultural practices may have been smoothed in household-level aggregation, limiting finer-scale insights.

Future research

- Future studies may adopt longitudinal or panel-based designs to capture temporal transitions in vulnerability and adaptive responses under evolving climatic conditions.
- Integration of high-resolution gridded climate datasets, remote sensing indicators, and micro-climatic measurements could further strengthen the exposure dimension and improve spatial precision.
- Comparative robustness analysis employing alternative weighting and aggregation approaches (e.g., PCA-based weights, equal weighting, or multi-criteria decision methods) may enhance methodological transparency and index stability assessment.
- Stratified analysis across herd-size categories, landholding classes, and gender-disaggregated roles within buffalo-rearing households may provide deeper insights into differential vulnerability patterns.
- Incorporation of mitigation-oriented indicators, including emission intensity and feed efficiency metrics, could extend the framework toward comprehensive climate-smart livestock assessment.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The study was conducted with prior approval from the Institutional Animal Ethics Committee (IAEC) of the ICAR–Central Institute for Research on Buffaloes (CIRB), following ratification by the Committee for Control and Supervision of Experiments on Animals (CCSEA), Government of India (Approval No. IAEC-CIRB/2023-24/A/101; dated 28 August 2023). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

SA: Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. GM: Formal analysis, Methodology, Validation, Visualization, Writing – review & editing. SB: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – review & editing. AB: Investigation, Project administration, Supervision, Writing – review & editing. SP: Project administration, Supervision, Writing – review & editing. SK (sixth author): Data curation, Project administration, Writing – review & editing. SK (seventh author): Project administration, Supervision, Writing – review & editing. EH: Formal analysis, Methodology, Software, Visualization, Writing – review & editing. MS: Investigation, Writing – review & editing. AKB: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This study was funded by the Bill & Melinda Gates Foundation (BMGF INV-061664; Ref. No. AS/12/77/2023-ASR-II dated 08.01.2024).

Acknowledgments

Authors express their sincere gratitude to Indian Council of Agricultural Research (ICAR), Department of Agricultural Research and Education, Government of India and the Bill & Melinda Gates Foundation. Authors also acknowledge the Director, ICAR–Central Institute for Research on Buffaloes, Hisar, for providing the necessary facilities to carry out the research.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was used in the creation of this manuscript. The author(s) acknowledge the use of Generative AI in the preparation of this manuscript. The tools were employed solely to improve the clarity, coherence, and readability of specific sections through language refinement and structural suggestions. All aspects of research design, data collection, analysis, interpretation, and core intellectual content are entirely the authors' own work. The final version of the manuscript represents the authors' original contribution, with all AI-assisted edits thoroughly reviewed to ensure accuracy and uphold scientific integrity.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

References

20th Livestock Census Report (2019). All India report. Available online at: https://ruralindiaonline.org/en/library/resource/20th-livestock-census-2019-all-india-report/ (Accessed 15 May, 2025).

Adger, W. N. (2003). "Social aspects of adaptive capacity," in Climate change, adaptive capacity and development, 29–49.

Adger, W. N., and Hodbod, J. (2014). "Ecological and social resilience," in *Handbook of sustainable development* (UK: Edward Elgar Publishing), 91–102.

Aggarwal, A., and Upadhyay, R. (2012a). *Heat stress and milk production heat stress and animal productivity*. India: Springer India, 53–77.

Aggarwal, A., and Upadhyay, R. (2012b). "Shelter management for alleviation of heat stress in cows and buffaloes," in *Heat stress and animal productivity* (India: Springer India), 169–183.

Aiswarya, S., Makarabbi, G., Saxena, N., and Sharma, M. L. (2025). Perception of Buffalo farmers towards scientific buffalo husbandry practises: applying the extended UTAUT framework. *Fron. in Ani. Sci.* 6:1618632. doi: 10.3389/fanim.2025.1618632

Aliyu, M. B., Kaltungo, B. Y., Alhaji, N. B., and Allah, S. S. N. (2025) Herd health management Programme for smallholder goat production

Ape, T. S., Singha, S., Marma, U., Rumi, H. J., Sagor, S. I., and Chiariotti, A. (2025). Water buffalo farming, udder health and its dairy production status in Bangladesh: practices, challenges, and potentialities. *Vet. Res. Commun.* 49, 1–17. doi: 10.1007/s11259-025-10823-8

Ayoola, M. O., Ogunlakin, A. D., and Oguntunji, A. O. (2025). Status of ethno-veterinary medicine in the management of dairy animals in Nigeria. *J. of Ani. Heal. Prod.* 13, 88–105. doi: 10.17582/journal.jahp/2025/13.1.88.105

Bal, S. K., Prasad, J. V. N. S., Rao, K. V., and Singh, V. K. (2025). *Heatwaves: Impacts and management strategies in agriculture*, vol. 54. Hyderabad, Telangana, India: ICAR-Central Research Institute for Dryland Agriculture.

Bandiera, O., and Rasul, I. (2006). Social networks and technology adoption in northern Mozambique. *Econ. J.* 116, 869–902. doi: 10.1111/j.1468-0297.2006.01115.x

Behere, J., Jha, S. K., Maiti, S., and Garai, S. (2025). Measuring livelihood vulnerability to floods among livestock rearers using a composite index in Odisha, India. *Int. J. Environ. Climate Chang.* 15, 58–68. doi: 10.9734/ijecc/2025/v15i74913

Below, T. B., Mutabazi, K. D., Kirschke, D., Franke, C., Sieber, S., Siebert, R., et al. (2012). Can farmers' adaptation to climate change be explained by socio-economic household-level variables? *Glob. Environ. Chang.* 22, 223–235. doi: 10.1016/j.gloenvcha.2011.11.012

Binswanger-Mkhize, H. P. (2012). Is there too much hype about index-based agricultural insurance? *J. Dev. Stud.* 48, 187–200. doi: 10.1080/00220388.2011.625411

Biradar, J., Deo, S., and Kaur, S. (2025). Do agricultural extension services really matter to Indian farmers? Evidence from situation assessment survey on farmers. *Indian Econ. J.*:00194662251332867. doi: 10.1177/00194662251332867

Birthal, P. S., Khan, T. M., Negi, D. S., and Agarwal, S. (2014). Impact of climate change on yields of major food crops in India: implications for food security. *Agric. Econ. Res. Rev.* 27, 145–155. doi: 10.5958/0974-0279.2014.00019.6

Black, R., Adger, W. N., Arnell, N. W., Dercon, S., Geddes, A., and Thomas, D. (2011). The effect of environmental change on human migration. *Glob. Environ. Chang.* 21, S3–S11. doi: 10.1016/j.gloenvcha.2011.10.001

Blasiak, R., Spijkers, J., Tokunaga, K., Pittman, J., Yagi, N., and Österblom, H. (2017). Climate change and marine fisheries: least developed countries top global index of vulnerability. *PLoS One* 12:e0179632. doi: 10.1371/journal.pone.0179632

Brooks, N., Adger, W. N., and Kelly, P. M. (2005). The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Glob. Environ. Chang.* 15, 151–163. doi: 10.1016/j.gloenvcha.2004.12.006

Chauhan, A. S., Singh, S., Maurya, R. K. S., and Danodia, A. (2022). Impact of monsoon teleconnections on regional rainfall and vegetation dynamics in Haryana, India. *Environ. Monit. Assess.* 194:485. doi: 10.1007/s10661-022-10146-0

Chhabra, V., and Arora, G. (2024). *The impact of climate change on food security and agricultural livelihoods*. Cambridge: Cambridge Scholars Publishing.

Dalenius, T., and Hodges, J. L. Jr. (1957). The choice of stratification points. *Scand. Actuar. J.* 1957, 198–203.

Department of Animal Husbandry and Dairying (DAHD). (2019). 20th livestock census – all India report. Ministry of Fisheries, animal husbandry and dairying, government of India. Available online at: https://dahd.nic.in (Accessed March 9, 2025)

Department of Fisheries, Animal Husbandry and Dairying (DAHD). (2024). BAHS-2024. Ministry of Fisheries, animal husbandry and dairying. Available online at: https://dahd.gov.in/sites/default/files/2024-10/AnnualReport202324.pdf (Accessed 15 May, 2025)

Deressa, T. T., Hassan, R. M., Ringler, C., Alemu, T., and Yesuf, M. (2009). Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. *Glob. Environ. Chang.* 19, 248–255. doi: 10.1016/j.gloenvcha.2009.01.002

Dutta, M., Husain, Z., and Ghosh, S. (2021). *Can peer and neighbourhood effects improve maternal health outcomes in rural Bihar? Assessing the role of formal and informal networks*. London: Final report, International Growth Centre.

Fadlalla, I. M. (2022). The interactions of some minerals elements in health and reproductive performance of dairy cows. New advances in the dairy industry

Filmer, D., and Pritchett, L. H. (2001). Estimating wealth effects without expenditure data—or tears: an application to educational enrollments in states of India. *Demography* 38, 115–132. doi: 10.1353/dem.2001.0003

Guja, M. M., and Bedeke, S. B. (2025). Smallholders' climate change adaptation strategies: exploring effectiveness and opportunities to be capitalized. *Environ. Dev. Sustain.* 27, 17927–17956. doi: 10.1007/s10668-024-04750-y

Gupta, S. (2025). Developing India's food processing sector: farm politics, federalism, and state-directed development. *Stud. Comp. Int. Dev.*, 1–26. doi: 10.1007/s12116-025-09462-6

Hahn, M. B., Riederer, A. M., and Foster, S. O. (2009). The livelihood vulnerability index: a pragmatic approach to assessing risks from climate variability and change—a case study in Mozambique. *Glob. Environ. Chang.* 19, 74–88. doi: 10.1016/j.gloenvcha.2008.11.002

Hansen, P. J. (2004). Physiological and cellular adaptations of zebu cattle to thermal stress. *Anim. Reprod. Sci.* 82-83, 349–360. Available online at: https://pubmed.ncbi.nlm.nih.gov/15271465/

Heltberg, R., and Bonch-Osmolovskiy, M. (2011). *Mapping vulnerability to climate change*. Washington: World Bank Policy.

Herrero, M., Wirsenius, S., Henderson, B., Rigolot, C., Thornton, P., Havlík, P., et al. (2015). Livestock and the environment: what have we learned in the past decade? *Annu. Rev. Environ. Resour.* 40, 177–202. doi: 10.1146/annurev-environ-031113-093503

IPCC (2014). *Climate change 2014 synthesis report*, vol. 1059. Geneva, Szwitzerland: IPCC, 1072.

Ishizaka, A., and Labib, A. (2009). Analytic hierarchy process and expert choice: Benefits and limitations. *OR insight*, 22, 201–220.

Jolliffe, I. (2025). "Principal component analysis," in *International encyclopedia of statistical science* (Berlin, Heidelberg: Springer Berlin Heidelberg), 1945–1948.

Kaliravana, N., and Rao, A. N. (2024). Desertification, water and women in Banni grasslands of India. *Histo. Sociol. of South Asia* 18, 151–167. doi: 10.1177/22308075231226360

Kanwal, V., Sirohi, S., and Chand, P. (2022). Risk perception, impact, and management by farmer households in Rajasthan (India). *Environ. Hazar* 21, 416–432. doi: 10.1080/17477891.2022.2035664

Kropff, W., Ortiz Crespo, B., Steinke, J., Tesfaye, L., and Ramírez Villegas, J. A. (2023) Mainstreaming digital approaches for adaptation in agriculture in Kenya

Lata, S. (2019). "Profile of the study area: Uttar Pradesh," in *Irrigation water Management for Agricultural Development in Uttar Pradesh, India* (Cham: Springer International Publishing), 21–47.

Legg, S. (2021). IPCC, 2021: climate change 2021-the physical science basis. *Interaction* 49, 44–45. doi: 10.3316/informit.315096509383738

Lowder, S. K., Bhalla, G., and Davis, B. (2025). Decreasing farm sizes and the viability of smallholder farmers: implications for resilient and inclusive rural transformation. *Glob. Food Secur.* 45:100854. doi: 10.1016/j.gfs.2025.100854

Madhulatha, C. (2023). Prevalent diseases and their effect on performance of dairy animals in Haryana: A farmer's perspective. Doctoral dissertation, ICAR-National Dairy Research Institute, Karnal, Haryana, India

Maiti, S., Jha, S. K., Garai, S., Nag, A., Chakravarty, R., and Kadian, K. S. (2014). Vulnerability to climate change among the livestock rearers of eastern coastal region of India: a household level assessment. *Indian J. Anim. Sci.* 84, 1048–1054. doi: 10.56093/ijans.v84i10.44239

Makarabbi, G., Aiswarya, S., Saxena, N., and Sharma, M. L. (2025). Assessing veterinary education outcomes in livestock systems: a quasi-experimental study of scientific buffalo husbandry training. *Fron. Vet. Sci.* 12:1656517. Available online at: https://www.frontiersin.org/journals/veterinary-science/articles/10.3389/fvets.2025.1656517/full

Manjunath, K. (2023). Development of climate services and its impact on murrah buffalo farmers of Haryana. Doctoral dissertation, ICAR-National Dairy Research Institute, Karnal, Haryana, India

Mazziotta, M., and Pareto, A. (2016). On a generalized non-compensatory composite index for measuring socio-economic phenomena. *Soc. Indic. Res.* 127, 983–1003. doi: 10.1007/s11205-015-0998-2

Moyo, M., and Nsahlai, I. (2021). Consequences of increases in ambient temperature and effect of climate type on digestibility of forages by ruminants: a meta-analysis in relation to global warming. *Animals* 11:172. doi: 10.3390/ani11010172

Muner, R. D., Moaeen-ud-Din, M., Saleem, A. H., Ullah, Q., Abbas, G., and Maqbool, B. (2025). Genomic selection, gene editing, and reproductive biotechnology: a triad for the improvement of native buffalo breeds in a developing country perspective like Pakistan. *Trop. Anim. Health Prod.* 57, 1–16. doi: 10.1007/s11250-025-04352-4

Nardo, M., Saisana, M., Saltelli, A., and Tarantola, S. (2005). Tools for composite indicators building. *European Comission, Ispra*, 15, 19–20.

Nardone, A., Ronchi, B., Lacetera, N., Ranieri, M. S., and Bernabucci, U. (2010). Effects of climate changes on animal production and sustainability of livestock systems. *Livest. Sci.* 130, 57–69. doi: 10.1016/j.livsci.2010.02.011

National Bureau of Animal Genetic Resources (NBAGR). Buffalo breeds of India. (2025). Available online at: https://nbagr.res.in/buffalo-breed. (Accessed on 14 November 2025)

Nhemachena, C., and Hassan, R. (2007). Micro-level analysis of farmers adaption to climate change in southern Africa. *Intl Food Policy Res Inst.* Available online at: https://ageconsearch.umn.edu/record/42399/files/IFPRIDP00714.pdf

Nidhishree, R., Singh, N., Padaliya, M., and Patel, U. B. (2025). The export trends and market potential of Gujarat's dairy industry. *Arch. Cur. Res. Intern.* 25, 574–582. doi: 10.9734/acri/2025/v25i61302

OECD. (2008). Handbook on constructing composite indicators: Methodology and userguide.

Panchal, J., Patel, S., Patel, A., Chauhan, H., Sharma, K., and Dabhi, M. (2025). Longitudinal surveillance and analysis of antimicrobial resistance in bovine pathogens in North Gujarat: an 18-month perspective. *Discover Applied Sci.* 7, 1–18. doi: 10.1007/s42452-025-06977-4

Pandey, S. (2022). Prioritising extension interventions for resource poor dairy farming households in Haryana. Doctoral dissertation, ICAR-National Dairy Research Institute, Karnal, Haryana, India

Pant, M., Bhatla, R., Ghosh, S., Das, S., and Mall, R. K. (2024). How climate change is affecting the summer monsoon extreme rainfall pattern over the indo-Gangetic Plains of India: present and future perspectives. *Clim. Dyn.* 62, 1055–1075. doi: 10.1007/s00382-023-06953-x

Pashudhanpraharee. (2025). State-wise cattle-to-veterinarian ration in India. Available online at: https://www.pashudhanpraharee.com/state-wise-cattle-to-veterinarian-ratio-in-india/ (Accessed on 17 August 2025)

Perkins, S. E., Alexander, L. V., and Nairn, J. R. (2012). Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophys. Res. Lett.* 39, 1–5. doi: 10.1029/2012GL053361

Posit team (2025). *RStudio: Integrated development environment for R*. Boston, MA: Posit Software, PBC.

Ragasa, C., Ulimwengu, J., Randriamamonjy, J., and Badibanga, T. (2016). Factors affecting performance of agricultural extension: evidence from Democratic Republic of Congo. *J. Agric. Educ. Ext.* 22, 113–143. doi: 10.1080/1389224X.2015.1026363

Saaty, T. L. (1982). The analytic hierarchy process: a new approach to deal with fuzziness in architecture. *Archit. Sci. Rev.* 25, 64–69.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *Int. J. Serv. Sci.* 1, 83–98. doi: 10.1504/ijssci.2008.017590

Saltelli, A. (2007). Composite indicators between analysis and advocacy. *Soc. Indic. Res.* 81, 65–77. doi: 10.1007/s11205-006-0024-9

Savsani, H. H., Padodara, R. J., Bhadaniya, A. R., Kalariya, V. A., Javia, B. B., Ghodasara, S. N., et al. (2015). Impact of climate on feeding, production and reproduction of animals-a review. *Agric. Rev.* 36:003. doi: 10.5958/0976-0741.2015.00003.3

Sejian, V., Bhatta, R., Soren, N. M., Malik, P. K., and Ravindra, J. P. (2015). "Introduction to concepts of climate change impact on livestock and its adaptation and mitigation," in *Climate change impact on livestock: Adaptation and mitigation* (New Delhi: Springer India), 1–23.

Shannon, C. E. (1948). A mathematical theory of communication. *Bell Syst. Tech. J.* 27, 379–423.

Shekhar, S., Sinha, R. R. K., Kumar, K., and Nirala, R. (2025). "Livestock production under drought and heat stress," in *Drought and heat stress in agriculture: Implications, mitigation and policy approaches* (Singapore: Springer Nature Singapore), 93–110.

Singh, J., and Singh, H. (2025). A metamorphosis of Bārs: critical role of canal colonies in transforming Punjab's agricultural landscape. *J. Sikh Punjab Stud.* 32, 59–79. Available online at: https://giss.org/jsps_vol_32/04-singh_and_singh.pdf

Singh, K. M., Singh, P., Sinha, N., and Ahmad, N. (2020). An overview of livestock and dairy sector: Strategies for its growth in eastern Indian state of Bihar.

Singh, R., Maiti, S., Garai, S., Bhakat, M., Jha, S. K., Dixit, A. K., et al. (2025). Assessment of climate resilience index: insight from Murrah buffalo-based livestock production system of Western India. *Agric. Syst.* 228:104390. doi: 10.1016/j.agsy.2025.104390

Singla, N., and Singh, S. (2024). "Institutional interventions in dairy value chains in India: a case study of the impact of the Milk co-operative Vis-à-Vis informal Milk market channels on farmers in Punjab 1," in *Institutions and public policy for India's sustainable development* (India: Routledge), 148–165.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., and Averyt, K. (2007). IPCC fourth assessment report (AR4). *Clim. Chang.*:374. Available online at: https://www.ipcc.ch/site/assets/uploads/2018/03/ar4_wg2_full_report.pdf

Thornton, P. K., Ericksen, P. J., Herrero, M., and Challinor, A. J. (2014). Climate variability and vulnerability to climate change: a review. *Global change biology*, 20, 3313–3328.

Thornton, P. K., Herrero, M., Freeman, H. A., Okeyo Mwai, A., and McDermott, J. J. (2007) Vulnerability, climate change and livestock-opportunities and challenges for the poor

Thornton, P. K., Kristjanson, P., Förch, W., Barahona, C., Cramer, L., and Pradhan, S. (2018). Is agricultural adaptation to global change in lower-income countries on track to meet the future food production challenge? *Glob. Environ. Chang.* 52, 37–48. doi: 10.1016/j.gloenvcha.2018.06.003

Trivedi, R., and Dubey, M. (2025). Modified TOPSIS model enhanced by shannon's entropy weighting for evaluating agrarian advancement across multifarious Indian states. *Geol. J.* 90:75. doi: 10.1007/s10708-025-11321-9

Tyagi, B. (2018). "Animal breeding policies and strategies in India," in Animal breeding policies and strategies, vol. 52.

Upadhyay, S. K., Singh, D. P., and Saikia, R. (2009). Genetic diversity of plant growth promoting rhizobacteria isolated from rhizospheric soil of wheat under saline condition. *Current microbiology*, 59, 489–496.

Vijayalakshmy, K., Chakraborty, S., Biswal, J., and Rahman, H. (2023). The role of rural Indian women in livestock production. *Eur. J. Humanit. Soc. Sci.* 3, 91–98. doi: 10.24018/ejsocial.2023.3.1.395

Williams, M. (2015). "Rajasthan, India (1983)," in *Nile waters, Saharan Sands: Adventures of a geomorphologist at large* (Cham: Springer International Publishing), 123–129.