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SPATIOTEMPORAL ASSESSMENT OF CLIMATE CHANGE IMPACTS ON CEREAL CROP YIELDS IN PAKISTAN THROUGH SATELLITE BASED AND GEOSTATISTICAL APPROACHES: A SYSTEMATIC REVIEW

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ABSTRACT

Climate change significantly threatens cereal production in Pakistan, where wheat, rice, and maize constitute primary food sources for over 220 million people. Remote sensing and geospatial technologies have emerged as indispensable tools for monitoring climate-induced yield variations; however, a systematic synthesis of this research domain remains absent. This PRISMA 2020-compliant systematic review synthesizes evidence on satellite-based assessment of climate change impacts on cereal yields in Pakistan (2016-2025), identifies research trends and geographical gaps, and provides evidence-based recommendations. A comprehensive Scopus search conducted on November 3, 2025, using structured queries encompassing climate variables, cereal crops, geographic focus, and geospatial methodologies yielded 179 articles. After systematic screening, 140 peer-reviewed articles meeting inclusion criteria underwent qualitative synthesis and thematic analysis Thematic analysis identified seven major research domains: (1) vegetation indices-based monitoring using Normalized Difference Vegetation Index (NDVI) (344 mentions, most prevalent), (2) water stress and irrigation management (106), (3) food security implications (72), (4) drought monitoring and assessment (68), (5) machine learning and AI applications (61), (6) climate change adaptation strategies (56), and (7) spatiotemporal variability assessment (44). NDVI emerged as the dominant satellite index (23 studies) with Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat as primary platforms. Wheat dominated research focus (17 studies), while maize remained understudied (3 studies). Geographic analysis revealed severe imbalance: Punjab dominated with 141 mentions whereas Khyber Pakhtunkhwa showed critical underrepresentation (15 mentions). This review identifies critical gaps in geographic coverage, crop diversity, long-term temporal studies, and advanced geostatistical applications. These findings provide a roadmap for evidence-based climate-resilient agricultural policies in Pakistan.

KEYWORDS: Climate Change; Cereal Crops; Remote Sensing; NDVI; Pakistan; Systematic Review; PRISMA 2020; Spatiotemporal Analysis; Machine Learning; Food Security.

1. INTRODUCTION

Pakistan's agriculture sector faces unprecedented challenges from climate change, with cereal production systems particularly vulnerable to rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events. As the world's fifth most populous country with over 220 million inhabitants, Pakistan depends heavily on wheat, rice, and maize production, which together constitute the foundation of national food security and rural livelihoods (G. Rahman, Khalid, Arshad, Moazzam, et al., 2025). The agricultural sector contributes approximately 24% to the national GDP and employs nearly 45% of the labour force, making climate-induced agricultural disruptions a critical concern for economic stability and social welfare.

Recent evidence indicates that Pakistan is among the countries most affected by climate change globally, experiencing significant warming trends, erratic monsoon patterns, and intensification of drought and flood cycles. (Usama et al., 2025) documented precipitation deficits of 44.7% in February and 63.5% in August—critical months for crop development—along with marked warming trends of +2.7°C in February and +0.5°C in March during 1991-2023. The devastating 2010 floods and the severe drought period of 1998-2002 exemplify the climate extremes that have become increasingly frequent, with profound impacts on cereal production systems (Ullah et al., 2023).

The advent of remote sensing and geospatial technologies has revolutionized agricultural monitoring capabilities, offering unprecedented opportunities for large-scale, continuous assessment of crop conditions and climate impacts. Satellite-based indices such as the Normalized Difference Vegetation Index (NDVI), Vegetation Condition Index (VCI), and Temperature Condition Index (TCI) have emerged as powerful tools for monitoring crop health, detecting stress conditions, and predicting yields (G. Rahman, Khalid, Arshad, Moazzam, et al., 2025). The integration of machine learning algorithms with satellite data has further enhanced predictive capabilities, with recent studies achieving forecast accuracies exceeding 95% for wheat yield prediction (Ashfaq, Khan, Afzal, et al., 2025).

Despite the proliferation of research utilizing satellite-based approaches for climate-agriculture assessments in Pakistan, the literature remains fragmented and lacks systematic synthesis. Individual studies have focused on specific regions, crops, or methodologies, but no comprehensive review has integrated these diverse findings to identify patterns, gaps, and future research priorities. This systematic review addresses this critical knowledge gap by synthesizing evidence from 140 peer-reviewed studies published between 2016 and 2025, providing the first comprehensive assessment of how satellite-based and geostatistical approaches have been employed to understand climate change impacts on Pakistan's cereal production.

The primary objectives of this systematic review are threefold. First, to synthesize current knowledge on satellite-based assessment of climate impacts on cereal yields in Pakistan and identify dominant research themes, methodological trends, and geographic patterns. Second, to evaluate the integration of remote sensing with climate modelling for yield prediction and assess documented adaptation strategies. Third, to identify critical research gaps requiring urgent attention.

2. METHODOLOGY

This systematic review was conducted employing a rigorous methodological framework to comprehensively investigate the spatiotemporal assessment of climate change impacts on cereal crop yields in Pakistan through satellite-based and geostatistical approaches. The Scopus database served as the sole source for literature identification, a decision grounded in its recognized comprehensive coverage of high-quality, peer-reviewed literature across the relevant disciplines of environmental science, agricultural science, and geomatics (Jabeen, Khan, Bhatti, Khan, et al., 2025; Rattanawiboonsom et al., 2025). Scopus's robust indexing and advanced search functionalities were instrumental in executing a precise and replicable search strategy, ensuring the retrieval of the most pertinent scientific publications(Sikandar & Abdul Kohar, 2022).

Scopus was selected as the exclusive database for this systematic review due to its comprehensive coverage of agricultural and Earth sciences journals (Baas et al., 2020), superior indexing of regional publications from South Asian institutions, and standardized metadata that facilitates systematic screening(Martín-Martín et al., 2018). Compared to Web of Science, Scopus demonstrates broader coverage of conference proceedings and emerging journals relevant to remote sensing applications in developing countries (Mustapha et al., 2023). While Google Scholar offers wider coverage, its lack of systematic quality control and metadata standardization makes it unsuitable for rigorous systematic reviews. The exclusive use of a single database represents a methodological limitation, discussed further in the Limitations section, though Scopus coverage is considered comprehensive for the study geographic and thematic scope(Jabeen, Khan, Bhatti, Falahat, et al., 2025; Sikandar et al., 2023).

The study selection process was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement. The PRISMA framework was explicitly chosen to uphold the highest standards of methodological transparency, rigor, and reproducibility throughout the identification, screening, eligibility, and inclusion phases(N. Khan et al., 2025; Page et al., 2021). Adherence to these established guidelines mitigates selection bias and enhances the reliability of the review's findings. The initial search string was designed to capture studies intersecting the core concepts of climate variables, cereal crops in Pakistan, and remote sensing or geospatial methodologies.

A systematic screening process was then implemented based on pre-defined eligibility criteria. Studies were included if they constituted original research published in English between 2016 and 2024, focusing specifically on the influence of climate variables on wheat, rice, or maize yields in Pakistan, and explicitly utilized satellite data or geostatistical analysis. The initial search yielded 179 records. Following the application of a publication year filter, 160 records underwent a thorough full-text eligibility assessment. This assessment led to the exclusion of 20 studies, primarily for not being original research articles or for not employing the requisite methodological approaches. Ultimately, 140 studies satisfied all inclusion criteria and were synthesized in this review.

Data extraction from the final set of included studies was performed systematically to facilitate a thematic synthesis. The extracted information encompassed key details such as the specific geographical focus within Pakistan, the climate variables and remote sensing indices analysed, the satellite platforms and geostatistical models employed, and the principal findings concerning climate-crop yield relationships. This analytical approach allowed for a comprehensive evaluation of the evidence on spatiotemporal patterns of climate change impacts across Pakistan's diverse agro-ecological zones, while also identifying prevailing methodological trends and critical research gaps in the field.

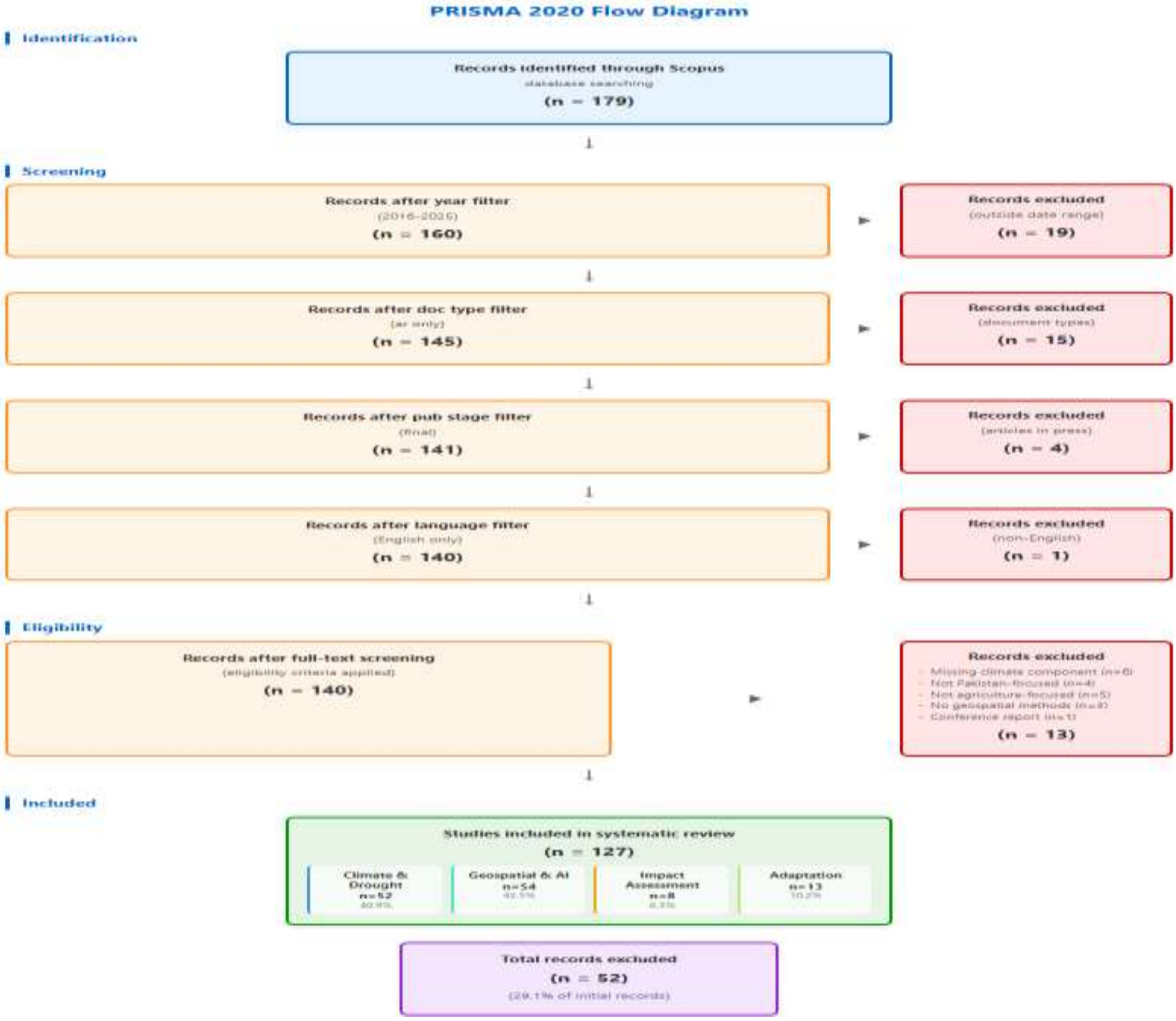

Figure 1: Prisma 2020 Flow Chart for Inclusion and Exclusion Criteria

2.1. Descriptive Analysis

2.1.1. Publication Growth

Figure 2 depicts the annual and cumulative publication trends for studies focusing on the spatiotemporal assessment of climate change impacts on cereal crop yields in Pakistan using satellite-based and geostatistical approaches. The yearly publication count shows gradual growth from 2016 to 2020, followed by a sharp rise after 2021, reflecting the increasing research interest in integrating remote sensing, GIS, and geostatistical tools for climate-agriculture studies. The cumulative trend line highlights a continuous upward trajectory, indicating that the field is maturing, with accelerating contributions in recent years driven by advancements in data availability, computational tools, and policy relevance concerning agricultural resilience to climate change.

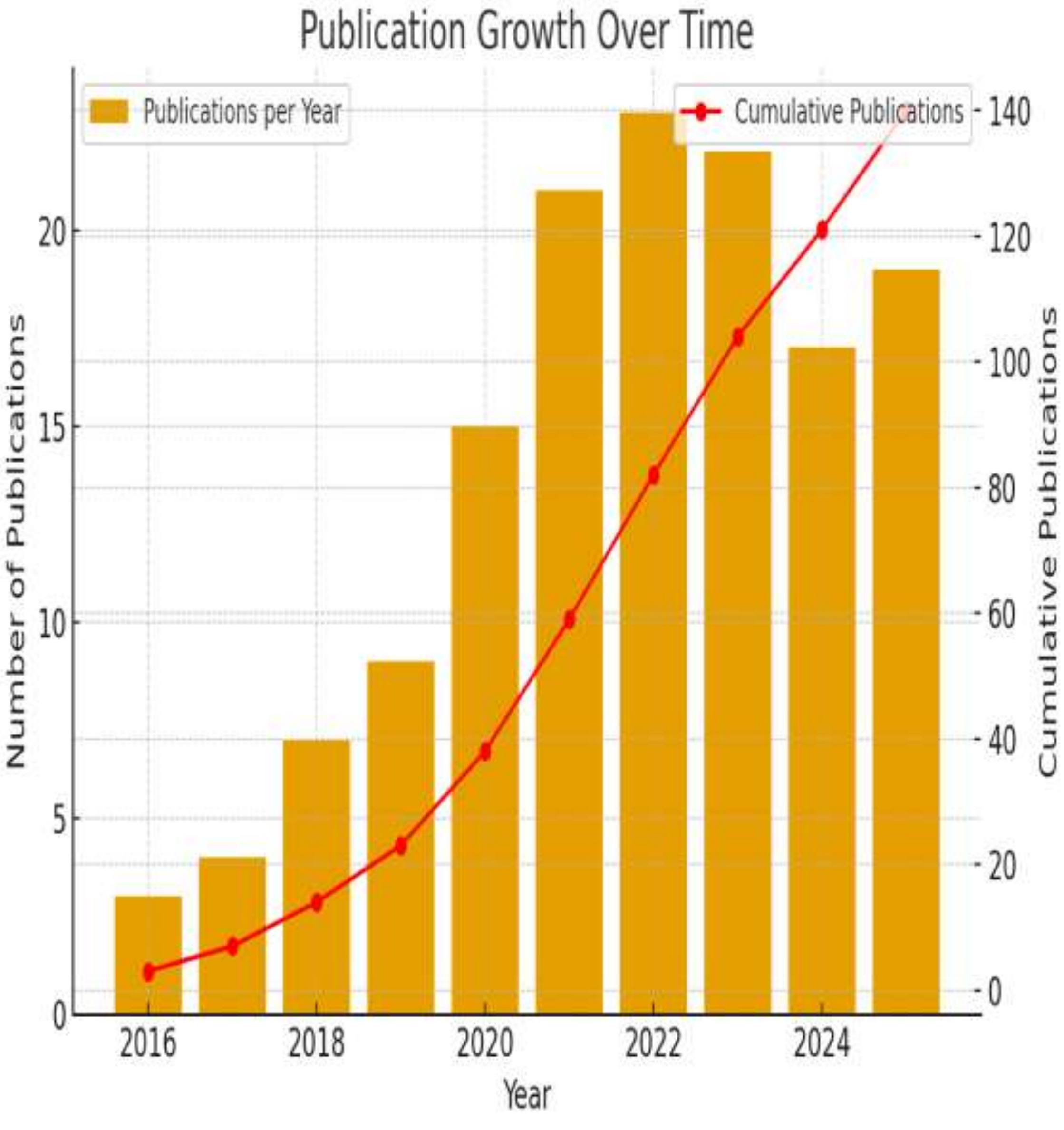

Figure 2: Publication Growth Over Time.

2.2. *Subject Area*

Figure 3 presents the subject-wise distribution of publications related to Spatiotemporal Assessment of Climate Change Impacts on Cereal Crop Yields in Pakistan. The majority of studies fall under Environmental Science (58 publications), Earth and Planetary Sciences (48), and Agricultural and Biological Sciences (47), reflecting the strong environmental and agronomic orientation of the research domain. Moderate representation in Social Sciences (21) and Computer Science (11) indicates growing interdisciplinary interest, particularly in modelling, policy, and data-driven approaches. The smaller contributions from fields such as Engineering, Energy, and Medicine highlight the limited integration of technological and health perspectives, suggesting potential areas for future cross-disciplinary research.

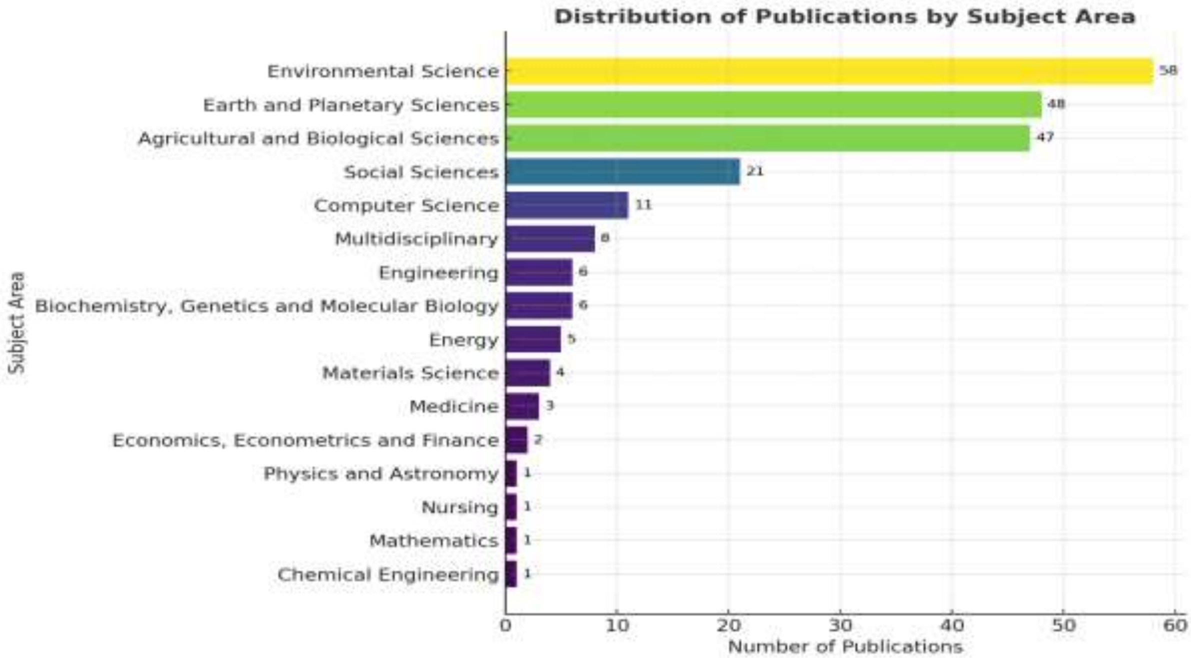

Figure 3: Subject-Wise Distribution of Publications.

2.3. Top Cited Articles

Table 1 lists the most globally cited papers in the field of spatiotemporal assessment of climate change impacts on cereal crop yields using satellite and geostatistical methods. The paper by **Tariq (2023)** published in *Geo-Spatial Information Science* received the highest global citations (160), indicating its strong international visibility and methodological contribution to remote sensing and climate modelling. Other highly cited studies, such as those by **Aaron-Morrison (2016)** in *Bulletin of the American Meteorological Society* and **Peng (2020)** in *Environmental Research,* demonstrate the integration of climate monitoring and geospatial approaches in understanding climate change impacts. The high citation counts reflect the global relevance of these studies and their influence on subsequent research across environmental and agricultural sciences.

Table 1: Most Globally Cited Papers.

Paper	Source	DOI	Total Citations	TC per Year	Normalized TC
TARIQ, 2023, GEO-SPATIAL INF SCI	Geo-Spatial Information Science	10.1080/10095020.2022.2100287	160	53.33	7.33
AARON-MORRISON, 2016, BULL AM METEOROL SOC	Bulletin of the American Meteorological Society	10.1175/2016BAMSStateoftheClimate.1	140	14	2.59
PENG, 2020, ENVIRON RES	Environmental Research	10.1016/j.envres.2020.110046	116	19.33	3.82
ASLAM, 2024, GONDWANA RES	Gondwana Research	10.1016/j.gr.2023.12.015	97	48.5	6.15
MUEEN QAMER, 2023, SCI REP	Scientific Reports	10.1038/s41598-023-30347-y	92	30.67	4.22

Table 2 presents the most locally cited papers, showing those that have been most referenced within the reviewed dataset. The study by Ahmad (2018) in *Journal of the Indian Society of Remote Sensing* ranks highest in local citations (4), highlighting its foundational role in shaping regional applications of geospatial analysis for climate impact studies. Papers by Amin (2020) and Akhtar (2020, 2021) published in

Journal of Water and Climate Change and *Theoretical and Applied Climatology* respectively, also show notable local influence. Although these papers have fewer global citations, their high LC/GC ratios suggest strong thematic relevance and methodological applicability within the specific context of Pakistan and South Asia.

Table 2: Most Locally Cited Papers.

Paper	Source	DOI	Year	Local Citations	Global Citations	LC/GC Ratio (%)
AHMAD, 2018, J IND SOC REMOTE SENS	Journal of the Indian Society of Remote Sensing	10.1007/s12524-018-0825-8	2018	4	70	5.71
AMIN, 2020, J WATER CLIM CHANGE	Journal of Water and Climate Change	10.2166/wcc.2020.232	2020	3	25	12
AKHTAR, 2021, THEOR APPL CLIMATOL	Theoretical and Applied Climatology	10.1007/s00704-020-03492-x	2021	2	5	40
AKHTAR, 2020, THEOR APPL CLIMATOL	Theoretical and Applied Climatology	10.1007/s00704-020-03337-7	2020	2	11	18.18
AZIZ, 2018, GEOMATICS NAT HAZARDS RISK	Geomatics, Natural Hazards and Risk	10.1080/19475705.2018.1499558	2018	2	24	8.33

3. CLASSIFICATION OF LITERATURE

3.1. Thematic Framework

Following the systematic screening process, all 140 included studies were subjected to comprehensive thematic analysis to identify dominant research patterns and methodological approaches. Through iterative coding and categorization of study objectives, methodologies, and focal areas based on abstract content, keywords, and research focus, four distinct but interconnected themes emerged from the literature. These themes represent the major research trajectories in the application of satellite-based and geostatistical approaches to assess climate change impacts on cereal crop yields in Pakistan.

The thematic framework encompasses: (1) Climate Change, Drought, and Hydro-Climatic Hazards (56 studies, 40.0%); (2) Advanced Geospatial and AI Techniques for Agricultural Monitoring (61 studies, 43.6%); (3) Impacts on Agricultural Production and Food Security (9 studies, 6.4%); and (4) Sustainable Land and Water Resource Management and Adaptation Strategies (14 studies, 10.0%). This classification provides a structured foundation for synthesizing the extensive body of literature and identifying critical knowledge gaps. The distribution reveals that methodological innovation (Theme 2) and climate characterization (Theme 1) dominate the research landscape, accounting for over 83% of studies, while direct impact assessment and adaptation strategies remain comparatively underexplored.

Theme 1: Climate Change, Drought, And Hydro-Climatic Hazards

This theme encompasses 56 studies (40.0%) spanning 2016-2025 that primarily focus on characterizing climate variability, quantifying drought severity, and assessing hydro-climatic hazards affecting cereal production systems in Pakistan. Geographic focus is heavily concentrated in Punjab (24 studies) with limited coverage in Sindh (6 studies), Balochistan (4 studies), and Khyber Pakhtunkhwa (1 study). Wheat dominates crop-specific investigations (19 studies), followed by rice (11 studies) and maize (6 studies). The theme shows increasing integration of Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models (13 studies) for future projections.

3.2. Drought Monitoring and Index Development

Drought monitoring emerged as the central focus, with multiple studies developing composite drought indices. Nasar-u-Minallah et al., (2025) integrated seven indices (NDVI, LST, VCI, TCI, VHI, PDSI, and NDWI) through Google Earth Engine to assess drought trends in Bahawalpur division over 2012-2022, identifying 2012, 2017, and 2022 as drought years with 2017 most severe (21.82% area affected), employing ARIMA modelling to project continued warming in Bahawalpur and Rahim Yar Khan districts. Hassan et al., (2025) conducted geospatial assessment of the Thal region using MODIS-derived STVI and NDVI alongside CHIRPS precipitation and CRU temperature data, revealing highest drought severity in 2001 and 2002 with significant correlations between monsoon temperature, rainfall, and vegetative indices.

Comparative analysis revealed important distinctions in drought index suitability. Qaisrani et al., (2024) evaluated SPI, RDI, and Precipitation Deciles across 13 Balochistan meteorological stations over 40 years (1981-2020), concluding RDI outperformed SPI when temperature data was available, particularly for identifying severe drought episodes of 1999-2000 and 2002-2003. Usama et al. (2025) analysed precipitation and air temperature anomalies using ERA-5 reanalysis data for Pakistan's Agro-Ecological Zones from 1991-2023, documenting precipitation deficits of 44.7% in February and 63.5% in August—months critical for wheat and rice development—alongside marked warming trends in February (+2.7°C) and March (+0.5°C), highlighting that the 2022 floods compounded by erratic droughts devastated wheat, cotton, barley, and rice.

Novel composite indices advanced beyond simple aggregation. Ismail et al., (2024) created two composite drought indexes for the China-Pakistan Economic Corridor: PSDI (simple aggregation) and GBMDI (Gradient Boosting Method Drought Index). GBMDI demonstrated stronger correlations with in-situ drought indices (SPI, SPEI, SC-PDSI), explaining greater variance in winter wheat yields from 2003-2022, emphasizing machine learning-enhanced composite indices' superiority over traditional weighted averaging approaches.

3.3. Climate Projections and Future Scenarios

Regional climate projections increasingly adopt CMIP6 models. Shaheen et al. (2025) analysed 13 CMIP6 GCMs validated against CRU TS4.03 datasets for Punjab and Sindh provinces under SSP245 and SSP585 pathways, projecting minimum temperature would increase more substantially than maximum (5.22°C versus 4.02°C by 2100 under SSP585), with precipitation showing steady upward trends of 28-53% depending on scenario, revealing increasing temperatures indicate growing heat stress that could offset precipitation benefits.

Advanced machine learning enhanced climate extreme predictions. Shah & Chen, (2025) employed 23 CMIP6 GCMs combined with multiple ML algorithms (LSTM, Gradient Boosting, ANN, SVM, Linear Regression) to predict temperature and precipitation extremes over Pakistan for 1980-2100, with LSTM networks outperforming all other models in capturing nonlinear climate dynamics. Under SSP5-8.5, projections revealed severe vulnerabilities including intensified heatwaves and prolonged droughts substantially reducing crop yields and disrupting pastoral livelihoods. Abbas et al., (2022) assessed 13 CMIP6 models using Taylor diagrams, modified Mann-Kendall tests, and Sen's slope estimators for 1951-2100, demonstrating substantial precipitation increases under high forcing scenarios (SSP3-7.0 and SSP5-8.5) with statistically significant trends in summer and annual precipitation.

3.4. Agricultural Drought Monitoring for Wheat Systems

Agricultural drought monitoring received considerable attention for wheat production systemsGoheer et al., (2023) integrated MODIS products (MOD09A1 for vegetation, MOD11A2 for temperature) with CHIRPS rainfall data to create weighted overlay drought risk maps for the rainfed Potohar region over 2000-2020, identifying Chakwal and western Jhelum experiencing moderate drought with agricultural production highly dependent on spatiotemporal rainfall distribution. Amin et al., (2020) developed combined agricultural risk maps for the Thal region using MOD13Q1, SPI, NDVI, VCI, and STVI through geospatial weighted overlay analysis, revealing wheat Rabi seasons of 2000-2002 experienced extreme agricultural drought with 12.76% of area classified as moderate drought risk.

The Vegetation Temperature Condition Index (VTCI) emerged as particularly effective for real-time drought assessment. Khan et al., (2018) demonstrated through near-real-time coupling analysis using MODIS-Aqua data that VTCI exhibited high positive correlation with cumulative winter precipitation (r=0.88) across Punjab's wheat belt during 2003-2008 growing seasons, outperforming NDVI and LST alone. Ullah et al. (2023) confirmed VTCI's utility in both rainfed and irrigated regions, showing positive correlation with winter precipitation (r=0.60) and strong links with accumulative precipitation anomaly (r=0.77) while documenting the 2010 flood's impact on wheat production decline from 19.041 to 17.7389 million tons in Punjab.

Table 1: Representative Studies in Climate Change, Drought, And Hydro-Climatic Hazards Theme.

Author(s)	Location/Crop	Methods	Key Findings
(Nasar-u-Minallah et al., 2025; Ullah et al., (2023)	Bahawalpur division, Punjab	7 drought indices (NDVI, LST, VCI, TCI, VHI, PDSI, NDWI),	Identified 2012, 2017, 2022 as drought years; 2017 most

		GEE platform, ARIMA modelling	severe with 21.82% area affected; projected continued warming in region
(Ismail et al., 2024)	CPEC region, Winter wheat	PSDI and GBMDI composite indices, Gradient Boosting ML	GBMDI showed stronger correlations with in-situ indices; explained greater variance in wheat yields 2003-2022; ML-enhanced indices superior to simple aggregation
(Shaheen et al., 2025)	Punjab and Sindh provinces	13 CMIP6 GCMs, SSP245 & SSP585 scenarios, CRU TS4.03 validation	Min temp increase 5.22°C vs max temp 4.02°C by 2100 (SSP585); precipitation up 28-53%; heat stress could offset precipitation benefits for Rabi/Kharif seasons
(M. A. Khan & Salah, 2018)	Punjab wheat belt	VTCI from MODIS-Aqua, near-real-time coupling approach	VTCI showed high correlation with cumulative winter precipitation (r=0.88) during 2003-2008; outperformed NDVI and LST alone for real-time drought monitoring
(Qaisrani et al., 2024)	13 stations in Balochistan	SPI, RDI, Precipitation Deciles comparison (1981-2020)	RDI outperformed SPI when temperature data available; identified severe droughts of 1999-2000 and 2002-2003 in arid zone

Theme 2: Advanced Geospatial and AI Techniques for Agricultural Monitoring

This theme represents the largest category with 61 studies (43.6%) spanning 2017-2025, reflecting the dramatic surge in integration of machine learning, deep learning, and advanced geostatistical techniques in crop monitoring, yield prediction, and agricultural decision support systems. The studies demonstrate a clear transition from traditional regression approaches to sophisticated artificial intelligence architectures, with 25 recent studies (2023-2025) accounting for 41% of the theme. Geographic concentration mirrors Theme 1 with Punjab dominating (18 studies), while Sindh receives minimal attention (2 studies) and Balochistan and KPK are entirely absent. Wheat is the predominant crop focus (31 studies), followed by rice (14 studies) and maize (10 studies). This theme shows substantially higher engagement with satellite remote sensing: MODIS (12 studies), Landsat (19 studies), Sentinel (7 studies), and GEE platform (9 studies).

3.5. Deep Learning Architectures for Yield Prediction

Deep learning architectures showed substantial performance improvements over conventional methods. Ashfaq, Khan, Shah, et al., (2025) developed DeepAgroNet, a three-branch framework combining CNN, RNN, and ANN for winter wheat yield estimation at district level in southern Pakistan. Using Google Earth Engine to integrate satellite imagery, meteorological data, and soil characteristics for 2017-2022 with detrended yield data, CNN achieved R^2=0.77 and 98% forecast accuracy one month before harvest, while RNN and ANN achieved R^2=0.72 and R^2=0.66 respectively, with all models maintaining yield error rates below 10%, demonstrating effective integration of spatial, temporal, and static data despite complex climatic-soil-environmental interactions.

Ashfaq, Khan, Afzal, et al., (2025) divided the wheat growth cycle into four key stages and tested multiple ML and DL models against conventional approaches, achieving R^2 values between 0.40 and 0.88 through integration of diverse data sources with advanced AI, benchmarking AI models against traditional methods across computational efficiency, spatial generalizability, and prediction stability. Aslam & Farhan, (2024) employed a ResNet50-LSTM hybrid model for rice yield prediction in Gujranwala district, achieving exceptional accuracy (R^2=0.9903) by combining EVI, FPAR, climate, and soil variables, illustrating potential for integrating convolutional architectures with recurrent networks for sequential agricultural data.

3.6. Machine Learning Dominance: Random Forest as Gold Standard

Random Forest emerged as the dominant algorithm across yield prediction, crop classification, and drought forecasting applications. Ahmed et al., (2025) compared RF and LASSO for wheat yield prediction using multiple vegetation indices (GNDVI, NDVI, EVI, SAVI) combined with climate variables (Tmax, Tmin, PPT, WS, PET, RDI), finding RF excelled with R^2=0.88, substantially outperforming linear LASSO (R^2=0.71-0.81) by unveiling intricate nonlinear relationships.

Superior performance appeared consistently across diverse applications. Ashfaq et al., (2024) achieved R^2=0.88 in Multan region where RF outperformed both SVM and LASSO by effectively combining climate, satellite, soil properties, and spatial information. Saeed et al., (2017) demonstrated highly accurate forecasts for eight Punjab districts using MODIS-derived NDVI and weather data for 2001-2014, achieving R^2=0.95 with RMSE of only 175.6 kg/ha. Kanwal et al., (2021) showed 88-96% accuracy for wheat area classification in semi-arid Punjab using Landsat-8 temporal NDVI and LST over 2008-2018, with predicted yields closely related to observed yields (R^2=0.69-0.75). Raza et al., (2022) recommended RF as best-fit for crop classification in Sahiwal district, achieving 84% accuracy for wheat and 81% for maize using Sentinel-2 data, significantly outperforming NDVI density estimation. Wahla et al., (2022) extended RF applications to drought prediction at one-month and three-month timescales in Cholistan, Punjab, achieving R^2=0.80 and R^2=0.78 using SPEI with climatic factors, with ROC-AUC metrics confirming suitability for operational drought prediction.

3.7. Novel Composite Indices and Integrated Approaches

Studies developed novel composite indices integrating multiple data streams. G. Rahman, Khalid, Arshad, Farhan, et al., (2025) developed an Integrated Agricultural Drought Index (IADI) combining SMCI (soil moisture from ERA5-Land), TCI, VHI, VCI, and TVDI (LST-NDVI derived) through Structural Equation Modelling and Bayesian Principal Component Analysis across ten agro-ecological zones of Punjab for 2000-2020, demonstrating dominance in analysing drought's role on crop yield, explaining 59% of maize yield variations in Rajanpur district. The prominence of LST-derived indices highlighted temperature's critical role in drought onset, while the relationship between TVDI, VCI, and ERA5-Land soil moisture was insignificant across most AEZs.

Javed et al., (2023) introduced the Temperature Vegetation ET Dryness Index (TVEDI) for Peshawar Valley, incorporating evapotranspiration into the traditional temperature-vegetation space. TVEDI showed significantly higher positive correlation with crop yield (r=0.60-0.80) compared to traditional TVPDI, demonstrating that inclusion of ET effectively captured changes in crop water status that temperature and vegetation alone missed.

3.8. Operational Forecasting and Early Warning Systems

Studies focused on developing operational forecasting systems. Black et al., (2024) created a novel yield forecasting system for winter wheat across Punjab, Sindh, and Baluchistan provinces using NDVI and VHI, demonstrating skillful forecasts up to 2 months in advance, enabling anticipatory release of Disaster Risk Financing funds and addressing the challenge of devising monitoring systems that function across environmentally and economically diverse regions while providing actionable information within policy-relevant timeframes.

Majeed et al., (2025) evaluated seven ML models (Random Forest, XGBoost, Decision Tree, SVM, Naïve Bayes, CNN-RNN hybrid) for predicting wheat crop yield loss using monthly drought indices from MODIS products for South Punjab during 2001-2022. XGBoost and DT achieved highest classification accuracy (98%, 96%), followed by RF, CNN-RNN, and SVM (94%), revealing increasing wheat yield loss risk from 2001-2022 primarily influenced by climate change and drought conditions, suggesting these models could support policymakers and farmers in building early warning systems for irrigation planning and drought resilience strategies in vulnerable agricultural regions.

Table 2: Representative Studies In Advanced Geospatial And AI Techniques Theme.

Author(s)	Location/Crop	ML/AI Methods	Key Findings
(Ashfaq, Khan, Shah, et al., 2025)	Southern Pakistan, Winter wheat	DeepAgroNet: CNN, RNN, ANN; GEE platform for data integration	CNN achieved R^2=0.77, 98% forecast accuracy 1 month before harvest; <10% yield error for all models; demonstrated effective integration of spatial, temporal, and static data
(Ahmed et al., 2025)	Punjab, Wheat	Random Forest vs LASSO; Multiple VIs (GNDVI, NDVI,	RF achieved R^2=0.88 with SAVI+climate variables,

		EVI, SAVI)	outperforming LASSO (R^2=0.71-0.81); unveiled nonlinear relationships classical methods cannot capture
(Aslam & Farhan, 2024)	Gujranwala, Rice	Hybrid ResNet50-LSTM; EVI, FPAR, climate, soil data	Exceptional accuracy R^2=0.9903; hybrid CNN-RNN architecture effective for sequential agricultural data
(K. U. Rahman et al., 2024)	10 AEZs Punjab, Maize	IADI composite index; SEM & Bayesian PCA; ERA5-Land soil moisture	IADI explained 59% of maize yield variations in Rajanpur; LST-derived indices critical for drought onset; revealed data integration challenges
(Majeed et al., 2025)	South Punjab, Wheat yield loss	7 ML models: RF, XGBoost, DT, SVM, NB, CNN-RNN; MODIS drought indices	XGBoost & DT achieved 98%, 96% accuracy; RF, CNN-RNN, SVM 94%; increasing yield loss risk trend 2001-2022; support early warning systems
(Black et al., 2024)	Punjab, Sindh, Baluchistan, Wheat	Operational forecasting using NDVI & VHI	Skillful forecasts 2 months before season end; enabled anticipatory Disaster Risk Financing; functional across diverse regions

Theme 3: Impacts On Agricultural Production and Food Security

This theme comprises only 9 studies (6.4%) spanning 2019-2025, representing the smallest thematic category despite food security being a stated priority in Pakistan's agricultural policy discourse. This disparity between policy rhetoric and research allocation is striking. The studies in this category bridge biophysical assessments with socioeconomic outcomes, food security implications, and human welfare indicators, employing interdisciplinary approaches that integrate remote sensing, economic modelling, health data, and social surveys. Geographic distribution is more diverse than Themes 1-2, with Punjab (2 studies), Sindh (1 study), and KPK (1 study) represented, though the small sample size limits robust geographic comparisons.

3.9. Soil Erosion and Land Degradation Threats

Soil erosion emerged as critical yet underexplored threats. Zhang et al., (2025) applied the RUSLE model with Sentinel-2 imagery to quantify soil loss in Swat district, estimating total annual potential soil loss at approximately 173,816 $t \cdot ha^{-1} \cdot year^{-1}$ through integration of rainfall erosivity (R), soil erodibility (K), slope length-steepness (LS), crop management (C), and support practice (P) factors, emphasizing soil erosion's contribution to undermining SDG 2 (Zero Hunger) by depleting productive capacity of agricultural soils. Sarwar et al., (2024) employed similar RUSLE methodology in southeastern Peshawar basin, documenting soil erodibility challenges for agricultural soils, sustainable farming systems, and water-food security.

3.10. Water Dependency and Blue Water Stress

Water dependency emerged as critical determinant of food security vulnerability. Ismaeel et al., (2025) developed a fine-scale evapotranspiration-based blue-water dependence index (BDI) for South Asian croplands using hierarchical decision tree approaches for crop rotation mapping over 2003-2020, revealing Pakistan exhibited high averaged BDI of 0.65, with cotton and sugarcane showing highest dependence on irrigation water while wheat and rice showed moderate dependence, with projections indicating arid to semi-arid croplands would require substantially more irrigation water under future climate scenarios.

3.11. Extreme Weather Events and Production Losses

Extreme weather events caused devastating immediate production losses. Qamer et al., (2023) conducted an integrated assessment of the catastrophic August 2022 floods in Sindh province using multi-sensor satellite data (Sentinel-1 for flood extent, Sentinel-2 for crop cover, GPM for rainfall intensity), documenting that 1.1 million hectares of cropland were inundated, with expected production losses estimated at 80% for rice, 88% for cotton, and 61% for sugarcane, providing useful tools for evaluating Loss and Damage (L&D) of agricultural production critical for climate finance mechanisms.

3.12. Socioeconomic Pathways to Food

Insecurity

Explicit modelling of socioeconomic pathways linking climate change to food insecurity provided valuable mechanistic insights. Usman et al., (2023) employed Partial Least Square Structural Equation Modelling (PLS-SEM) based on primary data surveys of 1,080 farmers across 12 districts representing rice-wheat and cotton-wheat systems, demonstrating that climate change had significant negative impacts on irrigation water availability, crop productivity, livestock health, rural livelihoods, and ultimately food security through cascading pathways, with the cotton-wheat cropping system more severely affected by climatic hazards than the rice-wheat system, suggesting differential vulnerabilities across Pakistan's major production systems that should inform region-specific adaptation policies.

Table 3: Representative Studies In Agricultural Production And Food Security Impacts Theme.

Author(s)	Location/Focus	Methods	Impact Findings
(Qamer et al., 2023)	Sindh province, 2022 floods	Multi-sensor: Sentinel-1, Sentinel-2, GPM	1.1 M ha cropland inundated; 80% rice, 88% cotton, 61% sugarcane production losses; provided L&D assessment tools for climate finance
(Ismaeel et al., 2025)	South Asia, Water dependency	Blue-water dependence index (BDI), ET-based	Pakistan BDI=0.65 (high); cotton/sugarcane highest dependency; future climate requires substantially more irrigation; profound water security concerns
(Usman et al., 2023)	12 districts, Rice-wheat & cotton-wheat	PLS-SEM, 1,080 farmer surveys	Climate change negatively impacted irrigation water, crop productivity, livestock, livelihoods, food security through cascading pathways; cotton-wheat more vulnerable than rice-wheat
(Zhang et al., 2025)	Swat district, Soil erosion	RUSLE model with Sentinel-2	173,816 t·ha^{-1} year^{-1} soil loss; undermines SDG 2 by depleting productive capacity; quantitative erosion-yield relationships needed

Theme 4: Sustainable Land and Water Resource Management and Adaptation Strategies

This theme comprises 14 studies (10.0%) spanning 2019-2025 that focus on sustainable resource management, irrigation optimization, adaptation pathways, and strategic planning for climate-resilient agriculture. While larger than Theme 3, it remains substantially underrepresented given the urgency of water scarcity and adaptation needs in Pakistan. Geographic concentration is extreme, with Punjab dominating (3 studies explicitly), while Sindh, Balochistan, and KPK receive zero coverage—a concerning pattern given that water management challenges vary dramatically across Pakistan's diverse agro-ecological zones. Wheat (7 studies) and rice (6 studies) receive comparable attention, with maize trailing (3 studies).

Evapotranspiration Dynamics and Crop Water Requirements

Evapotranspiration dynamics received substantial attention as foundational components of irrigation planning. Qamar et al., (2025) employed the Penman-Monteith model to analyse reference evapotranspiration (ET_0) trends across 36 districts in Punjab from 1950-2021, revealing decadal increases in Crop Water Requirement (CWR), particularly in southern regions for cotton, wheat, and sugarcane, with hotspot analysis identifying spatial concentration of water demand increases. Ashraf et al., (2023) conducted similar spatiotemporal analysis across five agroclimatic zones of Punjab using Penman-Monteith with Geographically Weighted Regression (GWR) and Multi-Scale GWR (MGWR) for 1950-2021, documenting an average increasing slope of 5.18 mm/year in ET_0 over 70 years, with minimum temperature identified as highest monthly dominant factor influencing ET_0.

3.13. Irrigation Demand-Supply Gaps

Quantification of irrigation demand-supply gaps provided sobering evidence of unsustainable water use patterns. Haseeb et al., (2023) used supervised classification of Landsat 8 OLI and Landsat 5 TM imagery to assess Multan's water balance for 2010 and 2020, revealing available irrigation water supply

(2,432 Mm^3) was 26% less than total irrigation water demand (3,281 Mm^3) in 2020, coinciding with 49% increase in urbanization over the decade, providing crucial database for sustainable water management and equitable distribution.

Optimization of Cropping Systems for Water Efficiency

Optimization of crop planting structures offered promising pathways for enhancing water-use efficiency. Li et al., (2022) applied Bayesian probability networks for the China-Pakistan Economic Corridor, demonstrating that moderately increasing the maize proportion in cropping systems (relative to wheat and cotton) could enhance grain yield by 9% while simultaneously decreasing total irrigation requirement from 277.61 km^3 to 240 km^3, a remarkable 13.6% water savings, revealing potential win-win scenarios for improving regional water and food security simultaneously.

3.14. Field-Level Adaptation and Breeding Strategies

Field-level adaptation strategies were evaluated empirically through controlled experiments. Ahmad et al., (2022) conducted a field experiment at the Wheat Research Institute, Faisalabad under rainfed conditions using alpha lattice design, demonstrating yield showed significant positive correlation with NDVI (0.87-0.97) at booting and grain filling stages while canopy temperature expressed negative relationships with yield (-0.11) under drought stress, with specific genotypes (V-19274, V-19177) showing superior performance under drought conditions, providing tangible breeding targets for climate adaptation. (Zulkiffal et al., 2022) investigated terminal heat stress adaptation through parametric stability analysis over two years, demonstrating that while delayed planting reduces yield due to heat stress, this can be alleviated by strategically altering sowing times, with specific wheat lines showing tolerance in very late sowing environments, recommending that altered planting time combined with proper nutrient management could achieve higher production under future climate scenarios.

Table 4: Representative Studies in Land/Water Management and Adaptation Strategies Theme.

Author(s)	Location/Focus	Methods	Adaptation Findings
(Li et al., 2022)	CPEC region, Cropping system optimization	Bayesian probability networks	Increasing maize proportion enhanced grain yield 9% while reducing irrigation 13.6% (277.61 to 240 km^3); win-win for water-food security
(Qamar et al., 2025)	36 districts Punjab, ET trends	Penman-Monteith model (1950-2021)	Decadal CWR increases in southern regions for cotton, wheat, sugarcane; zone-specific strategies crucial for sustainable production
(Haseeb et al., 2023)	Multan, Water balance	Landsat 8 OLI & Landsat 5 TM classification	2020: Water supply 26% less than demand (849 Mm^3 deficit); 49% urbanization increase; unsustainable water use patterns evident
(Ahmad et al., 2021)	Faisalabad, Wheat breeding	Field experiment, alpha lattice design, NDVI & canopy temp	Genotypes V-19274, V-19177 showed superior drought performance; NDVI correlated with yield (0.87-0.97); tangible breeding targets for climate adaptation

3.15. Cross-Theme Synthesis and Research Priorities

Several overarching patterns emerged across all four themes. First, clear temporal progression in methodological sophistication occurred, with studies published after 2020 increasingly employing machine learning and deep learning techniques compared to earlier reliance on traditional regression approaches, reflecting broader trends in agricultural remote sensing globally, though raising concerns about reproducibility, interpretability, and accessibility of increasingly complex analytical pipelines to researchers in resource-constrained settings.

Second, spatial concentration in Punjab province was strikingly evident. Punjab accounted for 47 of 140 studies (33.6%) with explicit provincial identification, while Sindh received moderate but substantially lower attention (9 studies), and Balochistan (4 studies) and Khyber Pakhtunkhwa (2 studies) remained severely underrepresented despite significant cereal production and climate vulnerability, reflecting Punjab's agricultural dominance and research infrastructure but creating dangerous blind spots in understanding climate impacts and adaptation needs across Pakistan's heterogeneous agricultural landscapes.

Third, wheat dominated research focus with 59 total studies (42%), while rice received moderate attention (33 studies, 24%) and maize significantly lagged (18 studies, 13%). Barley, millets, and other minor cereals were virtually absent despite their importance for food security in marginal environments, reflecting wheat's economic importance but underserving diversification strategies increasingly promoted for climate resilience.

Fourth, short time series (2-5 years) characterized most studies, fundamentally limiting robust trend analysis, model validation under diverse conditions, and long-term impact assessment. Only a handful of studies exceeded 20-year analysis periods, and virtually none approached the 30-50-year timescales needed to distinguish climate change signals from natural variability or adequately test model performance across climatic extremes.

Fifth, Google Earth Engine emerged as the transformative platform enabling integration of multi-source data and scalable analysis across at least nine explicitly identified studies. GEE's democratization of access to petabytes of satellite imagery and computational resources has clearly catalyzed Pakistan's agricultural remote sensing research, though dependence on external platforms raises questions about long-term sovereignty and accessibility.

Sixth, interdisciplinary integration between biophysical and socioeconomic analysis remained limited despite frequent rhetoric emphasizing connections. Theme 1 focused on climate characterization with minimal food security linkages; Theme 2 emphasized technical accuracy with limited farmer adoption considerations; Theme 3's small size (9 studies) reflected insufficient attention to production impacts and food security outcomes; Theme 4 proposed technical solutions with limited economic, social, or policy analysis. Genuinely integrated studies bridging physical, biological, economic, and social dimensions were exceedingly rare.

Finally, stakeholder engagement and farmer perspectives were largely absent from research design and implementation. Few studies involved participatory approaches, co-production of knowledge with farmers, or explicit consideration of smallholder constraints and priorities, disconnecting research from users and raising fundamental questions about the relevance, accessibility, and adoption potential of proposed monitoring systems, prediction models, and adaptation strategies.

3.17. Critical Research Gaps and Future Directions

Despite notable progress, key research gaps limit the translation of Pakistan's growing climate-agriculture knowledge into actionable food security outcomes. Table 5 summarizes the major gaps across themes to guide future research priorities and institutional coordination.

Table 5: Critical Research Gaps Across Thematic Areas.

Gap Category	Specific Research Gaps by Theme
Temporal Coverage	Theme 1: Short analysis periods (2-5 years) limit robust trend detection; lack of multi-decadal datasets (>30 years) essential for distinguishing climate signals from natural variability. Theme 2: ML models trained on short time series may fail during unprecedented extreme events when accurate predictions are most crucial. Theme 4: Absence of long-term monitoring of adaptation effectiveness over multi-year periods.
Geographic Bias	All Themes: Punjab dominates (47 of 140 studies, 33.6%) while Sindh (9 studies), Balochistan (4 studies), and KPK (2 studies) severely underrepresented. Theme 1: Mountainous agricultural regions (northern Pakistan, Himalayan foothills) receive minimal attention despite unique climate vulnerabilities. Theme 4: Zero coverage in Sindh, Balochistan, KPK despite diverse water management challenges across agro-ecological zones.
Crop Diversity	All Themes: Wheat dominates (59 studies, 42%) while rice (33 studies, 24%) and maize (18 studies, 13%) lag behind. Barley, millets, and minor cereals virtually absent despite importance for food security in marginal environments. This bias underserves

	crop diversification strategies promoted for climate resilience.
Forecasting Timeframes	Theme 1: Sub-seasonal to seasonal (S2S) forecasting systems largely absent; most studies focus on either historical analysis or long-term projections, missing the 1–6-month timeframe most relevant for agricultural decision-making and planting calendar adjustments.
Validation & Ground-Truthing	Theme 1: Inconsistent validation of remotely-sensed drought indices against ground-truth agricultural impacts (actual yield losses, farmer-reported drought timing). Theme 2: Poor understanding of relationships between drought indices and soil moisture measurements across different agro-ecological zones; Rahman et al. (2024) found insignificant relationships between TVDI, VCI, and ERA5-Land soil moisture across most AEZs.
Model Interpretability	Theme 2: ML models function as black boxes lacking interpretability of feature importance and variable interactions. While studies employ feature selection, mechanistic understanding of why certain variables contribute to predictions remains elusive, limiting translation into actionable agronomic recommendations for farmers and policymakers.
Cross-Regional Transferability	Theme 2: Cross-regional validation of models exceedingly rare, raising fundamental questions about spatial transferability. Models developed in Punjab may not generalize to Sindh's irrigation systems, Balochistan's arid conditions, or KPK's mountainous terrain. Only Black et al. (2024) explicitly addressed multi-provincial forecasting.
Impact Assessment	Theme 3: Severe underrepresentation (9 studies, 6.4%) despite food security policy priority. Nutritional quality impacts beyond caloric production receive zero attention. Gender dimensions of food security entirely unexplored. Supply chain disruptions, storage losses, market access constraints, and price volatility receive zero coverage. Single-season focus limits understanding of long-term resilience and intergenerational impacts.
Adaptation Implementation	Theme 4: Limited representation (14 studies, 10.0%) relative to adaptation urgency. Economic feasibility analysis rarely conducted—studies propose technical solutions without assessing financial viability, cost-effectiveness, or farmer ROI. Institutional and policy barriers to adoption receive minimal attention. Social equity dimensions of water allocation and adaptation benefits largely unexplored (smallholders vs. large farms, upstream vs. downstream, men vs. women farmers).
Cascading Effects	Theme 1: Integration between hydro-climatic hazards (floods, droughts) and their cascading effects on soil moisture, groundwater, and subsequent crop seasons remains superficial. Theme 3: Quantitative erosion-yield relationships absent despite documentation of massive soil loss (173,816 $t \cdot ha^{-1} \cdot year^{-1}$ in Swat).
Interdisciplinary Integration	All Themes: Limited integration between biophysical and socioeconomic analysis. Theme 1 focuses on climate with minimal food security linkages. Theme 2 emphasizes technical accuracy without farmer adoption considerations. Genuinely integrated studies bridging physical, biological, economic, and social dimensions exceedingly rare. Pest/disease dynamics under climate change virtually absent (only 1 study on fruit flies).
Stakeholder Engagement	All Themes: Farmer perspectives largely absent from research design and implementation. Few studies involve participatory approaches, co-production of knowledge with farmers, or explicit

	consideration of smallholder constraints and priorities. This disconnect raises fundamental questions about relevance, accessibility, and adoption potential of proposed monitoring systems, prediction models, and adaptation strategies.

In summary, Pakistan's research on climate impacts on cereal systems has made impressive strides in methodological innovation (Theme 2) and climate characterization (Theme 1), with 117 of 140 studies (83.4%) contributing to these domains. However, critical gaps persist in impact assessment (Theme 3: only 9 studies), adaptation implementation (Theme 4: only 14 studies), geographic coverage beyond Punjab, crop diversity beyond wheat, temporal depth for robust trend analysis, ground-truth validation, interdisciplinary integration, and stakeholder engagement. Addressing these gaps will require strategic research investments, institutional coordination, and commitment to translating knowledge into action for Pakistan's 220 million people dependent on climate-vulnerable cereal production systems.

.4. DISCUSSION

This systematic review of 140 studies (2016–2025) on the spatiotemporal assessment of climate change impacts on cereal yields in Pakistan reveals a technically advanced yet fragmented research landscape.

The growing use of remote sensing, GIS, and geostatistical methods such as Random Forest, CNN-RNN-ANN, and LSTM indicates remarkable analytical capability. However, these advances have not been equally matched by progress in translating model outputs into actionable adaptation strategies or policy responses.

This reflects an expanding "knowledge-to-action" divide in Pakistan's climate-agriculture domain, where technical innovation has not evolved into effective decision-support mechanisms.

The thematic imbalance between climate monitoring (83.4 percent) and adaptation-focused studies (16.6 percent) highlights this gap. While predictive modelling has improved precision in estimating climate impacts, most outputs remain academic, detached from farm-level and institutional decision-making.

The issue is not the absence of sophisticated models but the lack of contextual embedding and end-user integration.

Models rarely consider behavioural, economic, and institutional realities that influence farmers' adaptive choices or regional implementation capacities.

Spatial and crop coverage biases further constrain the generalizability of findings. The overrepresentation of Punjab (33.6% percent) contrasts sharply with the underrepresentation of Sindh, Balochistan, and Khyber Pakhtunkhwa—regions facing distinct climatic threats and resource scarcities. Similarly, the concentration on wheat (42 percent) sidelines minor cereals like barley, millet, and sorghum, which could strengthen resilience through diversification. This skew indicates that current research agendas remain driven by production priorities rather than by comprehensive resilience strategies.

Temporal and methodological limitations also weaken predictive confidence.

Most studies employ datasets spanning only two to five years, insufficient to capture decadal climate variability or long-term adaptation effects. Validation with field-based data remains limited, and few models are tested against extreme climatic events.

This weakens their operational utility in early warning systems and climate risk management frameworks.

Conceptually, the literature shows minimal integration between monitoring, impact assessment, and adaptation mechanisms.

Although 23 studies link climatic trends with yield outcomes, few develop iterative learning cycles where empirical evidence refines models and guides policy. This compartmentalization of research within disciplinary boundaries restricts its practical relevance.

Moreover, the lack of participatory engagement—from farmers, extension agents, and local institutions, reduces the contextual validity and usability of findings.

These limitations have direct implications for national food security. Pakistan's agriculture faces intensifying risks from heat stress, droughts, floods, and erratic rainfall. Despite increasing predictive precision, recent disasters such as the 2022 floods illustrate that warnings seldom lead to preventive action.

Bridging this disconnect requires frameworks that connect scientific knowledge with adaptive governance, ensuring that research outputs inform real-time decisions at both farm and policy levels.

This persistent gap constitutes what may be termed the "Knowledge-to-Action Paradox" (Figure 4).

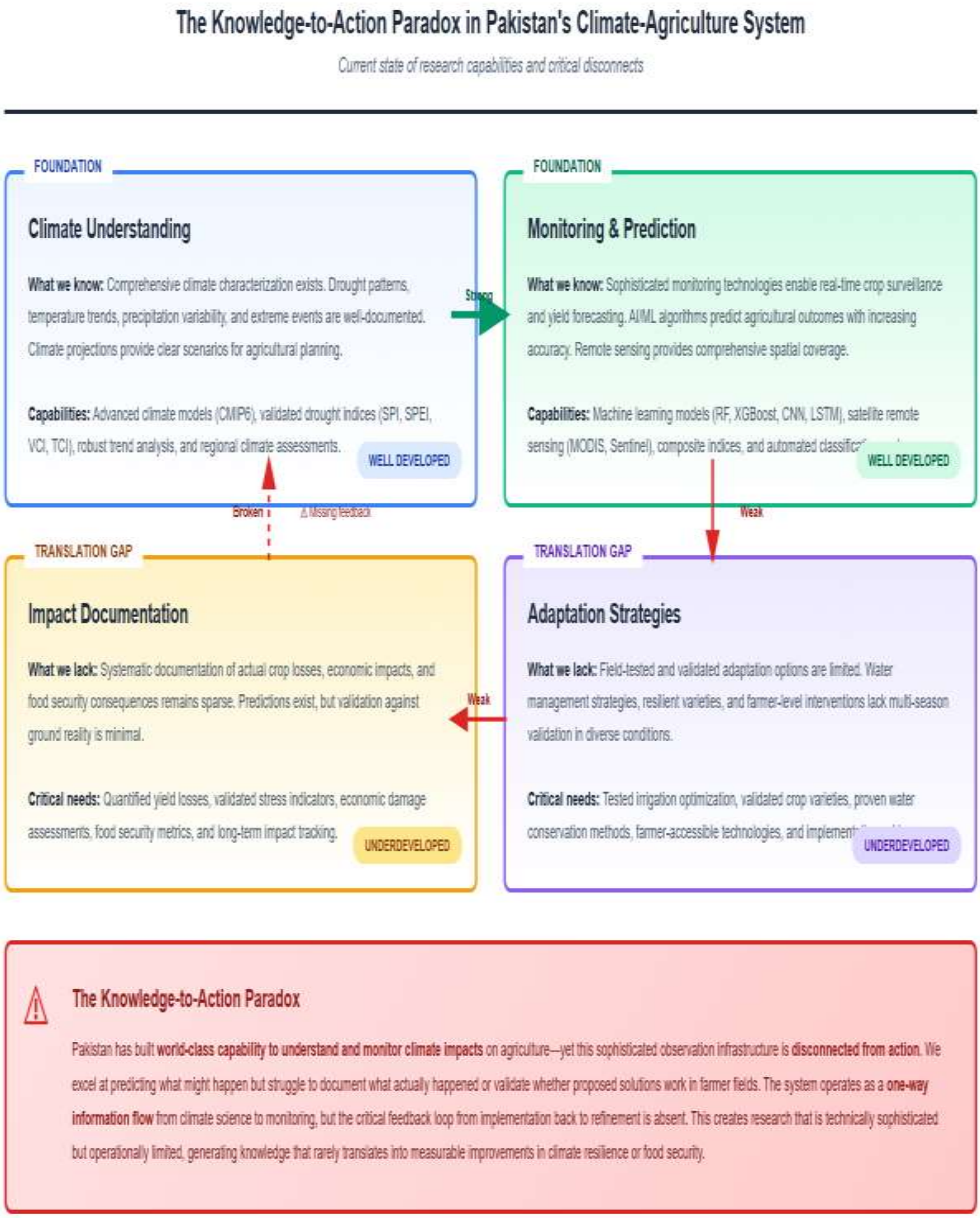

Figure 4: Conceptual Depiction of The Knowledge-To-Action Paradox.

It represents a situation where advances in climate modelling and data analytics have outpaced their operational application in resilience building. Pakistan has accumulated significant predictive capacity but lacks the institutional, participatory, and technological linkages needed to translate this knowledge into practice. The paradox underscores a systemic weakness in transforming "what is known" into "what is done."

To overcome this paradox, this study proposes an

Operational Framework for Climate-Resilient Cereal Production in Pakistan (Figure 5).

Figure 5: Operational Framework for Climate-Resilient Cereal Production in Pakistan.

The framework transforms climate-agriculture research into a cyclical process integrating five interconnected phases:

1. Characterize Climate Hazards through sustained monitoring and regional projections.
2. Monitor Crop Systems using satellite and AI-based tools for near real-time detection of crop stress.
3. Assess Impacts by quantifying yield losses, economic damages, and food security effects with field validation.
4. Implement Adaptations by testing and scaling climate-smart technologies and resilient crop varieties.
5. Evaluate and learn by continuously assessing adaptation outcomes and incorporating farmer feedback into future research cycles.

At the core of this framework are three enabling mechanisms—institutional coordination, participatory engagement, and evidence standardization—that ensure the system remains adaptive, transparent, and grounded in real-world needs. Institutional mechanisms establish long-term observatories and data-sharing networks; participatory integration promotes co-production of knowledge with farmers and policymakers; and evidence standards guarantee empirical testing, multi-season validation, and socio-economic evaluation of adaptation outcomes.

The operational framework is governed by eight guiding principles that close the loop between knowledge creation and action:

1. Cyclicality – establishing a continuous learning system where feedback from implementation informs future planning.
2. Geographic Inclusivity – ensuring that research covers all agro-ecological zones, including arid, mountainous, and rainfed regions.
3. Crop Diversification – promoting multiple cereal crops to distribute climatic risks and strengthen food security.
4. Long-Term Perspective – supporting multi-decadal datasets and longitudinal assessments to distinguish persistent trends from short-term anomalies.
5. Co-Production of Knowledge – integrating farmer and community knowledge into scientific processes to enhance local relevance and adoption.
6. Mandatory Validation – requiring empirical field testing of models and adaptation measures before large-scale implementation.
7. Impact Orientation – shifting evaluation metrics from academic output to measurable improvements in yield stability, livelihoods, and resilience.
8. Open Accessibility – promoting transparency and data-sharing to enable collaboration and informed policymaking.

Together, these principles establish a continuous feedback cycle linking scientific observation, local experience, and adaptive governance. By embedding learning, validation, and co-production at every stage, the proposed framework converts Pakistan's analytical sophistication into a living system that evolves with climatic and socio-economic realities. In doing so, it bridges the knowledge-to-action divide and offers a pathway toward climate-resilient cereal production and sustainable food security for more than 220 million people.

5. CONCLUSION

This systematic review highlights that Pakistan's research on the spatiotemporal assessment of climate change impacts on cereal crop yields through satellite and geostatistical methods has evolved technically but remains uneven in focus and application. While the country has made remarkable strides in developing sophisticated monitoring and predictive tools, most research (over 80%) centres on climate characterization rather than translating findings into practical impact assessments or validated adaptation strategies. This imbalance has created a knowledge-to-action gap where scientific progress does not yet translate into improved decision-making or resilience at the farm level, posing a serious challenge to national food security under intensifying climate pressures.

The analysis also reveals a strong methodological concentration in Punjab and on wheat, while rainfed regions and other cereals remain neglected. This limits the generalizability of findings and the inclusivity of research outcomes. The conceptual framework derived from the synthesis shows strong links between climate characterization and monitoring but weak downstream connections to adaptation implementation and almost no feedback loops that incorporate field experience into model refinement. This top-down approach risks making technological innovation detached from farmers' realities.

To move forward, Pakistan's research community must shift focus toward long-term monitoring, impact documentation, and rigorous validation of adaptation strategies, supported by stronger collaboration between scientists, policymakers, and local stakeholders. Geographic inclusivity should be prioritized by strengthening research capacity in underrepresented provinces like Sindh, Balochistan, and KPK. Most importantly, research should transition from being expert-driven to participatory, enabling co-production of knowledge where farmer experience guides innovation and evaluation. Pakistan's impressive technical capabilities in remote sensing and data analytics must now be leveraged toward tangible outcomes that enhance climate resilience and food security. Building a climate-smart agricultural future will depend not on more prediction, but on research that bridges science and practice through inclusive, adaptive, and impact-oriented approaches.

Key Action-Oriented Recommendations are

- Shift research focus from monitoring to impact assessment and adaptation validation: Future studies must prioritize rigorous field trials of adaptation strategies rather than purely observational climate monitoring.
- Expand geographic coverage to underrepresented provinces: Research capacity in Sindh, Balochistan, and KPK requires strengthening through institutional partnerships and dedicated funding mechanisms.
- Establish long-term field monitoring networks: Continuous ground-truth data collection is essential to validate remote sensing models and improve prediction accuracy.
- Transition from expert-driven to participatory research approaches: Engage farmers and local

stakeholders as co-producers of knowledge to ensure research relevance and practical applicability.
- Strengthen science-policy-practice linkages: Create formal mechanisms for translating research findings into extension services, policy reforms, and farmer training programs.

6. LIMITATIONS

This systematic review, though comprehensive, has several limitations. Reliance on the Scopus database and English-language sources likely excluded local and grey literature, including farmer-led or community-based studies. The precise search strategy may have missed research using different climate or agriculture terms, while the 2016–2025 timeframe excludes earlier foundational work and recent publications beyond November 2025. Thematic categorization involved subjective judgment, and alternative criteria might yield different insights. Geographic and linguistic biases persist, with Punjab-based institutions overrepresented and limited input from Sindh, Balochistan, and Khyber Pakhtunkhwa. The absence of a quality assessment treated all studies equally, regardless of rigor. The proposed conceptual framework remains theoretical and needs empirical validation.

7. FUTURE DIRECTIONS

Future research should rebalance Pakistan's climate-agriculture agenda toward measurable impacts and adaptive outcomes rather than further refining monitoring tools. Rigorous multi-year assessments linking satellite indicators with ground yield data and farmer feedback are needed to enhance reliability and policy relevance. The geographic focus must extend beyond Punjab to include climate-vulnerable regions such as Balochistan, Sindh, and Khyber Pakhtunkhwa. Establishing regional research centres and building local capacity will ensure equitable representation of diverse agroecological zones.

A national observatory should institutionalize long-term monitoring integrating remote sensing, meteorological, and socioeconomic data to support model validation and evidence-based policymaking. Research should prioritize participatory approaches where farmers, extension workers, and policymakers co-produce knowledge and shape research design and technology testing, enhancing social legitimacy and usability. Expanding research beyond wheat to crops like barley, sorghum, and millets can diversify risk and strengthen food system resilience.

Integrative, transdisciplinary collaborations connecting climate science, agronomy, and socioeconomic research are vital for technically sound and socially feasible adaptation strategies. Standardizing field validation protocols and embedding research into policy through labs, fellowships, and rapid evidence synthesis will bridge the gap between science and implementation. Collectively, these directions chart a path to shift Pakistan's climate-agriculture research from observation to action for resilient and sustainable cereal production.

REFERENCES

Ahmad, N., Iqbal, J., Shaheen, A., Ghfar, A., AL-Anazy, M. M., & Ouladsmane, M. (2021). Spatio-temporal analysis of chickpea crop in arid environment by comparing high-resolution UAV image and LANDSAT imagery. *International Journal of Environmental Science and Technology 2021 19:7*, *19*(7), 6595–6610. https://doi.org/10.1007/S13762-021-03502-Z

Ahmad, N., Javed, A., Gohar, S., Ahmed, J., Sher, A., Abdullah, M., Asghar, S., Javed, K., Iqbal, J., Kumar, S., & Qayyum, A. (2022). Estimation of drought effects on different bread wheat genotypes using morpho-physiological traits. *Biochemical Systematics and Ecology*, *104*, 104483. https://doi.org/10.1016/J.BSE.2022.104483

Ahmed, N., Mahmood, S. A., Haseeb, M., Tahir, Z., & Batool, S. (2025). Enhancing food security: machine learning-based wheat yield prediction using remote sensing and climate data in Pakistan. *Theoretical and Applied Climatology 2025 156:5*, *156*(5), 1–19. https://doi.org/10.1007/S00704-025-05475-2

Amin, M., Khan, M. R., Hassan, S. S., Khan, A. A., Imran, M., Goheer, M. A., Hina, S. M., & Perveen, A. (2020). Monitoring agricultural drought using geospatial techniques: a case study of Thal region of Punjab, Pakistan. *Journal of Water and Climate Change*, *11*(S1), 203–216. https://doi.org/10.2166/WCC.2020.232

Ashfaq, M., Khan, I., Afzal, R. F., Shah, D., Ali, S., & Tahir, M. (2025). Enhanced wheat yield prediction through integrated climate and satellite data using advanced AI techniques. *Scientific Reports 2025 15:1*, *15*(1), 1–25. https://doi.org/10.1038/s41598-025-02700-w

Ashfaq, M., Khan, I., Alzahrani, A., Tariq, M. U., Khan, H., & Ghani, A. (2024). Accurate Wheat Yield Prediction Using Machine Learning and Climate-NDVI Data Fusion. *IEEE Access*, *12*, 40947–40961.

https://doi.org/10.1109/ACCESS.2024.3376735

Ashfaq, M., Khan, I., Shah, D., Ali, S., & Tahir, M. (2025). Predicting wheat yield using deep learning and multi-source environmental data. *Scientific Reports 2025 15:1*, *15*(1), 1–20. https://doi.org/10.1038/s41598-025-11780-7

Ashraf, H., Qamar, S., Riaz, N., Shamshiri, R. R., Sultan, M., Khalid, B., Ibrahim, S. M., Imran, M., & Khan, M. U. (2023). Spatiotemporal Estimation of Reference Evapotranspiration for Agricultural Applications in Punjab, Pakistan. *Agriculture 2023, Vol. 13, Page 1388*, *13*(7), 1388. https://doi.org/10.3390/AGRICULTURE13071388

Aslam, A., & Farhan, S. (2024). Enhancing rice yield prediction: a deep fusion model integrating ResNet50-LSTM with multi source data. *PeerJ Computer Science*, *10*, e2219. https://doi.org/10.7717/PEERJ-CS.2219/TABLE-5

Baas, J., Schotten, M., Plume, A., Côté, G., & Karimi, R. (2020). Scopus as a curated, high-quality bibliometric data source for academic research in quantitative science studies. *Quantitative Science Studies*, *1*(1), 377–386. https://doi.org/10.1162/QSS_A_00019

Black, E., Maidment, R. I., Rees, E., & Nderitu, E. (2024). A new drought model for disaster risk management in the Punjab, Sindh and Baluchistan provinces of Pakistan. *Frontiers in Climate*, *6*, 1332233. https://doi.org/10.3389/FCLIM.2024.1332233/BIBTEX

Goheer, M. A., Aftab, B., Farah, H., & Hassan, S. S. (2023). Spatio-temporal risk analysis of agriculture and meteorological droughts in rainfed Potohar, Pakistan, using remote sensing and geospatial techniques. *Meteorological Applications*, *30*(6), e2138. https://doi.org/10.1002/MET.2138;REQUESTEDJOURNAL:JOURNAL:14698080;WGROUP:STRING:PUBLICATION

Hassan, S. S., Goheer, M. A., Farah, H., Hafeez, F., Sheraz, K., Fahad, J., & Tariq, A. (2025). Geospatial assessment of climate variability and drought patterns: a case study from Pakistan. *Theoretical and Applied Climatology 2025 156:3*, *156*(3), 1–15. https://doi.org/10.1007/S00704-025-05414-1

Ismaeel, A., Wu, J., Letters, A. T.-E. R., & 2025, undefined. (2025). Fine-scale assessment of blue-water dependence via crop rotation systems in South Asia under a changing climate. *Iopscience.Iop.OrgA Ismaeel, J Wu, APK TaiEnvironmental Research Letters, 2025•iopscience.Iop.Org*. https://doi.org/10.1088/1748-9326/ADC7CC/META

Ismail, M., Li, Y., Niu, B., Ghaffar, M. A., Saleem, M. A., & Siddique, K. H. M. (2024). A multi-sensor drought index for improved agricultural drought monitoring and risk assessment in the heterogeneous landscapes of the China–Pakistan Economic Corridor (CPEC). *Atmospheric Research*, *310*, 107633. https://doi.org/10.1016/J.ATMOSRES.2024.107633

Javed, T., Bhattarai, N., Acharya, B. S., & Zhang, J. (2023). Monitoring agricultural drought in Peshawar Valley, Pakistan using long -term satellite and meteorological data. *Environmental Science and Pollution Research 2023 31:3*, *31*(3), 3598–3613. https://doi.org/10.1007/S11356-023-31345-3

Kanwal, H. H., Ahmad, I., Ahmad, A., & Li, Y. (2021). Yield forecasting and assessment of interannual wheat yield variability using machine learning approach in semi-arid environment. *Pakistan Journal of Agricultural Sciences*, *58*(2), 461–470. https://doi.org/10.21162/PAKJAS/21.661

Khan, M. A., & Salah, K. (2018). IoT security: Review, blockchain solutions, and open challenges. *Future Generation Computer Systems*. https://doi.org/10.1016/j.future.2017.11.022

Li, Y., Chen, Y., Duan, W., Cao, M., & Qin, J. (2022). Spatiotemporal variation in irrigation water requirements in the China–Pakistan Economic Corridor. *Scientific Reports 2022 12:1*, *12*(1), 1–13. https://doi.org/10.1038/s41598-022-21685-4

Majeed, F., Ahmad, H., Siddique, A., Iftikhar, M., Khurshaid, T., Abdel Samee, N., & Ashraf, I. (2025). Enhancing drought monitoring through multi-stage crop yield and machine learning. *Theoretical and Applied Climatology 2025 156:11*, *156*(11), 1–27. https://doi.org/10.1007/S00704-025-05803-6

Martín-Martín, A., Orduna-Malea, E., Thelwall, M., & Delgado López-Cózar, E. (2018). Google Scholar, Web of Science, and Scopus: A systematic comparison of citations in 252 subject categories. *Journal of Informetrics*, *12*(4), 1160–1177. https://doi.org/10.1016/J.JOI.2018.09.002

Mustapha, I., Ali, M., Khan, N., & Sikandar, H. (2023). The Impact of Industry 4.0 on Innovative Organisations, A Thematic Review Using the PRISMA Statement 2020. *International Journal of Interactive Mobile Technologies*. https://doi.org/10.3991/ijim.v17i09.39465

Nasar-u-Minallah, M., Parveen, N., Shahzad, M. F., & Tabassum, R. (2025). Spatial and temporal assessment of drought dynamics in Bahawalpur (Pakistan) using remote sensing and meteorological data. *Environmental Earth Sciences 2025 84:19*, *84*(19), 1–23. https://doi.org/10.1007/S12665-025-12520-W

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., & Moher, D. (2021). Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement. *Journal of Clinical Epidemiology*, *134*, 103–112. https://doi.org/10.1016/J.JCLINEPI.2021.02.003

Qaisrani, Z. N., Nuthammachot, N., Techato, K., Asadullah, Jatoi, G. H., Mahmood, B., & Ahmed, R. (2024). Drought variability assessment using standardized precipitation index, reconnaissance drought index and precipitation deciles across Balochistan, Pakistan. *Brazilian Journal of Biology*, *84*, e261001. https://doi.org/10.1590/1519-6984.261001

Qamar, S., Ashraf, H., Sultan, M., Ibrahim, S. M., & Khan, M. U. (2025). Data-Driven Irrigation Scheduling: A Spatiotemporal Assessment of Crop Water Requirements for Major Crops in Punjab, Pakistan. *Earth Systems and Environment 2025 9:3*, *9*(3), 2023–2043. https://doi.org/10.1007/S41748-025-00729-5

Qamer, F. M., Abbas, S., Ahmad, B., Hussain, A., Salman, A., Muhammad, S., Nawaz, M., Shrestha, S., Iqbal, B., & Thapa, S. (2023). A framework for multi-sensor satellite data to evaluate crop production losses: the case study of 2022 Pakistan floods. *Scientific Reports 2023 13:1*, *13*(1), 1–11. https://doi.org/10.1038/s41598-023-30347-y

Rahman, G., Khalid, S., Arshad, S., Farhan, M., Moazzam, U., & Kwon, H.-H. (2025). Remote sensing-based spatiotemporal assessment of agricultural drought and its impact on crop yields in Punjab, Pakistan. *Nature.ComG Rahman, S Khalid, S Arshad, MFU Moazzam, HH KwonScientific Reports, 2025•nature.Com*. https://doi.org/10.1038/s41598-025-06095-6

Rahman, G., Khalid, S., Arshad, S., Moazzam, M. F. U., & Kwon, H. H. (2025). Remote sensing-based spatiotemporal assessment of agricultural drought and its impact on crop yields in Punjab, Pakistan. *Scientific Reports 2025 15:1*, *15*(1), 1–20. https://doi.org/10.1038/s41598-025-06095-6

Rahman, K. U., Ejaz, N., Shang, S., Balkhair, K. S., Alghamdi, K. M., Zaman, K., Khan, M. A., & Hussain, A. (2024). A robust integrated agricultural drought index under climate and land use variations at the local scale in Pakistan. *Agricultural Water Management*, *295*, 108748. https://doi.org/10.1016/J.AGWAT.2024.108748

Rattanawiboonsom, V., Sikandar, H., Thatsaringkharnsakun, U., & Khan, N. (2025). The Role of Mobile Technologies in Tracking Cyberbullying Trends and Social Adaptation among Teenagers. *International Journal of Interactive Mobile Technologies*, *19*(1), 171. https://doi.org/10.3991/IJIM.V19I01.52747

Raza, D., Shu, H., Khan, S. U., Ehsan, M., Saeed, U., Aslam, H., Aslam, R. W., & Arshad, M. (2022). Comparative geospatial approach for agricultural crops identification in interfluvial plain - A case study of Sahiwal district, Pakistan. *School of Natural Resources: Faculty Publications*. https://doi.org/10.21162/PAKJAS/22.127

Saeed, U., Dempewolf, J., Becker-Reshef, I., Khan, A., Ahmad, A., & Wajid, S. A. (2017). Forecasting wheat yield from weather data and modis ndvi using random forests for punjab province, Pakistan. *International Journal of Remote Sensing*, *38*(17), 4831–4854. https://doi.org/10.1080/01431161.2017.1323282;REQUESTEDJOURNAL:JOURNAL:TRES20;WGROUP:STRING:PUBLICATION

Sarwar, A., Ali, M., Israr, M., Gulzar, S., Khan, M. I., Ali, M. A. S., Majid, A., & Rukh, S. (2024). Mapping annual soil loss in the southeast of Peshawar basin, Pakistan, using RUSLE model with geospatial approach. *Geology, Ecology, and Landscapes*. https://doi.org/10.1080/24749508.2024.2373493;ISSUE:ISSUE:DOI

Shaheen, N., Ahmad, Q.-U.-A., Masood, A., Goheer, M. A., Ur, M. A., & Tariq, R. (2025). CMIP6-Based Climate Projections and Trends for Exploring Adaptations and Policies in Pakistan. *Pakistan Journal of Engineering and Applied Sciences*, *33*, 50–69. https://doi.org/10.5281/zenodo.3987736

Sikandar, H., & Abdul Kohar, U. H. (2022). A systematic literature review of open innovation in small and medium enterprises in the past decade. In *Foresight* (Vol. 24, Issue 6, pp. 742–756). Emerald Publishing Limited. https://doi.org/10.1108/FS-01-2021-0030

Sikandar, H., Kohar, U. H. A., Sanda, G., Salman, A., Cilan, T., Shabbir, M. S., Ramos-Meza, C. S., Abdul Kohar, U. H., Kohar, U. H. A., Sanda, G., Salman, A., Cilan, T., Shabbir, M. S., Ramos-Meza, C. S., Salam, S., Senin, A. A., Sikandar, H., Sheeraz, M. I., Ali, A., … Ullah, A. (2023). Eco-innovation in Small and Medium Enterprises (SMEs): a Systematic Literature Review. *Journal of the Knowledge Economy*, *8*(1), 129. https://doi.org/10.1007/s13132-023-01367-w

Ullah, R., Khan, J., Ullah, I., Khan, F., & Lee, Y. (2023). Assessing Impacts of Flood and Drought over the Punjab Region of Pakistan Using Multi-Satellite Data Products. *Remote Sensing 2023, Vol. 15, Page 1484*, *15*(6), 1484. https://doi.org/10.3390/RS15061484

Usama, R. M., Abbas, S., Almazroui, M., Bilal, M. F., & Ali, A. (2025). Evolving climatic patterns and drought risk in Pakistan's agro-ecological zones. *Theoretical and Applied Climatology 2025 156:9*, *156*(9), 1–16. https://doi.org/10.1007/S00704-025-05681-Y

Usman, M., Ali, A., Bashir, M. K., Mushtaq, K., Ghafoor, A., Amjad, F., Hashim, M., & Baig, S. A. (2023). Pathway analysis of food security by employing climate change, water, and agriculture nexus in Pakistan: partial least square structural equation modeling. *Environmental Science and Pollution Research 2023 30:38*, *30*(38), 88577–88597. https://doi.org/10.1007/S11356-023-28547-0

Wahla, S. S., Kazmi, J. H., Sharifi, A., Shirazi, S. A., Tariq, A., & Joyell Smith, H. (2022). Assessing spatio-temporal mapping and monitoring of climatic variability using SPEI and RF machine learning models. *Geocarto International*, *37*(27), 14963–14982. https://doi.org/10.1080/10106049.2022.2093411;JOURNAL:JOURNAL:TGEI20;WGROUP:STRING:PUBLICATION

Zhang, L., Haseeb, M., Tahir, Z., Tariq, A., Almutairi, K. F., & Soufan, W. (2025). Assessment of soil erosion dynamics and implications for sustainable land management: A case study using the RUSLE model. *International Journal of Sediment Research*, *40*(3), 385–399. https://doi.org/10.1016/J.IJSRC.2024.12.001

Zulkiffal, M., Ahmed, J., Riaz, M., Ramzan, Y., Ahsan, A., Kanwal, A., Ghafoor, I., Nadeem, M., & Abdullah, M. (2022). Response of heat-stress tolerant and susceptible wheat lines in diverse planting environments by using parametric stability models. *Sabrao Journal of Breeding and Genetics*, *54*(1), 127–140. https://doi.org/10.54910/SABRAO2022.54.1.12