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Assessing climate change risk and vulnerability among Bhil and Bhilala tribal communities in Madhya Pradesh, India: a multidimensional approach

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Climate change presents significant risks to marginalized communities, particularly in tribal groups like the Bhil and Bhilala communities of Madhya Pradesh, India. Limited empirical studies have focused on the effects of climate change on tribes in India. This study aims to assess climate change risk and vulnerability among tribal communities, employing the modified Mann–Kendall (*MMK*) test to identify climate trends, a risk assessment framework based on the Intergovernmental panel on climate change sixth assessment report (*IPCC-AR6*), and multiple linear regression (*MLR*). The *MMK* test indicates an increasing trend in rainfall (*MMK* = 1.099) and temperature. However, household perceptions reveal a high awareness of climatic changes, with 97% of respondents reporting irregularity in rainfall and 98% documenting increased summer hot days. The risk assessment shows that Bhil households face higher risk (0.107) than Bhilala households (0.068), which is determined by higher exposure and sensitivity. *MLR* results further emphasize that 12 of 23 indicators significantly affect risk assessment (R-squared = 0.698), with climatic events (β = 0.015), housing structure (β = 0.07), and food security being key contributors. The findings indicate that long-term climate trends are already affecting tribal livelihoods. It calls for targeted adaptation strategies, incorporating enhanced infrastructure, crop diversification, and better access to climate information and government schemes.

Keywords Climate change, Risk assessment, *IPCC-AR6*, Tribal livelihood, Multiple linear regression, Adaptive capacity

Climate change significantly challenges global ecosystems and human livelihoods[1], with marginalized and vulnerable populations facing adverse effects[2]. The unpredictability of climate change, categorized by changing precipitation patterns, increasing temperatures, and extreme weather events such as floods, droughts, and heatwaves[3–6], poses severe challenges to the sustainability of millions of livelihoods, specifically in developing nations like India, Pakistan, Bangladesh, Sri Lanka[7,8], those dependent on natural resources and traditional agricultural practices[9]. These changes disrupt rural communities, particularly tribal populations' farming practices, affecting their social structures, economic stability, and access to essential health, water, and food security[10,11]. Agriculture, the primary livelihood source for these communities, is highly susceptible to climate variability, with an increased risk of crop failure, reduced yields, and degradation of land resources[12]. Moreover, the lower capital to spend on climate-resilient agricultural practices, such as crop diversification, irrigation, and soil conservation, further amplifies these communities' climate-related risks[13,14].

With its diverse geography and socioeconomic structure, India is one of the most vulnerable countries to climate change impacts[15], mainly affecting tribal communities that heavily depend on agriculture and have lower access to adaptive resources[16]. According to the 2011 Census of India, tribal communities comprise 8.6% of the total population, with many living in remote, ecologically sensitive regions[17]. These communities regularly practice subsistence farming and depend on natural resources such as water bodies, forests, and soil, making them more vulnerable to climate variability[18,19]. Their vulnerability is further exaggerated by erratic monsoons, inadequate infrastructure, poor road connectivity, limited access to markets and healthcare, and socioeconomic challenges, including high poverty levels and lower educational status. Limited irrigation facilities, dependence

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on single-crop farming, and small landholdings worsen their risk of droughts and floods[20]. Furthermore, restricted access to government schemes and a lack of awareness about climate adaptation strategies compound these issues[8]. The state of Madhya Pradesh, located in central India, is home to various tribal groups, including the Bhil and Bhilala communities, which have traditionally marginalized in access to essential services, including education, healthcare, and financial stability[21].

Previous research highlighted the vulnerability of smallholder farmers, especially those in marginalized communities, to climate change. For example, studies by Zeleke et al.[22] found that household vulnerability in Ethiopia is influenced by factors such as land holdings, economic stability, and social capital. Households in less favorable agroecological zones with limited market access encounter more significant climatic risks, expressing that vulnerability varies by location and socioeconomic conditions. Similarly, Omerkhil et al.[23] demonstrated that smallholder farmers in Afghanistan's hilly regions observe higher exposure and lower adaptive capacity due to poor infrastructure and resource access. Climate change disproportionately affects women due to limited resources and farming opportunities in conflict-prone areas of the Philippines, exhibiting the gendered aspect of vulnerability[24]. In Nepal[25], investigated the intersection of gender and social class, showing that female-headed households and marginalized groups face higher risks due to their dependency on agriculture, natural resources and inadequate social networks. In India, Kuchimanchi et al.[26] illustrated how various agricultural practices, such as mixed crops and livestock, experience varying vulnerability based on access to livelihood resources. These concerns were similarly highlighted in the Indo-Gangetic Plains by Venus et al.[27], who emphasized the influence of infrastructure and agricultural productivity on vulnerability dynamics. However, these studies often focus on agricultural risks without considering the socioeconomic factors intensifying vulnerability, such as access to infrastructure, financial stability, and social capital. A comprehensive multidimensional approach, incorporating both climatic and socioeconomic dimensions, is essential to deep understanding and addressing the vulnerability of marginalized people like tribal communities using the intergovernmental panel on climate change sixth assessment report (*IPCC-AR6*) framework.

The *IPCC-AR6* report presents a multidimensional technique for climate risk assessment, focusing on the interaction of hazards**,** exposure**,** sensitivity, and adaptive capacity[28]. Exposure and sensitivity are essential components of vulnerability, while adaptive capacity controls the ability to cope with or mitigate the impacts of climate threats[2]. The AR6 framework is more helpful in assessing vulnerability among marginalized groups, highlighting the importance of biophysical and socioeconomic factors[29]. However, its application to tribal communities in India, particularly in Madhya Pradesh, remains underexplored. A few researchers have focused on the unique challenges faced by tribal populations. In Tripura, Roy et al.[30] compared climate vulnerability between tribal and non-tribal communities using IPCC AR4 and highlighted that tribal households faced greater exposure and vulnerability due to higher sensitivity to climate variability and weaker adaptive capacities. Similarly, Das & Basu[16] further aided this discourse by evaluating the livelihood vulnerability of Munda, Santal, Lodha, and Bhumij tribal communities in West Bengal. Utilizing the livelihood vulnerability index (*LVI*) and Beta regression models, they found that the Lodha community presented the highest *LVI*, indicating higher vulnerability than other tribes. Deb & Mukherjee[31] focused on the major tribal groups of Santal, Munda, and Oraon in the Himalayan region of West Bengal. They identified important socioeconomic variables contributing to household vulnerability, such as lacking basic infrastructure, inadequate rations, and poor medical services. In Himachal Pradesh, Kumar et al.[32] examined the livelihood vulnerabilities of tribal families using the *LVI*. Their findings revealed significant differences in vulnerability levels, attributed to variances in adaptation strategies, sensitivity, and exposure to climate change. In Madhya Pradesh, Yadava & Sinha[33] investigated the relationship between economic conditions, educational status, and professional activities on community vulnerability to climate change. Much of the research on tribal populations in India remains limited in its methodological scope. For example, Roy et al.[30], Das & Basu[16] and Kumar et al.[32] have used frameworks such as *LVI*, which integrates exposure, sensitivity, and adaptive capacity. These evaluations have provided valuable insights but are frequently limited by a restricted emphasis on selected sectors, such as agriculture, without effectively integrating socioeconomic dimensions or considering cross-sectoral vulnerabilities. Moreover, these methodologies typically rely on household surveys, and while helpful, they can neglect community-level dynamics or broader socioeconomic limitations that influence vulnerability. It calls for a more holistic approach integrating climatic, socioeconomic, and infrastructural factors to present a sophisticated understanding of vulnerability.

Research on climate vulnerability among tribal communities has inadequately examined the impact of sociodemographic characteristics (gender, age, education, and occupation) and access to infrastructure (such as housing quality and transportation) on vulnerability. For instance, Yadava & Sinha[33] found inadequate access to infrastructure exaggerates vulnerability. Still, the influences of elements such as social security, livelihood diversification, and healthcare facilities remains to be investigated by tribal populations. Current studies have highlighted the necessity of adaptive capacity in mitigating climate change risks[34,35], but more detailed analysis is required to identify the specific socioeconomic drivers of vulnerability in tribal populations. This study fills these gaps using a comprehensive framework that integrates climatic hazards and socioeconomic aspects to assess the vulnerability of the Bhil and Bhilala communities in Madhya Pradesh. It offers a more holistic method, incorporating biophysical and socioeconomic dimensions using the *IPCC-AR6* framework. It provides a robust statistical foundation for identifying temperature and rainfall variability trends, using observed climate data from 1974 to 2023, analyzed through the modified Mann–Kendall test. Unlike prior studies concentrated primarily on household-level indicators, this research combines empirical climate data with community perceptions, offering a comprehensive understanding of vulnerability among the Bhil and Bhilala communities. Including multiple linear regression analysis further improves assessment, identifying determinants of vulnerability, such as landholding size, access to safe drinking water, housing structure, and diversified livelihood strategies. A comprehensive conceptual framework is presented in Fig. 1.

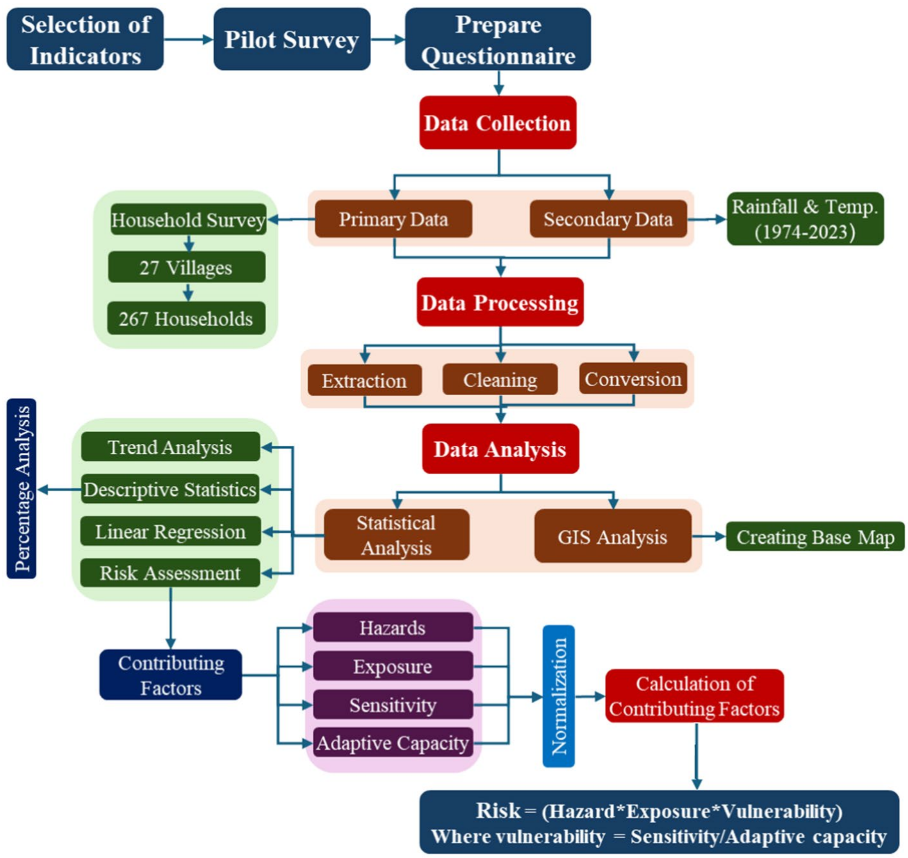

Fig. 1. Conceptual framework flowchart.

This study expands beyond supporting hazards, exposure, and sensitivity, rigorously evaluating adaptive capacities related to resources, education, healthcare, and financial services using the *IPCC-AR6* framework. Integrating local perceptions with scientific data presents a specific context analysis that is often lacking in previous studies. The findings offer valuable insights into the climate risks facing marginalized tribal communities, providing practical recommendations for improving resilience and adaptive capacity. These results are essential for leading policymakers, stakeholders and practitioners in constructing targeted adaptation measures to safeguard exposed communities. The primary objectives of this study are (a) analyzing climatic data (temperature and rainfall) to identify the long-term trends, (b) assessing community perceptions of climate change, (c) conducting a comprehensive climate risk assessment using the *IPCC-AR6* framework, (d) identifying the key determinants influencing climate vulnerability, and (e) providing policy recommendations based on the findings to augment the resilience of these communities to climate change impacts and supporting sustainable livelihoods.

Results

Sociodemographic characteristics of respondents

The sociodemographic characteristics of respondents from the Bhil ($N = 137$) and Bhilala ($N = 130$) communities show significant differences across various variables (Fig. 2). Most of the respondents were male, comprising 70.1% of the Bhil and 80% of the Bhilala groups. A higher percentage of respondents predominantly belonged to the 40–49 age group, representing 24.8% among the Bhil and 36.9% among the Bhilala, followed by 50–59 years (29.2% Bhil and 26.9% Bhilala). Marital status data indicated 89.8% of Bhil and 92.3% of Bhilala community were married. Educational attainment was generally low, with over half of the Bhil respondents (54.7%) and 40% of the Bhilala respondents being uneducated. However, a notable proportion of Bhilala respondents had completed primary education (22.3%) compared to Bhil respondents (15.3%). Family size varied, with most households comprising 5–7 members in both communities (48.2% Bhil, 49.2% Bhilala). Occupational data revealed that agriculture was the primary occupation of Bhilala respondents (65.4%), compared to Bhil respondents (29.2%). However, a larger proportion of Bhil respondents engaged in labor work (47.4% compared to 20.8% in Bhilala). These sociodemographic characteristics provide an important foundation for evaluating the vulnerability of these tribal communities to climate change impacts.

Observed climate change

The results of the *MMK* and *SS* test (Table A1, as provided in supplementary materials) applied to the climate data (1974–2023), focusing on four variables: rainfall, mean temperature (T_{mean}), maximum temperature (T_{max}),

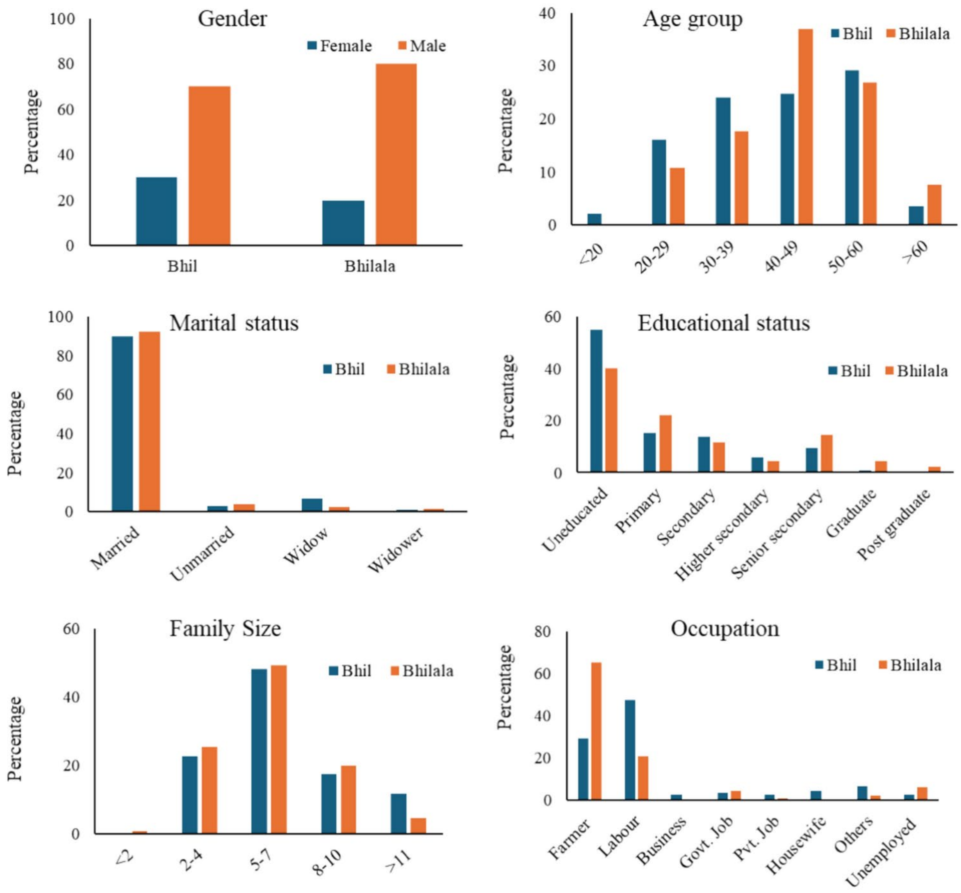

Fig. 2. Sociodemographic profile of Respondents in Bhil and Bhilala communities.

and minimum temperature (T_{min}). All these variables illustrated a statistically nonsignificant increasing trend (Fig. 3). Rainfall showed a positive trend ($MMK = 1.099$) with a magnitude of 2.431 mm/yearly. T_{mean} showed an increase ($MMK = 1.942$) with a magnitude of 0.004 °C/yearly. T_{max} ($MMK = 0.810$) and T_{min} ($MMK = 0.736$) also exhibited upward trends with the magnitude of 0.006 °C/yearly and 0.007 °C/yearly, respectively.

Perceived climate change

Most of the respondents from Bhil and Bhilala communities reported observing climate variability (Fig. 4). Over 85.4% of Bhil respondents and 75.19% of Bhilala respondents observed a decrease in the number of rainy days. Similarly, a higher percentage of respondents from Bhil (97.08%) and Bhilala (96.99%) reported irregular rainfall patterns, indicating widespread concerns about changing rainfall dynamics. Regarding temperature variations, 97.81% of Bhil and 96.99% of Bhilala respondents experienced an increase in temperature. Similarly, 96.35% of Bhil respondents and 96.99% of Bhilala respondents reported an increase in hot days, contributing to an overall perception of increased heat exposure (96.67%). These findings propose a strong consensus among the communities regarding the impacts of climate change, altered rainfall and rising temperatures.

Risk assessment

The integrated risk assessment of climate change impacts on the Bhil and Bhilala communities in Madhya Pradesh reveals valuable insights into these communities' hazards, exposure, sensitivity, and adaptive capacity (Fig. 5). The indexed values of risk assessment indicators for the Bhil and Bhilala communities are presented in Table A2 (as provided in supplementary materials).

Hazard

The overall hazard index is 0.36, with Bhil (0.37) and Bhilala (0.35) communities showing lower differences. The frequency of climate-related hazards such as floods, droughts, and hailstorms varies across the communities. Bhil respondents reported a flood frequency index of 0.11, while Bhilala respondents reported a slightly lower value of 0.08, resulting in an overall index of 0.10. The frequency of droughts over the last decade is higher in Bhilala (0.37) than in Bhil (0.32), yielding an overall index of 0.35. Similarly, hailstorm frequency was more pronounced among Bhil respondents (0.47) than Bhilala (0.31). The mean standard deviation of rainfall (0.30) and temperatures by month is consistent across the communities. The mean standard deviation of the daily

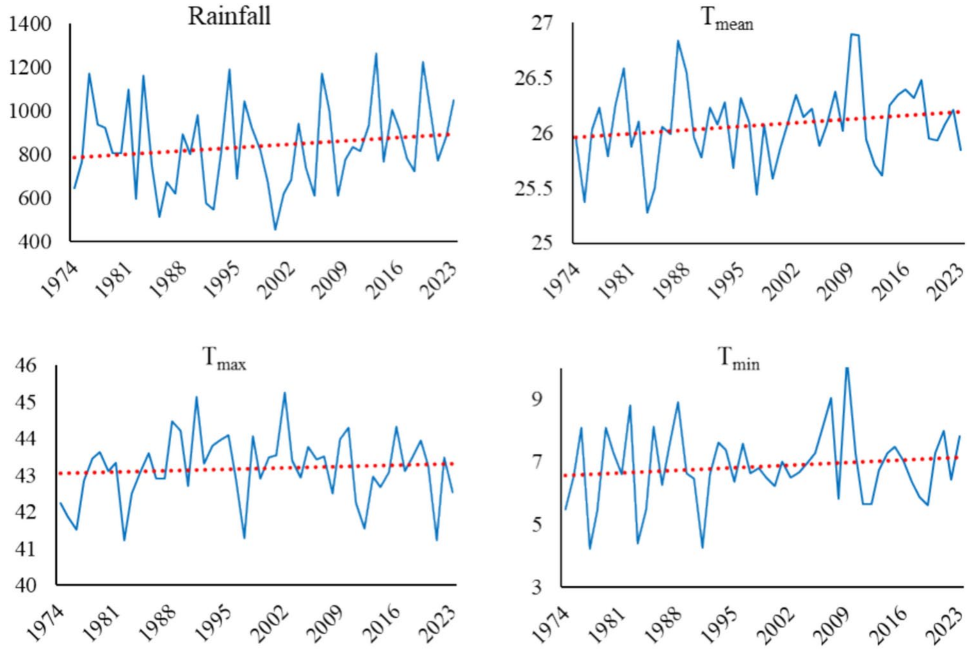

Fig. 3. Graphical representation of trend analysis results.

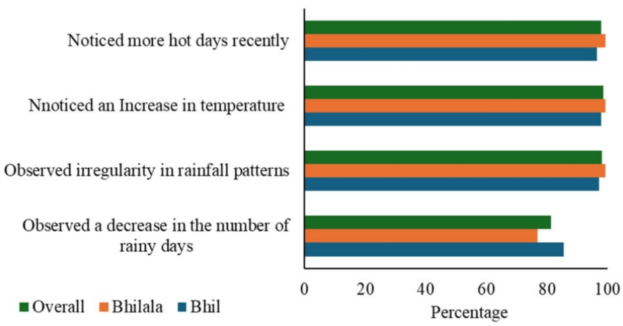

Fig. 4. Respondent's perception of climatic variability.

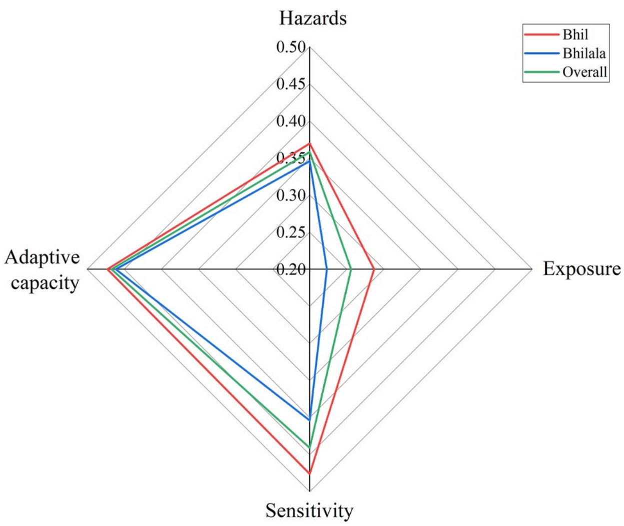

Fig. 5. Contributing factors of risk assessment.

average T_{min} (0.56) for the temperature variables is higher than T_{max} (0.46), supported by the perceived climate change.

Exposure
The overall exposure index is 0.26, with Bhil communities showing higher exposure (0.29) than Bhilala (0.22). Bhilala households held more land on average (3.6 acres) compared to Bhil (1.7 acres), contributing to an overall landholding index of 0.10. Irrigated land also showed better access for Bhilala (0.11) than Bhil (0.05). Rainfed agriculture was predominantly practiced by the Bhil community, covering 56% of their land, compared to Bhilala (19%), resulting in an overall index of 0.38. Bhil respondents also had better access to health services, with a shorter distance to the nearest health center (2.8 km) than Bhilala (3.9 km), but the overall accessibility index remained at 0.37. Housing structure vulnerability was higher among Bhil households (41%) living in Kutcha houses, compared to Bhilala (17%), contributing to an overall housing index of 0.29. Both communities had almost similar levels of accessibility to the main market (0.31). These indices point out the higher exposure of Bhil communities to climate risks in land use, agriculture, and housing conditions.

Sensitivity
Sensitivity to climate risks was more pronounced in Bhil communities (0.48) compared to Bhilala (0.40). Limited access to electricity and domestic drainage facilities escalates their vulnerability, with 72% of communities lacking domestic drainage facilities. The access to LPG connection was lower for Bhil (0.29) than for Bhilala (0.38). Firewood and dung cake remained the primary energy sources for 87% of households across both communities, exposing limited access to cleaner energy alternatives and more exposure to indoor pollution, leading to health issues. Regarding agricultural resilience, Bhil respondents had a higher crop diversity index (0.69) than Bhilala (0.31). Similarly, the livestock diversity index was higher for Bhil (0.62) than for Bhilala (0.33), demonstrating a broader base for livelihood diversification. Food security remains a major concern for both communities, with 66% of households reporting inadequate food for the entire year. The food insecurity index was close, ranging from 0.34 to 0.35, indicating the communities need more support from the government. The government advertised more about the public distribution system (*PDS*) during and after COVID-19, but a significant percentage of Bhil communities (15%) still lacking this benefit. Bhil households were more vulnerable regarding access to safe drinking water (0.45), and both communities reported significant groundwater depletion (0.91 for Bhil and 0.65 for Bhilala). After 10 years of "Har Ghar Sauchalay Yojana" (a scheme launched by the government of India in 2014 for toilets), 40% of Bhil and 42% of Bhilala are still struggling to access sanitary latrines. Around 32% of respondents still didn't practice preventive healthcare. Another scheme related to health, "Ayushman Bharat Yojana" (a scheme launched by the government of India in 2018 designed to achieve the vision of Universal Health Coverage), 40% of Bhil respondents were not benefitting from this scheme even in this digital era. These factors jointly increase the sensitivity of both communities, with the Bhil community showing higher sensitivity due to lower access to essential services and greater dependence on traditional practices.

Adaptive capacity
The overall adaptive capacity index to climate risks is 0.47, with Bhil slightly higher (0.47) than Bhilala (0.46). Education was a major differentiator, with Bhil households (0.55) lacking formal schooling compared to Bhilala (0.40). The dependency ratio was also higher in Bhil (0.26) than in Bhilala (0.18), indicating a larger proportion of the dependent population. Female-headed households were more prevalent among Bhil (0.48) than Bhilala (0.40). Agriculture remained the primary source of income for Bhilala (0.65) households compared to Bhil (0.29). The majority (47.4%) of Bhil households were working as labourers dominantly in agriculture. However, in the agricultural off-seasons, they do not have any employment opportunities, leading to a lack of food security. Livelihood diversification was limited across both communities, with a diversification index of 0.40 for Bhil and 0.42 for Bhilala. Migration for work or education was also low in Bhil (0.13) and Bhilala (0.11) families reporting migration in the past year, while 36% of overall respondents reported either they or their family members working outside the local area. Most respondents didn't undergo training or skill development programs to enhance their ability to generate income (0.97). Economic stability remains challenging for these communities as 94% of Bhil and 92% of Bhilala households lack permanent jobs. Around 80% of Bhil and 73% of Bhilala households relied on borrowing money, further highlighting economic vulnerability. When the government aims to achieve a trillion economy, a higher percentage of Bhil (0.8) and Bhilala (0.59) communities still live below the poverty line. The respondents who had heard about climate change before were low among both communities, in Bhil (0.31) and Bhilala (0.25), whereas understanding climate change was higher in Bhil (0.70) than in Bhilala (0.59). Access to communication or social media remains lacking in both communities (0.57). Similarly, access to transportation, vehicles, and banking services was limited, contributing to overall socioeconomic constraints. These results indicate that while awareness and some adaptive capacity exist, the socioeconomic challenges faced by both communities, especially Bhil, hinder their ability to adapt to climate risks.

Vulnerability and risk
The vulnerability index across both communities averaged 0.944, with Bhil having a higher vulnerability (1.007) than Bhilala (0.876). The increased vulnerability among Bhil communities is led by higher exposure to climate change and lower adaptive capacity. The overall risk index was calculated at 0.086, with Bhil facing a higher risk score (0.107) than Bhilala (0.068). The increased risk in Bhil is attributed to socioeconomic disadvantages, such as inadequate access to resources, poorer housing conditions, and lower educational status, which collectively limit the community's ability to respond to climate change impacts. However, Bhilala faces similar hazards but

has comparatively better adaptive capacity and lower exposure to climate change to contribute to a lower risk score.

Multiple linear regression analysis of risk determinants

The multiple linear regression analysis (Table A3, as provided in supplementary materials) identifies 12 out of 23 indicators as significant contributors to the climate change risk assessment for Bhil and Bhilala communities ($p<0.1$). The model's R-squared values indicate that 76% of the variance in the Bhil respondents, 73.8% in the Bhilala respondents, and 69.8% in the combined respondents is explained by the selected indicators, demonstrating a strong fit. Climatic events, mainly the frequency of extreme events such as floods, droughts, hailstorms over the past decade, are major determinants of risk for both Bhil ($\beta=0.015$, $p<0.01$) and Bhilala ($\beta=0.008$, $p<0.05$) communities, with a similar pattern observed in the combined sample ($\beta=0.017$, $p<0.01$). Sociodemographic factors**,** including age and occupation, show notable effects. Age negatively influences the risk index for Bhil households ($\beta=-0.001$, $p<0.01$), while farming as the primary occupation lowers the risk in both communities ($\beta=-0.015$, $p<0.05$). Infrastructure indicators significantly affect risk, particularly housing structure. Households living in Kutcha houses face increased risk in both Bhil ($\beta=0.07$, $p<0.01$) and Bhilala ($\beta=0.075$, $p<0.01$) communities. Landholding size contributes positively to risk for Bhilala households ($\beta=0.002$, $p<0.01$) but is insignificant for Bhil households. Food security emerges as an essential factor, with the number of crops growing significantly impacting risk in both Bhil ($\beta=0.012$, $p<0.01$) and Bhilala ($\beta=0.074$, $p<0.01$) households. Social security benefits, particularly from the *PDS*, reduce the risk for Bhilala ($\beta=-0.065$, $p<0.01$) and the overall respondents ($\beta=-0.032$, $p<0.01$). Awareness indicators demonstrate mixed results. Bhil households that have heard about climate change show a risk reduction ($\beta=-0.015$, $p<0.05$), while understanding climate change decreases risk for both Bhil ($\beta=-0.018$, $p<0.1$) and Bhilala ($\beta=-0.012$, $p<0.1$) communities. Financial stability significantly influences risk, with lower-income households residing below the poverty line facing higher risks across both communities. Health and water access indicators also play crucial roles, with the lack of access to safe drinking water increasing risk among Bhilala households ($\beta=-0.018$, $p<0.01$) and the total respondents ($\beta=-0.011$, $p<0.05$). These findings emphasize the multidimensional nature of climate risk, driven by climatic events, sociodemographic conditions, infrastructure, food security, awareness, and financial stability across both tribal groups.

Discussion

This study analyses the impacts of climate change on the livelihoods of Bhil and Bhilala communities in Madhya Pradesh, India. The integration of observed climate trends, household perceptions of climate variability, risk assessment, and vulnerability determinants highlight the composite nature of climate risk. These findings highlight the necessity of regional adaptation strategies considering socioeconomic conditions and environmental challenges, particularly for vulnerable, agriculture-dependent communities like the Bhil and Bhilala groups.

Observed climate trends and household perception of climatic variability

The observed climate trends, analyzed using the *MMK* test, show statistically insignificant increasing trends in rainfall and temperature from 1974 to 2023. These findings align with previous studies, though regional variations exist. For example, Jain et al.[36] identified increasing trends in annual and monsoon rainfall ($Z=0.192$ and 0.199, respectively) for west–central India from 1871 to 2016. Similarly, Kundu et al.[37] observed a long-term upward trend in annual, monsoon, and post-monsoon rainfall with a magnitude of 0.32, 0.37 and 0.02 mm, respectively, yearly within Dhar district over 111 years of data, while Duhan et al.[38] also reported a positive trend in annual ($Z=0.53$), monsoon ($Z=0.53$) and summer ($Z=0.61$) rainfall between 1901 and 2002. These findings imply that regional variations in rainfall could influence agricultural practices and water resources crucial to Bhil and Bhilala livelihoods, given their reliance on rain-fed agriculture[39]. Temperature analysis suggests similar regional warming patterns despite regional insignificance. Kundu et al.[39] found an increasing trend in T_{max} and T_{min} with the rate of 0.005 °C and 0.004 °C per year over 105 years in the Dhar district, while Devi et al.[40] also identified increasing T_{max} and T_{min} trends in Central India over 45 years (1971–2015). Rising temperatures can worsen crop stress and reduce yields, intensifying food insecurity among tribal communities if warming trends persist[41]. These communities are vulnerable to shifts in climatic variability that are not fully captured by local trends but align with broader regional patterns, compounded by their limited adaptive capacity[13].

However, despite these trends, the perceptions of Bhil and Bhilala households show a strong belief in climate variability. A higher proportion of households reported decreased rainfall days and increased irregularities in precipitation, temperature rise and experiencing more hot days, consistent with findings from similar rural communities in India that emphasize the increased vulnerability of rain-fed agriculture to perceived climate shifts[42–44]. This inconsistency between statistical trends and community perceptions indicates the importance of considering local experiences in climate risk assessments, where historical climate data could not comprehensively reflect the realities of vulnerable communities. The perceptions of Bhil and Bhilala households imply that climate variability already affects major livelihood factors such as water availability, food security, and agricultural productivity. It is consistent with findings from similar studies in semi-arid regions where communities report climate-induced disturbances despite limited evidence of long-term changes in climate data[12,14]. The strong perception of climate impacts calls for targeted adaptation interventions to improve water management, promote climate-resilient agriculture, enhance access to early warning systems, and government support for water and soil management[45].

Risk assessment and vulnerability

The overall index of contributing to vulnerability and risk factors is presented in Fig. 6. The risk assessment, calculated as a product of hazards, exposure, and vulnerability, presents Bhil households with a higher overall

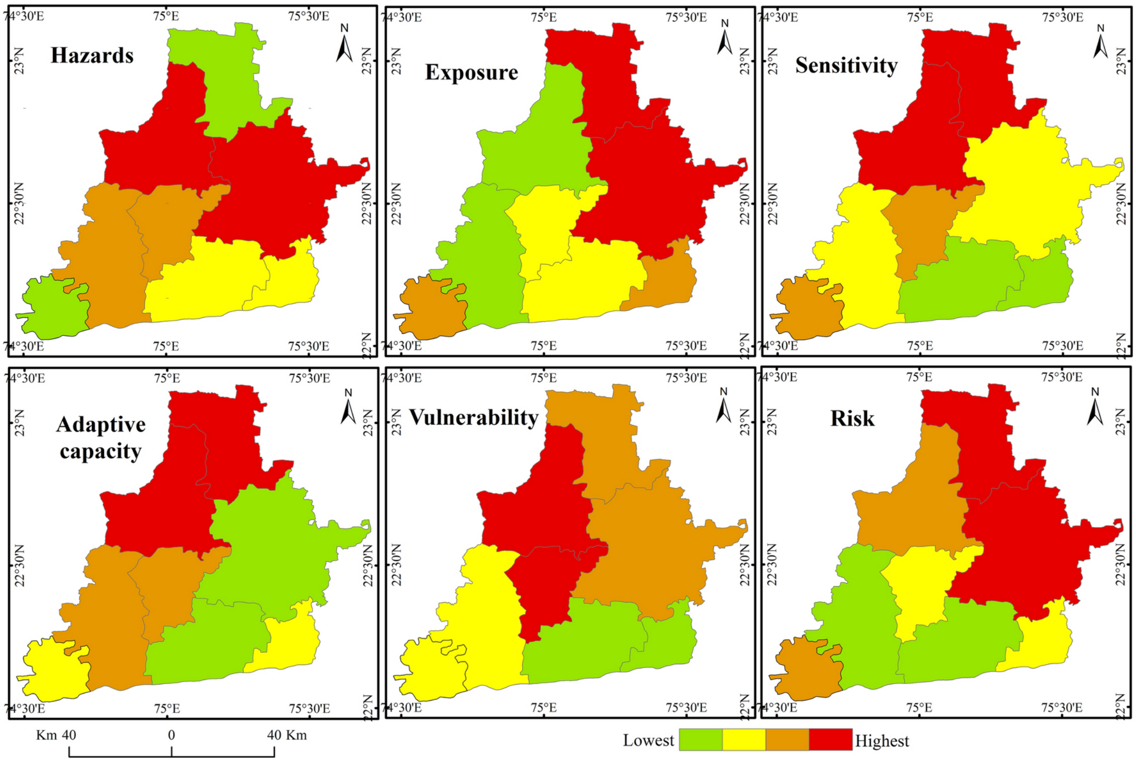

Fig. 6. Spatial distribution of indexed value of contributing factors, vulnerability, and risk in Dhar district. This map was created by authors using software ArcMap 10.8.

risk profile. The dependence on rainfed agriculture and limited irrigation infrastructure raises the vulnerability of Bhil households, whose agricultural productivity and food security are profoundly impacted by climate variability. The lack of adequate housing, safe drinking water, and sanitation facilities exacerbates their vulnerability because these basic needs are essential shields against climate-related events like floods or drought. It corresponds with prior studies emphasizing the increased vulnerability of tribal groups in India resulting from insufficient access to essential services and the exclusion of these areas from mainstream infrastructure development[20,33,46,47].

Bhilala households show lower adaptive capacity than Bhil households due to a higher awareness of climate change and access to climate-related information. Chetri et al.[48] and Sertse et al.[49] found that access to information extensively boosts households' ability to respond to climate risks. However, both communities express limited implementation of adaptive strategies, such as adopting climate-resilient farming practices and participating in skill development programs. Bhil households face serious economic barriers and lower educational attainment, which hinder proactive adaptation measures. It underlines the need for capacity-building initiatives tailored to these communities' socioeconomic contexts. Improved access to climate alerts and skill development programs that encourage livelihood diversification could dramatically improve the adaptive capabilities of these communities[13,41], reinforcing past appeals for targeted actions in vulnerable regions[50].

The persistent high-sensitivity indicators such as low crop diversity, dependence on traditional energy sources, and limited access to healthcare highlight an urgent need for inclusive strategies to augment adaptive capacity and overall resilience in the Bhil and Bhilala communities. Increasing crops and livestock diversity can offer households more robust sources of income and food security, thereby mitigating vulnerability to crop damage and economic losses[12,51]. Kumar et al.[52] and Ghosh[53] suggest that improving crop diversity among smallholder farmers in India enhances resilience to climatic risk. Additionally, transitioning from biomass fuels to clean energy sources would improve household health and lessen the labour burden, mostly on women, further supporting community resilience[54,55].

Infrastructure development emerges as a crucial focus area, recognizing the necessity of addressing deficiencies in transportation, communication, and market access that restrict these communities' inclusion into broader economic systems. Road infrastructure and communication network enhancement could facilitate more accessible and frequent access to markets and resources, aligning with Awokuse et al.[56], who support infrastructural investment to strengthen resilience in marginalized communities. Moreover, expanding collaborations with local institutions and NGOs could promote establishing early warning systems that enable communities to tackle climate challenges effectively[57]. These findings demonstrate the complicated relationship between socioeconomic condition, sensitivity, and adaptive capacity in the Bhil and Bhilala tribal communities. The greater sensitivity and diverse adaptation capacities highlight the urgent need for targeted interventions that respond to the risks of these communities. Fostering resilience and ensuring climate change issues do not jeopardize the socioeconomic well-being of the Bhil and Bhilala people who need an in-depth understanding of these processes. Mitigating these vulnerabilities is essential for supporting sustainable livelihoods in an ever-changing climatic future.

Determinants of risk assessment

As identified through multiple regression analysis, the determinants of risk emphasize the important role of exposure to extreme climatic events, sociodemographic factors, infrastructural access, and institutional factors. Increased exposure to climatic extremes such as droughts and floods significantly influences these communities' vulnerability, coherent with findings from rural communities in similar environmental situations[31,58,59]. The frequency and intensity of these occurrences directly affect agricultural productivity, further increasing food insecurity and financial instability[12,60,61] in the region.

Major sociodemographic factors, such as gender, age, educational level, and occupation, were found to influence the risk profile of households. For example, older people were less likely to understand higher risks due to accumulated knowledge and experience, although their physical capacity to adapt could be restricted. However, gender did not significantly affect risk in this study, probably due to the cultural and economic similarities in the roles of men and women in these communities. Similar studies have demonstrated that gender often plays an essential role in shaping vulnerability, as women typically face additional barriers related to decision-making and resource access in many rural areas[62,63]. The educational status of the household head insignificantly influences vulnerability, with the uneducated household head displaying higher vulnerability. Lu et al.[64] emphasize that education catalyzes resilience and adaptive capacity, extending access to information, adopting modern agricultural techniques, and decision-making in climatic events.

Infrastructural factors such as housing structure, access to electricity, and vicinity to health and market facilities emerged as significant determinants of risk assessment. Households with kutcha (mud) housing were more exposed to climate hazards, supporting results from studies in other tribal and rural areas emphasizing the correlation between poor housing and increased vulnerability[65,66]. Improving infrastructure, particularly housing and access to essential services, is necessary to reduce exposure to climate risks[67]. Diversified livelihood strategy also plays an important role in minimizing vulnerability, as households with multiple income sources were less sensitive to climate risks. It aligns with global research underlining diversified livelihood strategies for enhancing rural communities' resilience[22,52,68]. However, the dependence on rain-fed agriculture remains a significant challenge for both Bhil and Bhilala households, imposing efforts to promote alternative livelihoods and climate-resilient agricultural methods. Promoting diversified agricultural practices, implementing targeted skill development programs, and supporting small business initiatives can improve alternative income sources and economic resilience among vulnerable communities[69].

Moreover, access to government welfare programs, such as the public distribution system (PDS) Chief Minister Ladli Behna Yojana (CM-LBY) and Pradhan Mantri Kisan Samman Nidhi (PM-KSN), significantly reduce vulnerability, demonstrating the importance of social security in defending against climate-induced shocks[65,70,71]. Awareness of climate change and access to early warning systems also reduced climate risk. The study found that households that had heard of climate change or were familiar with early warning systems for natural disasters experienced lower vulnerability. Many tribal households still lack sufficient awareness and access to climate change information. Access to media is essential for climate change awareness and preparedness[72]. Enhancing digital literacy and internet access can reinforce information broadcasting[73]. Effective early warning systems rely on consistent communication, community involvement, and regular training[74]. It reinforces the significance of focused climate education and the development of early warning systems to boost adaptive capacity, especially among vulnerable populations. Educating families about climate risks and adaptative measures will enable them to adopt cautious strategies, thereby reducing their vulnerability to the impacts of climate change.

Conclusion

The study offers a multidimensional analysis of climate change impacts on the Bhil and Bhilala communities in Dhar district, Madhya Pradesh, revealing climate-induced vulnerabilities within these tribal populations. Climate data from 1974 to 2023 indicate higher temperature variability and intensified rainfall variations, aligning with households' perceptions of more frequent and severe climatic changes, particularly with increased temperature and irregular monsoon patterns. Based on the *IPCC-AR6* framework, the risk assessment shows that the interconnecting factors of frequent extreme weather events, sociodemographic vulnerabilities, inadequate infrastructure, and limited social security access contribute to the climate risk faced by these communities. Determinants such as the frequency of extreme climate events, housing structure, and access to essential services were impactful, with age and awareness about climate change also influencing perceived climate risk. Diversified livelihood strategies were associated with reduced vulnerability, highlighting the implication of adaptive capability. This assessment underlines the need for policies to encourage climate resilience practices for tribal populations. Policymakers, stakeholders, and academicians can more effectively focus on interventions that reduce vulnerability and enhance adaptive capacities. It will promote resilience within the Bhil and Bhilala communities that face climate-related challenges.

However, the study also has limitations concerning historical climate data, as it relies on past climatic trends to assess current and future risks, which cannot fully capture localized climate variations or emerging patterns. The research relied on primary data acquired via questionnaires; there is the possibility for bias in self-reported information, especially regarding perceptions of climate change consequences, which could impact the accuracy of the findings. Although the sample size is representative, future studies could benefit from a more varied and larger sample incorporating a broader range of tribal communities and regions to upgrade generalizability. Furthermore, the study primarily focuses on quantitative data, and integrating qualitative insights, such as community interviews, could offer a deeper understanding of the actual experiences of these communities and their adaptive strategies. While it highlights significant relationships between various indicators and risk, the model employed describes approximately 70–76% of the variance, leaving room for other unobserved variables that may contribute to risk levels. These limitations require further research to confirm and expand upon these findings.

Policy recommendations

The results of this study underline several essential areas for policy intervention to mitigate climate change risks in the Bhil and Bhilala communities. Strengthening resilience to climatic hazards is necessary, as extreme weather events such as floods and droughts influence vulnerability. Policies promoting climate-resilient infrastructure and sustainable agricultural practices, including drought-resistant crops and efficient irrigation systems, are crucial for minimizing the adverse impacts of climate change[75,76]. Similarly, improving access to essential services such as electricity, sanitation, and safe drinking water should be prioritized. The lack of such services exacerbates vulnerability, and the expanding rural infrastructure and strengthening government schemes like CM-LBY and PM-KSN will provide critical support during climate shocks[13,77]. With the prevalence of Kutcha houses, policy initiatives should focus on upgrading housing structures to be more resilient to climatic hazards. Providing subsidies or incentives for constructing durable and weather-resistant housing would reduce risk in these communities[78]. Furthermore, both communities had insubstantial awareness of climate change and access to early warning systems. Therefore, policies that promote adult education and skill-based training for households could play a transformative role in developing adaptive strategies[79].

Enhancing financial stability and promoting livelihood diversification are essential for increasing adaptive capacity. The findings reveal the vulnerability of households reliant on agriculture, emphasizing the need for policies that provide access to financial services such as low-interest credit, insurance, and income variation options. Policies that promote sustainable agricultural practices support community-based food security programs and improve access to PDS can mitigate food insecurity during climatic stress[80]. Supporting vocational training to augment livelihood opportunities beyond agriculture will further support resilience[81]. Simultaneously, these policy recommendations refer to the multidimensional aspects of climate vulnerability and offer pathways for reducing risk among the Bhil and Bhilala communities.

Methodology

Selection of study areas

Dhar district, located in southwestern Madhya Pradesh, lies between latitudes 22° 42′ N and 23° 10′ N and longitudes 75° 00′ E and 75° 26′ E (Fig. 7). It covers an area of 8153 km^2, which constitutes 2.64% of the state's total area. The district is segregated into three physiographic zones: the Malwa Plateau, Vindhya Range, and Narmada Valley. The southern region falls within the Narmada catchment, while the Chambal and Mahi rivers drain the northern areas. Dhar has 7.9% forest cover, mainly dry teak forests (Forest Survey of India, 2021) and experiences a dry climate with an average annual rainfall of 854 mm. May is the hottest month (average maximum temperature = 40 °C), and January is the coldest (average minimum temperature = 10 °C). As per the Census of India 2011, the total population of this district is 2,185,793 persons, with a decadal growth rate of 25.6%, where 81.1% of the population lives in rural areas. The population density is 268 persons per km^2, with a sex ratio of 964 women per 1000 men and a literacy rate of 59.0%. Scheduled tribes make up 55.9% of the population (1,222,814 persons), which makes Dhar the largest number of tribal people residents in the district of Madhya Pradesh. The district is home to many tribal communities such as Bhil, Bhilala, Gond, Bhil Mina, Bhunjia, Damaria, Kawar, Majhi, Korku, Munda, Oraon, Sahariya, Baiga, etc., but Bhil and Bhilala constitute highest proportion (Above 90%). Also, as per the study by Kumar & Mohanasundari[82] and Kumar et al.[83], this district is marked very high vulnerable due to climate change based on environmental and socioeconomic factors, making Dhar an important region for studying the impacts of climate change on tribal livelihoods.

Selection of indicators

Selecting appropriate indicators is essential for assessing climate vulnerability, although there is no universally accepted set[33]. Indicators must be applicable, quantifiable, and reflect hazards, exposure, sensitivity, and

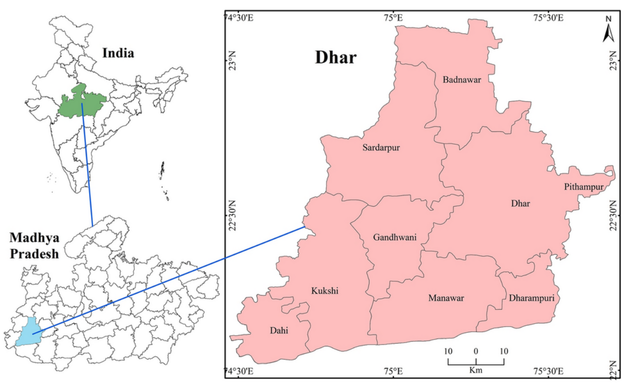

Fig. 7. Study area map. This Map was created by authors using software ArcMap 10.8.

adaptive capacity[84]. A participatory approach involving stakeholders is commonly applied to ensure context-specific application[85]. An extensive literature review and pilot survey identified major household vulnerability dimensions and indicators. It was refined through consultations with local environmentalists, agronomists, and economists to clarify the study area's socioeconomic conditions. The climate risk assessment indicators were grounded in theoretical and empirical literature[34]. A total of 74 indicators were initially selected, covering the four components of risk assessment per the *IPCC-AR6* framework: hazards, exposure, sensitivity, and adaptive capacity. These indicators were notified by previous studies[34,86,87], which underline the need to remove highly correlated variables to ensure robust results. Following Gujarati's (1995) guideline, the threshold criterion of 0.8 for correlation coefficients with highly collinear indicators was removed[88]. Finally, a set of 51 indicators was selected for this study to assess climate risk among tribal communities in Dhar district. These remaining indicators were then categorized into the respective risk components, with 6 indicators for hazards and exposure, 18 for sensitivity, and 21 for adaptive capacity (Fig. 8). These indicators were selected for their capability to widely represent the multidimensional nature of climate risk, encompassing climatic events, sociodemographic factors, infrastructure, food security, and livelihood strategies, in the Bhil and Bhilala communities.

Sampling framework and data collection

The sampling framework for this study was developed in four stages to ensure a suitable representation of the Bhil and Bhilala tribal communities. First, the sample size was calculated using Cochran's (1977) sampling method, which is widely recognized for its pertinence in large populations[34]. The formula determined the required sample size of 384 households based on a 95% confidence interval and a margin of error of ± 5%. However, this study exclusively focused on the Bhil and Bhilala communities, selected from a total tribal population of 1,222,814, which includes several other tribal groups (e.g., Gond, Bhil Mina, Korku, Sahariya). This intentional selection allowed the research to target the two communities most relevant to the study's objectives, providing deeper insights into their climate vulnerabilities. In the second stage, the calculated sample was proportionally distributed across the 27 selected tribal-dominated villages (Fig. 9), ensuring a representative sample (approx. 10 households) relative to the number of households in each village. Third, respondents were selected based on age, with only individuals above 18 years included to ensure that participants could provide informed consent and meaningful responses. Fourth, data quality was confirmed by sorting the collected samples and removing incomplete responses. This process resulted in a final valid sample of 267 households, comprising 137 Bhil (51.31%) and 130 Bhilala (48.69%) respondents.

Data collection was conducted from March to April 2024, utilizing face-to-face interviews based on the semi-structured interview schedule. Interviews were conducted in Hindi to ensure comfort and accuracy, and all responses were documented physically. Verbal informed consent was obtained from all participants before data collection. The questionnaire gathered detailed information on socioeconomic characteristics, livelihood practices, and access to essential utilities, including water supply, education, healthcare, drainage systems, transport, banking services, and proximity to markets. In addition to primary data, long-term historical data

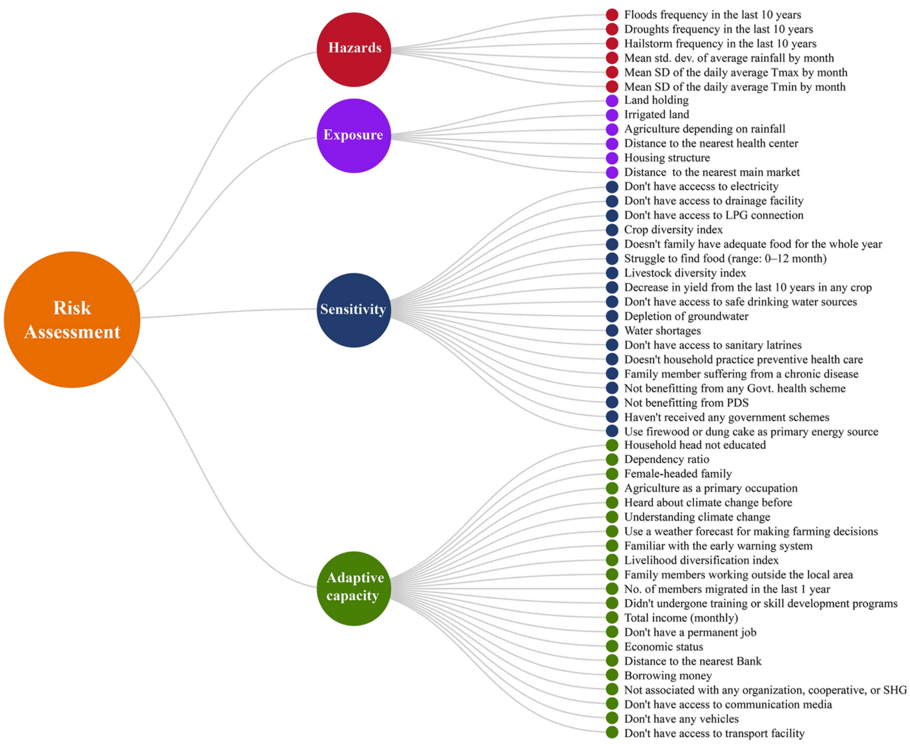

Fig. 8. Indicators used for risk assessment.

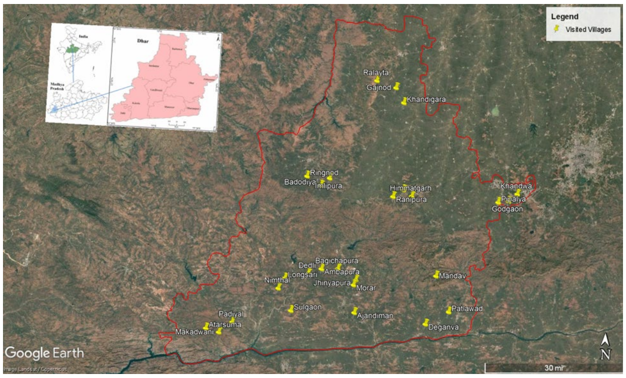

Fig. 9. Location of the villages visited in the study area. The maps were generated using Google Earth Pro (version 7.3) on desktop software (https://www.google.com/intl/en_in/earth/about/versions/#earth-pro).

(1974–2023) on rainfall and temperature were obtained from the Indian Meteorological Department (https://www.imdpune.gov.in/lrfindex.php). These data were used to analyze trends in climate variability and their potential impacts on the tribal communities' livelihoods.

Data analysis

This study employed multidimensional analytical methods to ensure a rigorous and comprehensive data assessment. Long-term climate variations were identified through the Modified Mann–Kendall (MMK) test[89], which offered detailed insights into changes in temperature and precipitation patterns over the 50 years. The perceived climate change was analyzed using descriptive statistics. The risk assessment was carried out using the *IPCC-AR6* framework, which provides an advanced, multidimensional approach to evaluating climate change risks. The *IPCC-AR6* framework separates risk into Exposure, Hazards, Sensitivity, and Adaptive Capacity, allowing for a systematic assessment of how different factors contribute to the vulnerability of the Bhil and Bhilala communities. Furthermore, a multiple linear regression (*MLR*) model was utilized to pinpoint the most influential factors contributing to household risk. Before running the regression analysis, several assumptions were meticulously tested. Multicollinearity was checked using the variance inflation factor (VIF) to guarantee the absence of highly correlated independent variables. Heteroscedasticity was examined using the White test, confirming that the model's residuals were homoscedastic, thus ensuring its validity[90]. After regression, robust checks were also performed to verify the consistency of the results and rule out potential model specification errors. Data cleaning, conversion, and preliminary analysis were done using Microsoft Excel to prepare structured and error-free datasets. R-Studio was employed for time-series analysis of temperature and precipitation trends. ArcMap 10.8 was used to create base maps. By integrating the *IPCC-AR6* framework, advanced statistical tools and tests, this study ensured a detailed understanding of the multidimensional risk tribal communities face in climate change. The Methodology, grounded in both field survey data and climate models, offers a scientifically robust foundation for assessing the impacts of climate change on tribal livelihoods.

Trend analysis

Trend analysis is crucial for detecting and quantifying long-term changes in time series data for environmental variables like rainfall, temperature, and other climate indicators[91]. The Modified Mann–Kendall (*MMK*) test and Sen's Slope (*SS*) are frequently used in climate studies.

Modified Mann–Kendall (MMK) test The Mann–Kendall (*MK*) test is a widely used non-parametric technique to detect trends in time series data without assuming the data's distribution[92]. However, when data exhibit autocorrelation (serial correlation), the standard *MK* test can create biased results. This problem is addressed by the *MMK* test, which corrects the original *MK* test by considering autocorrelation[93], thus providing a more accurate trend detection in the presence of autocorrelation. The test evaluates the null hypothesis (H_0), which shows no trend against the alternative hypothesis (H1), which has a monotonic trend in the data[94]. The *MK* statistic (*S*) is calculated using Eq. 1.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sign}(x_j - x_i) \tag{1}$$

where:

- x_i and x_j are the data points at times *i* and *j*, respectively.
- Sign($x_j - x_i$) is a function that returns:
  - $+1$ if $x_j - x_i > 0$
  - 0 if $x_j - x_i = 0$

- -1 if $x_j - x_i < 0$

Equation 2 give the variance of *S*.

$$Var\,(S) = \frac{n(n-1)(2n=5)}{18} \tag{2}$$

where n is the number of observations.

In time series data, positive autocorrelation can raise the magnitude of *S*, leading to an overestimation of trends. The *MMK* test accounts for this by adjusting the *Var (S)* based on the adequate sample size (*n'*) (Eq. 3), which is corrected for the presence of autocorrelation:

$$n' = n \times \left(\frac{1 - \sum_{k=1}^{n-1} \frac{\widehat{\rho_k}}{n-k}}{1 + \sum_{k=1}^{n-1} \frac{\widehat{\rho_k}}{n-k}} \right) \tag{3}$$

where:

- n is the original sample size.
- $\widehat{\rho_k}$ is the lag-k autocorrelation coefficient.

Sen's slope estimator (SS) While the *MMK* test detects the presence or absence of a trend, *SS* estimates the trend's magnitude[95,96,97]. It is a non-parametric approach that determines the slope between all pairs of data points[98]. The slope (Q_i) between two points in the time series is given by Eq. 4.

$$Q_i = \frac{x_j - x_i}{j - i} \tag{4}$$

For all $i < j$, x_i and x_j are the data values at time indices *i* and *j*.
The *SS* estimator (*Q*) is calculated using the Eq. 5.

$$Q_I = \begin{cases} P_{\left[\frac{(N+1)}{2}\right]}, & if\, N\, is\, odd \\ \frac{P_{\left[\frac{N}{2}\right]} + T_{\left[\frac{(N+2)}{2}\right]}}{2}, & if\, N\, is\, even \end{cases} \tag{5}$$

Calculation of risk index
The risk index was created following the *IPCC-AR6* framework, using risk as a function of hazards, exposure, and vulnerability, whereas vulnerability is a function of sensitivity and adaptive capacity. Before creating the risk index, all the indicators were normalized (0–1) using Eq. 6.

$$Normalisation = \frac{X\,(o) - X(a)}{X\,(b) - X(a)} \tag{6}$$

where *X(o)*, *X(b)*, and *X(a)* show the actual, maximum, and minimum values for each household, respectively.

An equal weight was assigned to all indicators and averaged to calculate the index of the indicator using Eq. 7.

$$M = \frac{\sum_{i=1}^{n} Normalisation}{n} \tag{7}$$

where n = no. of indicators, indexed by *i*,

M = index value of indicators.
After calculating the index, the contributing factors were computed using Eq. 8.

$$CF = \frac{\sum_{i=1}^{n} w_i M}{\sum_{i=1}^{n} w_i} \tag{8}$$

where CF = Contributing factors (hazards, exposure, sensitivity, and adaptation capacity), w_i = weight for each indicator, and M = index of the major indicators.

Once contributing factors were calculated, the risk index was computed using Eq. 9.

$$Risk = (Hazard \times Exposure \times Vulnerability) \tag{9}$$

where $Vulnerability = \frac{Sensitivity}{Adaptive\ Capacity}$

The risk index value was rescaled from 0 (least vulnerable) to + 1 (most vulnerable).

Multiple linear regression (MLR)

MLR is a statistical method that demonstrates the association between dependent and various independent variables[65]. In this study, *MLR* is used to identify the key factors influencing the risk assessment of climate change impacts on the livelihoods of the Bhil and Bhilala tribal communities. This method quantifies the effect of various socioeconomic, climatic, and infrastructural indicators on the overall climate risk. The *MLR* model is expressed in Eq. 10.

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots.. + \beta_n x_n + \varepsilon \tag{10}$$

where Y represents the dependent variable.

β_0 = intercept, representing the value of Y when all independent variables are zero.

$x_1, x_2, \ldots, x_n$ = independent variable (socioeconomic and environmental indicators in the study).

$\beta_1, \beta_2, \ldots, \beta_n$ = coefficients of the independent variables, indicating the strength and direction of the relationship between each predictor ($x_1, x_2, \ldots, x_n$) and the dependent variable.

ε = error term, capturing the variability in Y not explained by the independent variables.

The dependent variable for this study (*Y)* is the risk index derived from the vulnerability assessment using the *IPCC-AR6* framework. The independent variables included 1 variable for climatic events (no. of events including floods, droughts, and hailstorms), 4 sociodemographic variables (gender, age, education, occupation), 3 infrastructural variables (housing structure, access to electricity, land holding), 2 livelihood indicators (no. of livelihood strategies and family members migrated), 1 for food (crop diversity index), 3 for social security (benefitting from PDS, received any government schemes, distance to main market), 3 for awareness (heard about climate change before, understanding climate change, familiar with the early warning system), 2 for financial stability (monthly income), 2 for health (access to access to a sanitary latrine, distance to the nearest health centre), 1 variable for water (access to safe drinking water sources), and 1 variable for social network (access to communication media).

Data availability

All the data used in this study will be made available at minimal request from the corresponding author.

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Competing interests

We have nothing to declare.

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Additional information

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