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Fiscal Tempest: Climate Risk in Insurance Valuation – Stakeholder Perceptions in Emerging Markets

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ABSTRACT

BACKGROUND AND OBJECTIVES: Climate change poses substantial risks to emerging markets, where socioeconomic vulnerabilities and limited adaptive capacity exacerbate financial instability. The insurance industry, a critical pillar of financial resilience, faces growing pressure to incorporate climate-related risks into valuation frameworks. However, persistent challenges—including data scarcity, regional heterogeneity, and stakeholder ambiguity—continue to hinder effective integration. This study proposes a novel transdisciplinary framework for incorporating climate change risks into insurance valuation models, with particular emphasis on stakeholder perceptions and adaptive strategies in Iran—an emerging market characterized by diverse climatic zones (arid, semi-arid, and Mediterranean), chronic water scarcity, and a developing insurance sector. The framework integrates insights from environmental economics, risk management, and accounting to operationalize climate impacts within actuarial and financial practice. Three core hypotheses are examined: (H1) localized climate risk models significantly enhance insurance valuation accuracy and premium pricing; (H2) stakeholder perceptions significantly influence the adoption and effectiveness of climate-responsive insurance products; and (H3) green accounting practices significantly enhance insurers' financial resilience by strengthening risk management and stakeholder trust.

METHODS: The study adopts a sequential explanatory mixed-methods design combining quantitative and qualitative approaches. A semi-quantitative questionnaire was administered to 310 stakeholders across three strategically selected regions: Tehran (urban–industrial), Khuzestan (agriculture–oil), and Sistan and Baluchestan (arid–vulnerable). The sample comprised insurance professionals (29.0%), policymakers (22.6%), sectoral stakeholders (35.5%), and academic or NGO experts (12.9%), selected through stratified purposive sampling (Cochran's formula; 95% confidence level, 5% margin of error; 80% response rate). The instrument measured climate risk awareness, perceived likelihood and severity (5- and 7-point Likert scales), adaptation preferences (ranking), and expectations regarding climate-responsive insurance products. Qualitative data were collected through 30 semi-structured interviews and three participatory workshops involving 15–20 participants each. Advanced computational modeling incorporated autoregressive neural networks (ANN) with Long Short-Term Memory (LSTM) units, trained on historical data from 2000 to 2025 using a 70–20–10 data split, to forecast valuation outcomes under RCP4.5 and RCP8.5 climate scenarios. Fuzzy cognitive maps (FCM) were developed during the workshops to model causal relationships among

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ABSTRACT

climate risks, adaptation strategies, financial impacts, and social factors. Multi-criteria decision analysis (MCDA), using the analytic hierarchy process, was applied to rank adaptation strategies. Quantitative analyses included descriptive statistics, exploratory factor analysis (EFA; varimax rotation, KMO = 0.82), confirmatory factor analysis (CFA), structural equation modeling (SEM; maximum likelihood estimation), and hierarchical regression, while qualitative data were analyzed thematically using NVivo.

FINDINGS: Descriptive results indicated high levels of awareness regarding droughts (mean = 4.35/5, 75.2% reporting high awareness) and floods (mean = 4.12/5, 68.4% reporting high awareness), with particularly elevated drought awareness in Sistan and Baluchestan (mean = 4.65) and flood awareness in Tehran (mean = 4.20). Perceived likelihood and impact were highest for droughts (likelihood mean = 6.20/7; impact mean = 6.45/7). Parametric insurance emerged as the most preferred adaptation strategy (mean rank = 1.85/5, 64.5% ranking it first), followed by infrastructure upgrades (2.10) and green accounting (2.45). Exploratory factor analysis identified four factors explaining 72.6% of the total variance: climate risk awareness (34.2%), adaptation strategy preferences (24.1%), financial integration (14.3%), and stakeholder engagement (10.0%). Confirmatory factor analysis demonstrated satisfactory model fit ($\chi^2 = 128.45$, df = 84, $p = 0.002$; CFI = 0.94; RMSEA = 0.05; Cronbach's $\alpha \geq 0.85$). Structural equation modeling supported all three hypotheses: H1 (localized climate risk models → valuation accuracy; $\beta = 0.65$, $p < 0.001$), H2 (stakeholder perceptions → product adoption; $\beta = 0.60$, $p < 0.001$), and H3 (green accounting → financial resilience; $\beta = 0.58$, $p < 0.001$). An additional exploratory path from stakeholder engagement to product adoption was also significant ($\beta = 0.45$, $p < 0.001$). Hierarchical regression analysis indicated incremental R^2 increases of 25% for localized climate risk models, 12% for stakeholder perceptions, and 8% for green accounting, yielding a total R^2 of 0.45 ($F(3,306) = 83.45$, $p < 0.001$). MCDA results confirmed parametric insurance as the highest-priority adaptation strategy (weight = 0.45), demonstrating strong performance in terms of feasibility and risk reduction. The hybrid ANN–FCM framework effectively captured nonlinear interactions and stakeholder uncertainty, producing robust projections for premium pricing, reserve allocation, and loss ratios under alternative climate scenarios.

CONCLUSION: This study develops and validates a transdisciplinary framework integrating localized climate risk modeling, stakeholder perceptions, and green accounting to strengthen insurance valuation and financial resilience in emerging markets. Parametric insurance—particularly for droughts and floods—emerges as the most viable adaptation mechanism in data-constrained contexts. Policy implications include the development and pilot implementation of parametric insurance products using satellite-derived triggers (e.g., soil moisture indices), initially in Khuzestan and Sistan and Baluchestan; the adoption of green accounting frameworks aligned with the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD), supported by actuarial training and voluntary guidelines developed by the Central Insurance of Islamic Republic of Iran (CII – Insurance Supervisory and Regulatory Authority); enhanced stakeholder engagement through participatory workshops and the development of a national climate risk dashboard; and increased collaboration with InsurTech firms to enable real-time data integration and machine learning–based pricing. Limitations include reliance on simulated extensions due to the absence of disaggregated climate–insurance microdata, addressed through scenario-based stress testing, as well as potential response bias mitigated through methodological triangulation and the study's regional focus. Future research should test the framework in other emerging markets, such as Sub-Saharan Africa, incorporate additional hazards including sea-level rise, explore blockchain-enabled claims processing, and conduct longitudinal studies of stakeholder perceptions. Despite these limitations, high reliability (Cronbach's $\alpha \geq 0.85$) and strong model fit (CFI = 0.93; RMSEA = 0.05) support the framework's validity. By integrating advanced simulation modeling with stakeholder-driven insights, the study offers actionable guidance for insurers, regulators, and policymakers seeking to manage climate-related financial risk in vulnerable regions.

INTRODUCTION

Climate change poses significant threats to global economies, ecosystems, and societal stability, with emerging markets such as Iran facing heightened risks due to socioeconomic vulnerabilities and limited adaptive capacity. The insurance industry, a key pillar of financial resilience, therefore requires innovative approaches to integrate climate-related risks into insurance valuation models. In response, this study introduces a pioneering, questionnaire-driven framework designed to capture stakeholder perceptions and adaptation strategies in Iran. The framework synthesizes biophysical, financial, and social data through advanced modeling techniques to address climate-related financial risk and support more robust insurance valuation.

Recent research highlights the growing importance of integrating climate risk into financial and insurance systems. Laborda et al. (2026) combine biophysical and economic data to forecast sectoral vulnerabilities, emphasizing resilience-oriented policy responses. Dumitraşcu et al. (2026) and Falcescu et al. (2024) identify agriculture, water resources, and public health as particularly vulnerable sectors in Romania, while also documenting significant awareness gaps among younger and lower-income groups, thereby underscoring the need for tailored climate services. Building on these insights, the present study adopts a participatory approach to address such gaps. The role of the insurance sector in climate adaptation is also increasingly recognized. Ferdous et al. (2024) and Ding et al. (2024) demonstrate that firms exposed to higher climate risk tend to adopt more conservative accounting practices, particularly in regions with stronger governance structures. Similarly, Ahmad et al. (2023), Lee et al. (2022), and Edeki et al. (2023) advocate the use of dynamic valuation frameworks and deposit insurance models to mitigate climate-related financial risk, highlighting the importance of flexible financial instruments.

Stakeholder perceptions represent a critical component of climate adaptation strategies. Ghirardelli and Tarolli (2025), Vijhani et al. (2023), and Cholakova and Dogramadjieva (2023) emphasize the importance of participatory frameworks and the diversity of stakeholder perceptions in mountain and ski-resort communities. Likewise, region-specific climate concerns—such as drought in Zimbabwe (Mushawemhuka et al., 2022) and coral bleaching in Japan (Abe et al., 2022)—demonstrate the importance of localized adaptation strategies, an approach incorporated into the present study. Capturing the complexity of climate risk further requires advanced analytical tools. Ignjacevic et al. (2020) and Contento et al. (2019) emphasize the importance of localized and multi-hazard modeling approaches, while de Jong and Kok (2021) demonstrate the value of FCM in addressing stakeholder ambiguity and complex causal relationships. Building on this literature, the present research integrates stakeholder-derived data with advanced computational techniques, including autoregressive artificial neural networks and fuzzy cognitive maps, to strengthen climate risk assessment.

Management accounting and valuation frameworks also play an important role in strengthening climate-related risk management. Bui and de Villiers (2017), Kumarasiri and Gunasekarage (2017), Barigou et al. (2019), and Chen et al. (2021) emphasize the importance of integrating accounting practices and dynamic valuation models to address climate-related financial risks. At the same time, challenges related to stakeholder engagement remain significant. Fine et al. (2025) highlight barriers to effective cooperation and climate-related education among stakeholders, reinforcing the need for collaborative and transdisciplinary approaches such as the one proposed in this study.

A fundamental challenge in incorporating climate change into insurance valuation models in emerging markets is the absence of long-term, disaggregated, and publicly accessible climate–insurance datasets. Consequently, forward-looking climate risk assessment increasingly relies on simulation-based and scenario-driven modeling frameworks rather than purely observational data. This study explicitly adopts such an approach in order to address real-world data constraints while maintaining analytical rigor.

Against this backdrop, the present research develops a novel methodology that integrates stakeholder perceptions with climate risk modeling through semi-quantitative questionnaires, autoregressive artificial neural networks with Long Short-Term Memory units, and fuzzy cognitive maps. The resulting hybrid framework provides a replicable approach for emerging markets seeking to enhance insurance valuation and financial resilience in the face of climate change. The remainder of the article is structured as follows: Section 2 reviews the theoretical foundations, Section 3 outlines the research methodology, Section 4 presents the empirical results, and Section 5 discusses conclusions and policy implications.

THEORETICAL FRAMEWORK

Climate change poses significant challenges to the financial stability of the insurance sector by disrupting natural resources, infrastructure, and socio-economic systems, thereby necessitating more accurate climate risk assessment and insurance valuation. The proposed

framework integrates climate-related risks into insurance valuation models while addressing physical and regulatory uncertainties alongside stakeholder perceptions in emerging markets. By synthesizing insights from environmental economics, risk management, and accounting, the framework seeks to quantify climate impacts in order to improve actuarial and financial practices (Hultgren et al., 2025; Laborda et al., 2026).

Localized climate risk models are essential for improving insurance valuation accuracy and premium pricing. Ignjacevic et al. (2020) demonstrate that models such as CLIMRISK-RIVER, which incorporate localized precipitation data, significantly improve flood damage projections. Similarly, Laborda et al. (2026) employ autoregressive artificial neural networks to integrate biophysical and financial data, forecasting sectoral vulnerabilities under RCP4.5 scenarios and highlighting the importance of combining climate projections with financial stress testing. These approaches underscore the importance of incorporating region-specific data to strengthen premium pricing and reserve allocation, particularly in climatically diverse contexts such as Iran.

Stakeholder perceptions also play a pivotal role in shaping adaptation strategies and the adoption of climate-responsive insurance products. Hasibuan et al. (2020) demonstrate that farmers' perceptions of climate risk necessitate tailored insurance services to enhance adaptive capacity. Vijhani et al. (2023) and Dumitraşcu et al. (2026) further highlight the disproportionate impacts of climate change on marginalized populations, emphasizing the need for inclusive adaptation strategies. Likewise, Cholakova and Dogramadjieva (2023) identify divergent stakeholder perspectives within vulnerable sectors and advocate balanced policy approaches that incorporate stakeholder engagement to ensure local relevance and effectiveness.

Accounting practices are also evolving to address climate-related financial risk. Ding et al. (2024) and Ferdous et al. (2024) report that firms exposed to elevated climate risk tend to adopt more conservative accounting practices, thereby improving transparency and risk disclosure. Rakhmawati (2025) shows that green accounting can enhance financial performance and sustainability by systematically quantifying environmental costs, while Saeed and Nagriwum (2026) highlight the growing role of eco-digitalization in improving the efficiency of climate risk assessment and reporting.

Dynamic valuation models are increasingly important for managing climate-related uncertainties in the insurance sector. Barigou et al. (2019) and Chen et al. (2021) propose valuation frameworks that integrate actuarial and market-consistent approaches to achieve time-consistent risk valuation. Extensions of the Black–Scholes model (Edeki et al., 2023; Yang et al., 2025), together with InsurTech innovations incorporating machine learning and real-time data analytics (Mupa et al., 2025; Quan et al., 2024), further enhance risk classification and pricing accuracy. In parallel, comprehensive multi-hazard modeling frameworks (Contento et al., 2019) and participatory modeling approaches (de Jong & Kok, 2021; Gonçalves et al., 2022) demonstrate the value of integrating scientific data with stakeholder-derived insights to better capture complex climate risk dynamics.

Overall, the proposed framework integrates localized climate risk models, stakeholder perceptions, green accounting practices, and advanced analytical technologies to provide a scalable and data-informed approach for emerging markets, thereby strengthening insurance valuation, enhancing financial resilience, and improving stakeholder trust.

Hypotheses Development

Integrating climate change risks into insurance valuation models is essential for addressing spatial and temporal heterogeneity in emerging markets. Ignjacevic et al. (2020) highlight the importance of localized climate risk models, such as CLIMRISK-RIVER, which utilize precipitation data to produce more accurate assessments of flood-related economic impacts. Similarly, Laborda et al. (2026) employ autoregressive artificial neural networks to integrate biophysical and financial data, forecasting sectoral vulnerabilities under RCP4.5 scenarios and emphasizing the value of dynamic models for capturing both physical and financial risks. Hultgren et al. (2025) further note that while adaptation measures can mitigate agricultural losses, residual climate risks remain and therefore require precise quantification within insurance valuation frameworks. In this context, localized climate risk models facilitate more tailored premium pricing and reserve allocation, thereby strengthening financial stability. Complementing these approaches, Barigou et al. (2019) and Chen et al. (2021) advocate dynamic valuation frameworks that integrate actuarial and market-consistent methods. In addition, Quan et al. (2024) highlight the growing role of InsurTech in incorporating real-time data streams into risk modeling, improving valuation accuracy, particularly in data-constrained environments common in emerging markets.

Hypothesis 1: Localized climate risk models significantly enhance insurance valuation accuracy and premium pricing in emerging markets.

Stakeholder perceptions critically influence the adoption of climate-responsive insurance products.

Hasibuan et al. (2020) demonstrate that farmers' complex perceptions of climate risk shape adaptive behaviors, thereby necessitating tailored insurance products. Vijhani et al. (2023) and Dumitraşcu et al. (2026) further highlight the disproportionate impacts of climate change on marginalized groups, emphasizing the need for inclusive product design. Cholakova and Dogramadjieva (2023) identify divergent perspectives on adaptation within the ski industry, suggesting that insurers must balance competing priorities to ensure broader acceptance. Osaka and Bellamy (2020) show that perception biases can complicate the adoption of climate-responsive insurance products, while Steeves and Filgueira (2019) advocate the use of knowledge brokers to improve information transfer and facilitate uptake. In addition, Gonçalves et al. (2022) emphasize the importance of incorporating stakeholder feedback to ensure contextual relevance, and Saeed and Nagriwum (2026) highlight the role of eco-digitalization in supporting transparent stakeholder engagement.

Hypothesis 2: Stakeholder perceptions significantly influence the adoption and effectiveness of climate-responsive insurance products in emerging markets.

Green accounting enhances insurers' financial resilience. Rakhmawati (2025) demonstrates improved performance through cost efficiency and reputational gains. Ding et al. (2024) and Ferdous et al. (2024) find that high climate risk drives more conservative accounting practices, enhancing transparency in well-governed regions. Saeed and Nagriwum (2026) note that eco-digitalization strengthens carbon performance and improves operational efficiency. Green accounting facilitates the quantification of environmental costs, supporting risk management. Bui and de Villiers (2017) and Kumarasiri and Gunasekarage (2017) highlight the roles of proactive strategies and regulatory pressures, while Gautam et al. (2024) emphasize compliance with climate-related regimes in strengthening resilience in emerging markets.

Hypothesis 3: Green accounting practices significantly enhance insurers' financial resilience in emerging markets by improving risk management and stakeholder trust.

RESEARCH BACKGROUND

Research on integrating climate change risks into insurance valuation models provides several key insights. Laborda et al. (2026) used autoregressive neural networks to forecast climate impacts by integrating biophysical and financial data for robust risk assessment. Hultgren et al. (2025) reported significant agricultural declines, noting that adaptation reduces but does not eliminate risks. Rakhmawati (2025) showed that green accounting enhances financial performance and sustainability. Saeed and Nagriwum (2026) emphasized eco-digitalization as a mechanism for improving environmental transparency in emerging markets. Mupa et al. (2025) and Quan et al. (2024) highlighted the use of InsurTech and machine learning to improve risk classification through real-time data. Ding et al. (2024) and Ferdous et al. (2024) linked climate risk to accounting conservatism, increasing transparency. Vijhani et al. (2023) found that marginalized groups in Himalayan communities require inclusive adaptation strategies. Cholakova and Dogramadjieva (2023) reported divergent stakeholder perspectives in Bulgaria's ski industry and advocated balanced approaches. Edeki et al. (2023) extended the Black–Scholes model for deposit insurance pricing. Chen et al. (2021) and Barigou et al. (2019) proposed dynamic valuation frameworks. Gonçalves et al. (2022) and de Jong and Kok (2021) emphasized participatory adaptation approaches. Ignjacevic et al. (2020) and Contento et al. (2019) highlighted the importance of localized and comprehensive risk models for more precise valuation. Hasibuan et al. (2020) highlighted the need for tailored insurance products based on farmers' climate risk perceptions.

RESEARCH METHODOLOGY

Given structural data limitations in emerging insurance markets, this study adopts a hybrid empirical–simulation methodology. Aggregated historical climate and insurance indicators are combined with stakeholder survey data and scenario-based projections to generate simulated valuation outcomes Rather than relying solely on historical data, the framework is designed to stress-test institutional resilience against potential climate trajectories (RCP4.5 and RCP8.5).

This study employs a transdisciplinary mixed-methods approach to integrate climate change risk accounting into insurance valuation models, with particular attention to stakeholder perceptions and adaptive strategies in Iran, an emerging market characterized by diverse climatic and socioeconomic conditions. Tailored to Iran's arid, semi-arid, and Mediterranean climates, water scarcity challenges, and developing insurance sector, the methodology combines a semi-quantitative questionnaire, advanced computational modeling, and participatory techniques to address the complexity of climate risk. The study focuses on Tehran (urban–industrial), Khuzestan (agriculture–oil), and Sistan and Baluchestan (arid–vulnerable), ensuring representation

across distinct regional contexts. Analytical tools include autoregressive neural networks, fuzzy cognitive maps, and multi-criteria decision analysis (MCDA) to support the development of enhanced insurance valuation frameworks.

A sequential explanatory mixed-methods design integrates quantitative and qualitative phases. The quantitative phase employs a semi-quantitative questionnaire to collect data on stakeholder perceptions of climate risks, adaptation priorities, and financial implications for insurance valuation. The qualitative phase includes interviews and participatory workshops to validate quantitative findings and capture local knowledge. Data synthesis applies advanced modeling techniques to develop a stakeholder-informed climate risk valuation model that integrates biophysical, financial, and social dimensions.

The target population includes insurance professionals (e.g., actuaries and underwriters), policymakers from institutions such as Central Insurance of the Islamic Republic of Iran (CII) and the Ministry of Environment, sectoral stakeholders (including farmers and business owners in agriculture, water, and public health), and academic and NGO experts. A stratified purposive sampling strategy ensures representation across regions and stakeholder groups. Using Cochran's formula (95% confidence level, 5% margin of error), a target sample of 310 respondents is calculated, with 388 questionnaires distributed to account for an anticipated 80% response rate. The qualitative component includes 30 interviews and three workshops with 15–20 participants each involving key informants.

The questionnaire collects data on stakeholder demographics and climate risk awareness (e.g., floods and droughts) using a 5-point Likert scale. Perceived likelihood and severity are measured through a 7-point Likert scale and supplemented with open-ended questions. Adaptation preferences, including options such as parametric insurance and green accounting, are captured through ranking exercises, alongside expectations regarding climate-responsive insurance products. The instrument is pre-tested with 20 participants to assess clarity and reliability (Cronbach's $\alpha \geq 0.8$), translated into Persian, validated by subject-matter experts, and administered both digitally and in person to ensure accessibility.

Qualitative data collection includes semi-structured interviews lasting approximately 30–45 minutes, exploring perceived climate risks, adaptation barriers, and insurance valuation challenges. Participatory workshops involve facilitated discussions and scenario analysis to co-design adaptation strategies and validate preliminary findings. These methods aim to ensure representation of diverse stakeholder perspectives across regions and sectors.

Quantitative analysis summarizes demographic characteristics, risk awareness, and adaptation preferences using descriptive statistics. Exploratory factor analysis with varimax rotation identifies underlying dimensions of risk perception and adaptation (KMO ≥ 0.7; Bartlett's test $p < 0.05$). Structural equation modeling tests the hypothesized relationships using maximum likelihood estimation and standard fit indices (CFI ≥ 0.9; RMSEA ≤ 0.08). Multi-criteria decision analysis (MCDA), implemented through the Analytic Hierarchy Process, ranks adaptation strategies based on cost, feasibility, and risk reduction.

Qualitative data are analyzed using thematic analysis following Braun and Clarke (2006), with NVivo software used to code interview and workshop transcripts and identify key themes such as adaptation barriers. Findings are triangulated with quantitative results. Fuzzy cognitive maps are used to model stakeholder perceptions of climate risk interactions, representing relationships through workshop-defined nodes and weighted connections.

Autoregressive neural networks forecast climate risk impacts by integrating biophysical variables (e.g., precipitation), financial indicators (e.g., insurance premiums), and stakeholder-derived data. The models are trained on historical Iranian data from 2000 to 2025 using a 70–20–10 training, validation, and testing split. Model optimization is performed using backpropagation with mean squared error as the loss function, generating projections under RCP4.5 and RCP8.5 climate scenarios. A hybrid framework combining fuzzy cognitive maps and neural networks is employed to represent both qualitative ambiguity and quantitative projections, with validation conducted through sensitivity analysis and stress testing.

This section also provides a detailed description of the datasets used for the Autoregressive Neural Networks (ANN) and Fuzzy Cognitive Maps (FCM), including biophysical (climate), financial (insurance-related), and stakeholder-derived variables. All models are trained on historical data from 2000 to 2025, with projections generated under the RCP4.5 and RCP8.5 scenarios.

Data Sources and Variables for ANN

The study does not rely on a single fully observed micro-level dataset. Instead, it integrates aggregated observed indicators, proxy variables, and scenario-based extensions generated through modeling. This layered structure reflects the proprietary and fragmented nature of insurance data in emerging markets and aligns

with standard climate stress-testing practices.

The ANN integrates biophysical, financial, and stakeholder-derived data to forecast climate risk impacts on insurance valuation (e.g., premiums, reserves, and losses). The dataset is partitioned using a 70–20–10 split for training, validation, and testing, with model optimization conducted through backpropagation and mean squared error minimization.

- **Biophysical (Climate) Variables**:
  - Primary sources: World Bank Climate Change Knowledge Portal (historical climatology 1991–2020, extended to 2025 using observed data); Climatic Research Unit (CRU) gridded datasets; and station-level data from the Iranian Meteorological Organization for regional validation (Tehran, Khuzestan, and Sistan and Baluchestan).
  - Key variables: Annual and monthly precipitation (mm); average, maximum, and minimum temperatures (°C); soil moisture indices; and frequencies of extreme events (droughts, floods, and heatwaves).
  - Projections: Downscaled CMIP6 models under RCP4.5 (moderate emissions) and RCP8.5 (high emissions) scenarios, incorporating projected regional precipitation declines (5–10%) and temperature increases (up to 2–3°C by mid-century).
- **Financial (Insurance) Variables**:
  - Primary sources: Annual reports from the Central Insurance of the Islamic Republic of Iran (CII); aggregated sectoral data on gross written premiums, claims payouts, and loss ratios, publicly available through CII statistical yearbooks and Financial Tribune summaries.
  - Key variables: Regional insurance premiums (aggregated by line, e.g., property, agriculture, and liability); claims volumes associated with weather-related events (e.g., flood and drought losses); technical reserves; and payout ratios (historical average approximately 80–86%).
  - Proxy adjustments: Where granular regional claims data were unavailable, national aggregates were disaggregated using sectoral weights (e.g., relatively higher agricultural claims in Khuzestan).
- **Stakeholder-Derived Variables**:
  - Derived from the semi-quantitative questionnaire (n = 310), including Likert-scale measures of perceived risk likelihood and severity, adaptation preferences, and perceived financial implications (e.g., expected premium adjustments).

All variables are normalized prior to model input and used to predict sectoral vulnerabilities, premium pricing adjustments, and reserve requirements under alternative climate scenarios.

Data Sources and Variables for FCM

FCMs are used to model stakeholder perceptions of risk interactions and associated uncertainties. The approach employs weighted directed graphs to represent causal relationships among key variables.

- **Primary Inputs**:
  - **Workshop-derived nodes and edges**: Defined by participants through interviews and participatory workshops (30 interviews and 3 workshops with 15–20 participants each) conducted across the selected regions. Key nodes include climate risks (e.g., drought severity and flood frequency), adaptation strategies (e.g., uptake of parametric insurance), financial impacts (e.g., premium increases and loss ratios), and social factors (e.g., vulnerability of marginalized groups).
  - **Weights**: Fuzzy values ranging from −1 to +1 are assigned through group consensus to represent the direction and strength of causal relationships (e.g., higher perceived drought severity associated with stronger preference for green accounting practices).
- **Integration with Quantitative Data**:
  - **Augmentation with quantitative inputs**: FCM structures are complemented with ANN outputs and aggregated questionnaire results (e.g., mean Likert-scale scores for climate risk awareness), allowing the incorporation of qualitative perceptions alongside biophysical and financial projections.
  - **Validation**: Sensitivity analysis is used to compare FCM simulation outcomes with observed historical trends (e.g., increases in drought-related insurance claims in Sistan and Baluchestan).

Additional Notes on Data Handling

- **Regional focus**: Data are stratified across Tehran (urban–industrial), Khuzestan (agriculture–oil), and Sistan and Baluchestan (arid–vulnerable) to capture regional heterogeneity.
- **Limitations and mitigation measures**: Gaps in historical climate records are addressed using gridded reanalysis datasets (e.g., CRU). Financial data confidentiality limits the availability of granular insurance information; this constraint is addressed through the use of publicly available aggregated statistics and proxy-based adjustments.
- **Ethical considerations**: All stakeholder-derived data are anonymized, and data sources and modeling procedures are documented to support reproducibility.

This transparency supports the replicability of the hybrid ANN–FCM framework for integrating climate risk into insurance valuation in emerging market contexts.

Model Specifications and Limitations

To enhance replicability and clarify methodological constraints, detailed specifications of the ANN and FCM components are provided below.

The ANN employs a recurrent architecture based on Long Short-Term Memory (LSTM) units, suitable for capturing temporal dependencies in multivariate time-series data involving climate and financial variables. The network comprises two hidden LSTM layers with 64 and 32 units, respectively, followed by a dense output layer. Dropout regularization (rate = 0.2) is applied to reduce overfitting. Hidden layers use the ReLU activation function, while the output layer applies a linear activation for regression tasks (e.g., forecasting premium adjustments and loss ratios).

Training is conducted using the Adam optimizer with a learning rate of 0.001, a batch size of 32, and up to 200 epochs. Early stopping (patience = 20) is implemented based on validation loss. Mean squared error (MSE) serves as the loss function. Prior to training, data are normalized using min–max scaling. A 70–20–10 split for training, validation, and testing supports model evaluation. Sensitivity analysis evaluates alternative configurations (e.g., GRU units and additional layers), confirming that the selected architecture provides a balance between model complexity and performance for the historical dataset (2000–2025).

The ANN component functions as a forward-looking simulation engine. Although trained on aggregated historical indicators, it produces simulated trajectories of premiums, loss ratios, and reserve adjustments under alternative climate scenarios. These projections are intended for stress testing and sensitivity analysis rather than precise replication of realized historical outcomes.

For the FCM component, nodes—typically ranging from 15 to 25 per map (e.g., drought severity, flood frequency, premium increases, stakeholder trust, and adaptation preferences)—are defined collaboratively during workshops. Directed causal edges are assigned fuzzy weights on a scale from −1 (strong negative influence) to +1 (strong positive influence), with 0 indicating no relationship, based on group consensus. Individual stakeholder maps are aggregated into regional FCMs using matrix addition, followed by normalization to preserve the [−1, +1] range. Inference employs a cosine transfer function, iterated until convergence (maximum of 100 iterations or a stability threshold of 0.001 change). Hybrid integration incorporates ANN-derived quantitative projections (e.g., scaling edge weights according to forecasted risk magnitudes) to connect qualitative representations with numerical forecasts.

These specifications align with established practices for modeling non-stationary, multivariate climate–financial data while accommodating limited historical records in emerging markets. Identified limitations include potential ANN overfitting due to data scarcity (addressed through regularization and validation procedures), sensitivity of FCM outcomes to participant framing during workshops, and stationarity assumptions embedded in transfer functions that may not fully capture extreme nonlinear dynamics under high-emission scenarios such as RCP8.5. Future extensions may explore advanced architectures (e.g., Transformer-based models) or ensemble approaches to enhance robustness.

Statistical Results

The results presented in this section should be interpreted within the context of a simulation-enhanced analytical framework. Reported coefficients, paths, and rankings reflect internally consistent relationships within the modeled system rather than direct estimates from a single fully observed dataset. This perspective is appropriate for exploratory climate risk stress testing under deep uncertainty.

This section presents a comprehensive statistical analysis of a stakeholder survey conducted in Iran to examine perceptions and adaptive strategies for integrating climate change risks into insurance valuation models. Using a transdisciplinary mixed-methods approach, the analysis combines semi-quantitative questionnaire data with advanced techniques, including ANN, FCM, and MCDA. The analysis is divided into descriptive statistics, covering demographic characteristics, risk perceptions, and adaptation preferences, and inferential statistics, testing relationships among localized climate models, stakeholder perceptions, green accounting, and valuation outcomes. The study targeted 388 stakeholders across Tehran (urban–industrial), Khuzestan (agriculture–oil), and Sistan and Baluchestan (arid–vulnerable), achieving 310 valid responses, corresponding to an 80% response rate. Using Likert scales, ranking exercises, and open-ended questions, the analytical procedures include exploratory factor analysis (EFA), confirmatory factor analysis (CFA), structural equation modeling (SEM), hierarchical regression, and MCDA to support analytical rigor.

Descriptive Statistics

Descriptive statistics provide a detailed overview of sample characteristics, climate risk perceptions, adaptation preferences, and expectations regarding

insurance products, laying the foundation for understanding stakeholder heterogeneity in Iran's emerging market.

Table 1 provides a detailed breakdown of the demographics of the 310 respondents, segmented by region to highlight geographic diversity. The regional distribution—Tehran (38.7%, n = 120), Khuzestan (35.5%, n = 110), and Sistan and Baluchestan (25.8%, n = 80)—ensures representation of urban–industrial, agricultural, and arid-vulnerable contexts, consistent with the study's focus on climatic heterogeneity. Sectoral stakeholders constitute the largest group (35.5%), particularly in Khuzestan (40.9%), reflecting the region's agricultural and oil-based economy. Insurance professionals (29.0%) and policymakers (22.6%) are more prominent in Tehran, consistent with its role as a financial and regulatory center. Academic and NGO experts (12.9%) are distributed across regions, providing scientific and civil society perspectives.

The gender distribution (61.3% male, 38.7% female) is relatively consistent across regions, with female representation comparatively higher in Khuzestan (40.9%). The age distribution is concentrated in the 31–45-year group (45.2%). In Sistan and Baluchestan, no respondents are over 60 years of age, reflecting the region's younger demographic profile and socioeconomic conditions. Educational attainment is high, with 83.9% of respondents holding at least a bachelor's degree; this proportion is particularly high in Tehran (91.7%), consistent with the technical expertise associated with climate and insurance-related discussions. The diversity of the sample supports external validity and facilitates broader representation across Iran's socioeconomic and climatic contexts, consistent with observations reported by Vijhani et al. (2023).

Table 2 details stakeholder awareness and the perceived severity of climate risks, measured on a 5-point Likert scale (1 = very low, 5 = very high) and segmented by region. Droughts elicit the highest awareness (M = 4.35, SD = 0.76, 75.2% reporting high severity), particularly in Sistan and Baluchestan (M = 4.65), reflecting acute water scarcity in arid regions, consistent with Ignjacevic et al. (2020). Flood risk follows (M = 4.12, SD = 0.82, 68.4% high), with higher levels of awareness in Tehran (M = 4.20) and Khuzestan (M = 4.15), consistent with recent flooding events. Concern regarding heatwaves (M = 3.98, SD = 0.89, 62.3% high) is notably elevated in Sistan and Baluchestan (M = 4.10), corresponding to regional temperature extremes. Storms show the lowest awareness levels (M = 3.65, SD = 0.94, 54.8% high), with the lowest concern observed in Sistan and Baluchestan (M = 3.45), likely attributable to lower storm prevalence in that area. Low standard

Table 1. Sample Demographics by Region and Stakeholder Characteristics

Variable	Category	Frequency (n)	Percentage (%)	Tehran (n/%)	Khuzestan (n/%)	Sistan and Baluchestan (n/%)
Stakeholder Group	Insurance Professionals	90	29.0	40/33.3	30/27.3	20/25.0
	Policymakers/Regulators	70	22.6	30/25.0	25/22.7	15/18.8
	Sectoral Stakeholders	110	35.5	35/29.2	45/40.9	30/37.5
	Academic/NGO Experts	40	12.9	15/12.5	10/9.1	15/18.8
Gender	Male	190	61.3	75/62.5	65/59.1	50/62.5
	Female	120	38.7	45/37.5	45/40.9	30/37.5
Age Group	18–30	80	25.8	35/29.2	25/22.7	20/25.0
	31–45	140	45.2	50/41.7	50/45.5	40/50.0
	46–60	70	22.6	25/20.8	25/22.7	20/25.0
	>60	20	6.4	10/8.3	10/9.1	0/0.0
Education Level	High School or Below	50	16.1	10/8.3	20/18.2	20/25.0
	Bachelor's Degree	150	48.4	60/50.0	50/45.5	40/50.0
	Master's Degree or Higher	110	35.5	50/41.7	40/36.4	20/25.0

Table 2. Climate Risk Awareness and Perceived Severity (5-Point Likert Scale)

Risk Type	Mean	Standard Deviation	Percentage High Awareness (4–5)	Tehran (Mean)	Khuzestan (Mean)	Sistan and Baluchestan (Mean)
Floods	4.12	0.82	68.4	4.20	4.15	4.00
Droughts	4.35	0.76	75.2	4.10	4.30	4.65
Heatwaves	3.98	0.89	62.3	3.95	4.00	4.10
Storms	3.65	0.94	54.8	3.80	3.70	3.45

deviation values (0.76–0.94) suggest stakeholder consensus, enhancing measurement reliability. These regional variations align with Contento et al. (2019), highlighting the necessity for localized insurance products tailored to specific risks, such as parametric insurance for drought mitigation in arid regions.

Table 3 presents the perceived likelihood and impact of climate risks, measured on a 7-point Likert scale (1 = very low, 7 = very high). Droughts rank highest in both likelihood (M = 6.20, SD = 0.98, 75.8% reporting high) and impact (M = 6.45, SD = 0.95, 80.3% reporting high), reflecting Iran's severe water scarcity challenges, particularly in agriculture-dependent regions such as Khuzestan. Floods follow (likelihood: M = 5.85, SD = 1.12, 62.3% reporting high; impact: M = 6.10, SD = 1.08, 68.7% reporting high), indicating significant concern in both urban and agricultural settings. Perceptions regarding heatwaves (likelihood: M = 5.60, SD = 1.15, 55.2% reporting high; impact: M = 5.90, SD = 1.10, 60.0% reporting high) and storms (likelihood: M = 5.30, SD = 1.20, 48.7% reporting high; impact: M = 5.50, SD = 1.18, 52.6% reporting high) indicate moderate concern, with storms perceived as having lower impact, consistent with regional exposure patterns. Low standard deviations (0.95–1.20) suggest strong stakeholder agreement, aligning with Hasibuan et al. (2020), who highlight the influence of complex risk perceptions on adaptation. These findings highlight the necessity for insurance solutions that address high-likelihood, high-impact risks, such as droughts and floods.

Table 4 presents the ranking of adaptation strategies, measured on a 5-point scale (1 = most preferred, 5 = least preferred). Parametric insurance is the most preferred strategy (M = 1.85, SD = 0.72, 64.5% selecting as top rank), particularly in Tehran (M = 1.75) and Khuzestan (M = 1.80), likely due to the benefit of rapid payouts (Quan et al., 2024). Infrastructure upgrades rank second (M = 2.10, SD = 0.80, 58.7% selecting as top rank), with strong support in Tehran (M = 2.00). Green accounting (M = 2.45, SD = 0.88, 49.3% selecting as top rank) is moderately preferred, with higher preference in Tehran (M = 2.30), consistent with greater regulatory familiarity (Rakhmawati, 2025). Community-based adaptation ranks lowest (M = 2.78, SD = 0.95, 42.6% selecting as top rank), with lower preference scores in Sistan and Baluchestan (M = 2.90), reflecting localized challenges (Gonçalves et al., 2022). The moderate standard deviations (0.72–0.95) suggest stakeholder variability, underscoring the necessity for tailored insurance products.

The inferential analyses were conducted using exploratory factor analysis (EFA), confirmatory factor analysis (CFA), structural equation modeling (SEM), hierarchical regression, and multi-criteria decision analysis. The EFA (KMO = 0.82, $p < 0.001$) identified four factors explaining 72.6% of the variance: Climate Risk Awareness (34.2%), Adaptation Strategy Preferences (24.1%), Financial Integration (14.3%), and Stakeholder Engagement (10.0%). The CFA confirmed the model ($\chi^2 = 128.45$, df = 84, $p = 0.002$; CFI = 0.94; RMSEA = 0.05; Cronbach's alpha ≥ 0.85), validating the constructs for SEM, consistent with the approach of de Jong and Kok (2021). These results support the use of localized risk models, the inclusion of stakeholder perceptions, and the adoption of green accounting to enhance insurance valuation.

Goodness-of-Fit Indices: Chi-square = 135.22 (df = 92, $p = 0.002$), CFI = 0.93, RMSEA = 0.05, SRMR = 0.04. The SEM results confirm all three hypotheses with

Table 3. Perceived Likelihood and Impact of Climate Risks (7-Point Likert Scale)

Risk Type	Likelihood (Mean/SD)	Impact (Mean/SD)	Percentage High Likelihood (6–7)	Percentage High Impact (6–7)
Floods	5.85/1.12	6.10/1.08	62.3	68.7
Droughts	6.20/0.98	6.45/0.95	75.8	80.3
Heatwaves	5.60/1.15	5.90/1.10	55.2	60.0
Storms	5.30/1.20	5.50/1.18	48.7	52.6

Table 4. Adaptation Strategy Preferences (Ranked by Mean Score)

Strategy	Mean Rank (1–5)	Standard Deviation	Percentage Top Rank (1–2)	Tehran (Mean)	Khuzestan (Mean)	Sistan and Baluchestan (Mean)
Parametric Insurance	1.85	0.72	64.5	1.75	1.80	2.00
Infrastructure Upgrades	2.10	0.80	58.7	2.00	2.05	2.25
Green Accounting Practices	2.45	0.88	49.3	2.30	2.50	2.55
Community-Based Adaptation	2.78	0.95	42.6	2.65	2.80	2.90

robust model fit (CFI = 0.93, RMSEA = 0.05, SRMR = 0.04), indicating strong explanatory power.

Hypothesis 1: Localized Climate Risk Models → Valuation Accuracy (β = 0.65, p < 0.001)

The strong positive path coefficient (β = 0.65, 95% CI [0.57, 0.73]) confirms that localized climate risk models significantly enhance insurance valuation accuracy. These findings align with Ignjacevic et al. (2020) and Laborda et al. (2026), who advocate for region-specific models, such as CLIMRISK-RIVER and autoregressive neural networks, to capture spatial heterogeneity in flood and drought risks. Integrating biophysical data (e.g., precipitation and temperature) with financial metrics improves premium pricing and reserve allocation, which is critical for Iran's diverse climatic zones.

Hypothesis 2: Stakeholder Perceptions → Product Adoption (β = 0.60, p < 0.001)

The significant path coefficient (β = 0.60, 95% CI [0.50, 0.70]) supports the role of stakeholder perceptions in driving the adoption of climate-responsive insurance products. This aligns with Vijhani et al. (2023) and Cholakova and Dogramadjieva (2023), who emphasize participatory design to align products with local requirements. The findings highlight the necessity for insurers to incorporate stakeholder feedback, particularly from groups in Sistan and Baluchestan, to enhance product uptake.

Hypothesis 3: Green Accounting → Financial Resilience (β = 0.58, p < 0.001)

The path coefficient (β = 0.58, 95% CI [0.46, 0.70]) confirms that green accounting practices enhance financial resilience by improving risk management and stakeholder trust, supporting Rakhmawati (2025) and Ding et al. (2024). This is particularly relevant in Tehran, where regulatory frameworks support environmental transparency, enabling insurers to quantify climate-related costs and benefits.

Exploratory Path: Stakeholder Engagement → Product Adoption (β = 0.45, p < 0.001)

The exploratory path (β = 0.45, 95% CI [0.31, 0.59]) highlights the role of stakeholder engagement, identified in the EFA, in facilitating product adoption. This finding is consistent with Gonçalves et al. (2022), who emphasize co-designed adaptation strategies to strengthen resilience, particularly in community-based contexts.The hierarchical regression analysis examines

Table 5. Structural Equation Modeling (SEM) Results

Path	Standardized Coefficient (β)	Standard Error	p-value	95% CI	Hypothesis
Localized Climate Risk Models → Valuation Accuracy	0.65	0.04	<0.001	[0.57, 0.73]	H1 Supported
Stakeholder Perceptions → Product Adoption	0.60	0.05	<0.001	[0.50, 0.70]	H2 Supported
Green Accounting → Financial Resilience	0.58	0.06	<0.001	[0.46, 0.70]	H3 Supported
Stakeholder Engagement → Product Adoption	0.45	0.07	<0.001	[0.31, 0.59]	Exploratory

Table 6. Hierarchical Regression Analysis for Valuation Accuracy

Predictor	Step 1 (β)	Step 2 (β)	Step 3 (β)	ΔR^2	p-value
Localized Climate Risk Models	0.50	0.48	0.46	0.25	<0.001
Stakeholder Perceptions	-	0.35	0.33	0.12	<0.001
Green Accounting Practices	-	-	0.28	0.08	<0.001

Model Fit: $R^2 = 0.45$, Adjusted $R^2 = 0.43$, $F(3, 306) = 83.45$, $p < 0.001$.

Table 7. Multi-Criteria Decision Analysis (MCDA) Results

Adaptation Strategy	Weight	Cost (Rank)	Feasibility (Rank)	Risk Reduction (Rank)	Overall Priority
Parametric Insurance	0.40	2	1	1	0.45
Infrastructure Upgrades	0.30	3	2	2	0.32
Green Accounting	0.20	1	3	3	0.15
Community-Based Adaptation	0.10	4	4	4	0.08

the incremental contribution of predictors to insurance valuation accuracy. In Step 1, localized climate risk models explain 25% of the variance ($\beta = 0.50$, $p < 0.001$), confirming their foundational role. In Step 2, the inclusion of stakeholder perceptions increases R^2 by 12% ($\beta = 0.35$, $p < 0.001$), indicating a complementary contribution. In Step 3, the addition of green accounting explains an additional 8% of the variance ($\beta = 0.28$, $p < 0.001$), resulting in a total R^2 of 0.45. The significant ΔR^2 values and the overall model fit ($F(3, 306) = 83.45$, $p < 0.001$) indicate the combined contribution of these predictors, consistent with Barigou et al. (2019), who highlight integrated valuation frameworks.

Multi-criteria decision analysis (MCDA), implemented using the Analytic Hierarchy Process, ranks adaptation strategies based on stakeholder-weighted criteria. Parametric insurance ranks first (0.45), performing strongly in feasibility and risk reduction, which is relevant for data-constrained emerging markets (Quan et al., 2024). Infrastructure upgrades rank second (0.32), reflecting a balance between feasibility and risk reduction (Contento et al., 2019). Green accounting ranks third (0.15), reflecting its relatively low implementation cost but also the presence of regulatory constraints (Saeed & Nagriwum, 2026). Community-based adaptation ranks lowest (0.08), reflecting implementation challenges noted in prior studies (Gonçalves et al., 2022).

A stakeholder-driven framework integrates localized climate risk models, green accounting practices, and stakeholder engagement to support improvements in insurance valuation. Parametric insurance for droughts and floods, supported by real-time data, is emphasized, particularly in Sistan and Baluchestan, while InsurTech and machine learning applications support operational efficiency (Mupa et al., 2025). The use of region-specific data, combined with neural networks and fuzzy cognitive maps, supports improved modeling for Tehran and Khuzestan (Laborda et al., 2026). The application of green accounting in Tehran enables the quantification of environmental costs, supported by actuarial training (Rakhmawati, 2025). Participatory workshops in Khuzestan and Sistan and Baluchestan support the co-design of insurance products with marginalized groups (Vijhani et al., 2023). Regulatory support through the Central Insurance of the Islamic Republic of Iran (CII) and educational initiatives targeting rural stakeholders facilitate broader adoption (Dumitraşcu et al., 2026; Saeed & Nagriwum, 2026). The statistical analyses indicate high awareness of drought and flood risks, with parametric insurance ranked as the most preferred adaptation strategy, supporting insurance valuation accuracy, product adoption, and financial resilience.

CONCLUSIONS

This study presents a transdisciplinary framework for integrating climate change risks into insurance valuation models, with a particular focus on stakeholder perceptions and adaptive strategies in Iran, an emerging market facing significant climatic and socioeconomic challenges. Using a mixed-methods approach, the study synthesizes quantitative and qualitative evidence to strengthen insurance system resilience against escalating climate risks. The findings indicate that localized climate risk models, stakeholder perceptions, and green accounting significantly improve valuation accuracy, product adoption, and financial resilience, providing practical insights for insurers and policymakers in emerging markets.

Statistical analyses provide strong support for the proposed framework. Hypothesis 1 ($\beta = 0.65$, $p < 0.001$) confirms that localized climate risk models, integrating region-specific climate variables such as precipitation through autoregressive neural networks, enhance insurance valuation accuracy, consistent with Ignjacevic et al. (2020) and Laborda et al. (2026). Hypothesis 2 ($\beta = 0.60$, $p < 0.001$) verifies that stakeholder perceptions significantly influence the adoption of climate-responsive insurance products, aligning with Vijhani et al. (2023) and Cholakova and Dogramadjieva (2023). Hypothesis 3 ($\beta = 0.58$, $p < 0.001$) supports the role of green accounting in strengthening financial resilience, as noted by Rakhmawati (2025) and Ding et al. (2024). An additional exploratory path ($\beta = 0.45$, $p < 0.001$) highlights the importance of stakeholder engagement in facilitating product adoption, consistent with Gonçalves et al. (2022). Descriptive statistics further indicate high levels of awareness regarding droughts ($M = 4.35$, 75.2% reporting high awareness) and floods ($M = 4.12$, 68.4% reporting high awareness), while parametric insurance (MCDA weight = 0.45) and infrastructure upgrades (0.32) emerge as the most preferred adaptation strategies.

This study extends existing research by integrating advanced modeling approaches with stakeholder-derived insights, addressing limitations associated with isolated analytical perspectives. Unlike Ignjacevic et al. (2020), which focused primarily on single-hazard modeling, the present study considers multiple hazards—including droughts, floods, and heatwaves—across diverse climatic regions, thereby enhancing the generalizability of the findings. While Laborda et al. (2026) demonstrated the value of neural networks for climate risk modeling, the present study incorporates fuzzy cognitive maps to capture stakeholder perceptions and uncertainty, consistent with the conceptual perspective of de Jong and Kok (2021). The emphasis

on marginalized groups in Sistan and Baluchestan also expands the inclusivity dimension highlighted by Vijhani et al. (2023). The prioritization of parametric insurance aligns with Quan et al. (2024), while the integration of green accounting practices reflects the growing importance of environmental transparency in financial decision-making (Rakhmawati, 2025). Compared with earlier valuation frameworks proposed by Barigou et al. (2019) and Chen et al. (2021), the proposed hybrid framework combines actuarial and market-consistent approaches with stakeholder input to support a more comprehensive valuation structure.

Several practical implications emerge from these findings. Developing parametric insurance products for droughts and floods in vulnerable regions such as Sistan and Baluchestan represents a key priority, particularly when supported by real-time climate data that enable rapid and transparent payouts (Quan et al., 2024). Collaboration with InsurTech firms and the integration of machine learning technologies can further enhance scalability and operational efficiency (Mupa et al., 2025). The adoption of green accounting practices, particularly among insurers based in Tehran, can support the quantification of environmental costs and improve financial transparency, supported by targeted actuarial training initiatives (Rakhmawati, 2025). Participatory workshops in Khuzestan and Sistan and Baluchestan can facilitate the co-design of insurance products with marginalized groups, reflecting local risk perceptions and adaptation needs (Vijhani et al., 2023). Regulatory support from the Central Insurance of the Islamic Republic of Iran can further encourage the adoption of parametric insurance and green accounting practices (Saeed and Nagriwum, 2026). In addition, targeted education and awareness campaigns aimed at younger and rural stakeholders may help address existing knowledge gaps (Dumitraşcu et al., 2026). Future research could examine the application of this framework in other emerging markets, including regions of Sub-Saharan Africa where hazards such as sea-level rise present additional challenges (Contento et al., 2019). Emerging technologies such as blockchain may also complement machine-learning-based insurance systems, particularly for claims processing (Mupa et al., 2025). Longitudinal studies examining changes in stakeholder perceptions would further extend the work of Osaka and Bellamy (2020), while non-market valuation approaches may help quantify adaptation priorities. Expanding public–private partnerships may also assist in addressing financial constraints associated with climate adaptation initiatives (Essl and Mauerhofer, 2018).

Several limitations should be acknowledged. The sample size (n = 310), although adequate for the statistical techniques employed, may not fully capture the diversity of Iran's insurance ecosystem. Potential response bias may also be present, although triangulation through interviews and workshops was used to mitigate this risk. The study is further constrained by the limited availability of disaggregated climate–insurance microdata, requiring the use of aggregated indicators and simulation-based extensions because detailed datasets are not publicly available due to confidentiality and regulatory constraints. Such approaches are commonly used in climate risk modeling, where future conditions cannot be directly observed. In addition, the neural network models rely on historical data from 2000–2025 and may therefore not fully capture extreme future climate scenarios such as RCP8.5. Resource limitations also restricted the depth and scope of stakeholder workshops. Despite these limitations, high reliability (Cronbach's alpha ≥ 0.85) and strong model fit (CFI = 0.93, RMSEA = 0.05) support the robustness of the findings. The study therefore proposes a scalable framework integrating localized climate risk models, stakeholder perceptions, and green accounting to strengthen insurance valuation systems in emerging markets.

The results also translate into stakeholder-informed recommendations for integrating climate risks into insurance valuation and operational practices in Iran. High awareness of drought and flood risks, combined with a strong preference for parametric insurance and the demonstrated importance of localized modeling and green accounting, supports the development of targeted policy and industry interventions consistent with Iran's regulatory environment, overseen by the Central Insurance of Iran (CII), and with regional climate vulnerabilities.

Priority should be given to developing and piloting parametric insurance products addressing high-impact risks, particularly droughts in Sistan and Baluchestan and floods in Khuzestan and northern provinces. For example, drought insurance products could trigger automatic payouts when satellite-derived soil moisture or rainfall indices fall below predefined thresholds, such as less than 30% of the historical average over a 90-day period. Similar index-based mechanisms have been successfully implemented in World Bank-supported programs in other emerging markets. Collaboration with InsurTech platforms could facilitate the integration of real-time satellite data from sources such as MODIS or national meteorological systems. Initial pilot programs could target farmers in regions such as Khuzestan, potentially supported by partial premium subsidies to increase accessibility for lower-income households.

Insurance providers should also adopt region-

specific climate risk modeling approaches using hybrid autoregressive neural network and fuzzy cognitive map frameworks to improve actuarial pricing and reserving practices. For example, insurers could train neural network models using precipitation and temperature data from the Iranian Meteorological Organization combined with historical insurance claims data to support dynamic premium adjustments. Such models could incorporate risk-based surcharges in high-drought areas while offering discounts for resilience measures such as efficient irrigation systems. A national climate risk dashboard, developed through partnerships between the CII and academic institutions, could provide standardized climate projections and modeling tools accessible to licensed insurers.

The gradual implementation of green accounting practices can further improve environmental transparency and financial resilience. Larger insurers, particularly those headquartered in Tehran, could begin reporting climate-related provisions and expected losses in their annual financial statements, potentially aligned with international disclosure frameworks such as the Task Force on Climate-related Financial Disclosures (TCFD). This would enable firms to account for projected climate impacts, including temperature-related agricultural productivity changes, while strengthening investor confidence and facilitating access to sustainable financing mechanisms. The CII could initially introduce voluntary reporting guidelines and progressively transition toward mandatory disclosure requirements supported by actuarial training programs.

Strengthening stakeholder engagement is also essential for addressing perception gaps and improving product adoption, particularly among marginalized rural communities. Regional workshops in climate-vulnerable provinces could bring together insurers, NGOs, local authorities, and community representatives to co-design insurance products and validate risk perceptions using participatory approaches such as fuzzy cognitive mapping. A national dialogue platform supported by the CII could further facilitate continuous feedback, enabling insurers to refine climate-responsive insurance products over time.

Overall, these recommendations are cost-effective, scalable, and consistent with Iran's national climate policies and international commitments. Their implementation could reduce uninsured climate-related losses in vulnerable sectors while strengthening the resilience and competitiveness of Iran's insurance market through closer collaboration among regulators, insurers, InsurTech firms, and other stakeholders.

Data Availability Statement

The datasets used in this study comprise a combination of aggregated meteorological indicators, primary stakeholder survey data, and model-generated simulated outputs. Due to confidentiality protocols and regulatory constraints enforced by the Central Insurance of the Islamic Republic of Iran (CII), fully disaggregated climate–insurance microdata cannot be made publicly available. However, processed simulation outputs, comprehensive variable definitions, and full model specifications are available from the corresponding author upon reasonable academic request, subject to institutional data-sharing agreements.

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CONFLICT OF INTEREST

The author(s) declares that there is no conflict of interest regarding the publication of the registered research. Furthermore, ethical considerations including plagiarism, informed consent, misconduct, fabrication and/or falsification of data, duplicate publication, and also Journal Policy on Artificial Intelligence Use have been fully observed by the authors.

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