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Evaluating the role of climate variability and socio-economic determinants in shaping community-based climate actions for sustainable development in Pakistan

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Abstract

Climate unpredictability threatens sustainable development and the lives of local communities in Pakistan. Empirical knowledge of how socio-economic factors affect community-based climate efforts is sparse. The study examines Pakistan's community-based climate change initiatives from 1990 to 2022 and their environmental and socio-economic impacts. The study examined community engagement and a range of influencing factors, including carbon dioxide emissions, gross domestic product (GDP) per capita, potable water availability, precipitation, temperature change, and their interaction effects. The results of the autoregressive distributed lag model indicate that a country's per capita income and access to clean water promote community-based initiatives in the short run. Increasing carbon emissions and climatic variability constrain these efforts in the long run. Granger causality tests indicate unidirectional relationships between income, clean water, and community climate action. The study emphasizes integrating environmental management with socio-economic development to achieve local climate resilience. It also offers policymakers sustainable community adaptation strategies to minimize the climate-induced risks in vulnerable communities.

Keywords: Climate change; Access to clean water; Environmental sustainability; Community-based climate initiatives; Pakistan

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1. Introduction

German sociologist Ferdinand Tönnies originally described community as a socially cohesive group characterized by shared values, close relationships, and a collective sense of unity among its members. Community-based organizations are spearheading efforts to adapt to climate change, which aim to empower vulnerable communities, especially those in rural areas, to improve their livelihoods and resilience.[1] As more communities recognize the need for equitable climate adaptation, more municipalities are adopting community-based participatory planning processes. However, these methods still cannot ensure fair outcomes, even with increased integration of public feedback into climate adaptation plans.[2] In wealthy nations, community-based climate change programs provide people with the tools to deal with environmental threats, adapt to new circumstances, and reduce carbon emissions. Their efforts to encourage eco-conscious practices, build resilience, and support sustainable practices significantly reduce the effects of climate change and protect ecosystems.[3] Community-based climate change programs have had a considerable effect on Pakistan's ecosystems. Water shortages, air pollution, deforestation, and Pakistan's susceptibility to severe weather events caused by climate change are among the environmental challenges Pakistan faces.[4] When tackling environmental issues and reducing the effects of climate change, community-based programs in Pakistan are vital. In the long run, these efforts will help Pakistan become a more sustainable and eco-friendly nation by providing local solutions, strengthening resilience, preserving biodiversity, and promoting sustainable practices.

Extreme weather events and annual precipitation (AP) significantly influence community resilience infrastructure in Pakistan for several reasons, including susceptibility to climate change, water management, agriculture, public health, disaster risk reduction, and economic stability. The country is also experiencing rapid urbanization and infrastructure development. Climate change is adversely influencing Pakistan, with higher average temperatures, altered precipitation patterns, and more frequent and severe weather events on the horizon. Communities and their infrastructure are vulnerable to climate-related catastrophes such as heatwaves, droughts, and floods.[5] Proper water management is essential for agriculture, energy production, and economic stability in Pakistan, as the country's water supplies are highly dependent on AP. Water scarcity or heavy floods may result from extreme weather events that interrupt typical precipitation patterns. These water-related concerns may be better managed and mitigated by developing resilient infrastructure.[6] Seasonal rainfall is crucial to Pakistan's agricultural sector, which employs the majority of the population. Food insecurity and economic losses may result from agricultural damage caused by extreme weather events such as unpredictable monsoons or extended droughts. Farmers can better adapt to shifting precipitation patterns with resilient infrastructure, such as upgraded irrigation systems and water storage facilities.[7] Pakistan's infrastructure is already under significant pressure due to rapid urbanization. Disruptions to services and economic activity may result from extreme weather events that damage critical infrastructure, such as roads, bridges, and buildings. The continuous operation of cities and towns depends on the construction of climate-resilient infrastructure.[8] Moreover, yearly precipitation and severe weather events significantly affect Pakistan's growth and people's well-being. Investment in climate-resilient infrastructure, sustainable water management, disaster risk reduction, and community-empowered adaptation and recovery strategies is critical for enhancing community resilience in the face of climate change and severe weather.

It is essential to address the challenges of access to clean water in Pakistan to improve disaster preparedness, public health, and response capabilities. To better prepare for disasters and ensure public health, it is crucial to build water infrastructure that can withstand damage and implement efficient water management practices. This integration has the potential to contribute to ecologically friendly economic growth in Pakistan, and community resilience is a critical component in responding to climate change and promoting sustainable development. One of the most important ways to help vulnerable populations adjust is to build their resilience. Among these measures is providing people with the information, tools, and skills necessary to adapt to a changing climate.[9] Incorporating community resilience into climate change adaptation is a common component of ecosystem-based adaptation. Using mangroves to reduce coastal flooding is one example of how these solutions tap into nature to safeguard against climate change.[10] To maintain a consistent water supply despite precipitation fluctuations, resilient communities in Pakistan may adopt water management strategies, such as adequate irrigation and rainwater collection, highlighting the close link between sustainable development and community resilience.

Pakistan's strategic commitment to enhancing environmental quality and climate resilience through national and global initiatives operates within wider policy frameworks and institutional activities. The Upscaling Green Pakistan Programme prioritizes large-scale afforestation and ecosystem restoration to improve terrestrial carbon sinks and capture greenhouse gases.[11] Recharge Pakistan is improving groundwater recharge infrastructure and floodwater management with this program to address water security and climate variability.[12] Cross-sector priority activities under Pakistan's National Adaptation Plan reduce the country's susceptibility to climate change and help the hardest-hit communities to adapt. The government's efforts show its dedication to sustainable development and environmental protection. Georgescu *et al.*[13] argued that cluster analysis of transition pathways may help develop policies across different contexts. Multidimensional integration is crucial to climate neutrality. The European Union's climate-neutrality road is distinct from Pakistan's climate-adaptation environment; however, combining socio-economic progress with emissions reduction and resilience remains relevant. This study connects community-based climate activities with national programs and broader adaptation frameworks to better understand how policy environments shape localized adaptive responses in developing countries.

Resilient communities are better able to diversify their economies, which helps them rely less on industries vulnerable to climate change. Xu *et al.*[14] found that diversity may result in more stable lives and sustained economic development. By reducing the likelihood of infrastructure damage and repair costs, sustainable development is advanced through the construction of resilient infrastructure that can withstand climatic shifts and severe weather.[15] Food security and less reliance on imports are two outcomes that may be achieved when communities can adjust their agricultural practices to changing climate conditions. Sustainable agricultural practices also reduce greenhouse gas emissions. For economic development to be sustainable, it must be environmentally friendly. By combining community resilience with climate change adaptation, we can encourage the growth of renewable energy sources such as wind and solar power, reducing our reliance on fossil fuels and slowing global warming. Ecotourism is another way resilient communities can leverage their environment, creating long-term jobs and protecting delicate ecosystems. Green technology investments, such as energy-efficient appliances and sustainable building practices, can create new jobs and reduce carbon emissions.[16] Recent research shows that analyzing the advantages and drawbacks of development activities is essential to understanding how local communities respond to foreign pressures. Mondol *et al.*[17] found that local support for development initiatives is affected by both the perceived good and negative consequences of sustainable religious tourism. The former provides economic and social advantages, while the latter might reduce local development support. Community resilience in the face of climate adaptation depends on how local populations evaluate and react to environmental and developmental pressures. This cost–benefit analysis of community response highlights the wider impact of socio-economic perceptions on local engagement. Pakistan's dedication to community resilience can entice international support and collaborations, leading to eco-friendly economic growth and long-term sustainability. In short, if Pakistan wants to tackle climate change, reduce people's vulnerability, and promote sustainable development, it must combine community resilience with adaptation. Pakistan may achieve sustainable economic development while protecting its populations and ecosystems from the effects of climate change by strengthening its adaptive capacity, practicing prudent resource management, and adopting green technologies.

The discussion begets a series of research inquiries fundamental to the study's framework. Firstly, the investigation seeks to elucidate the extent to which carbon emissions influence the initiation and success of community-based climate programs. This scholarly pursuit aims to comprehensively understand the nuanced relationship between carbon dioxide (CO_2) emissions and the ultimate outcomes of community-driven climate endeavors within specific locales or communities.[18] Subsequently, a thorough exploration of the intricate role of income per capita in shaping and steering community-driven climate initiatives is pivotal for sustainable development. This line of inquiry examines the connection between income per capita and its capacity to actively support and engage in community-based climate initiatives, with careful consideration of economic capacity as a critical determinant. The third facet of research concerns the interplay between community-based climate measures and potable water accessibility. This investigative trajectory explores the correlation between the success of community-based climate projects and the availability of safe drinking water. The overarching objective is to unravel how this fundamental resource can fortify sustainability efforts on a broader scale. Lastly, the inquiry examines the influence of annual temperature and precipitation anomalies on the initiation and continuation of community-based climate initiatives across diverse regions. These research questions frame an empirical study, facilitating the analysis of relationships between independent variables and the dependent variable of community-based climate initiatives. This facet seeks to uncover the potential climate sensitivity of these initiatives, scrutinizing how local climate conditions, including AP and temperature anomalies, affect their development and outcomes.[19] This approach ensures a scholarly and informative lens through which to view the multifaceted dynamics of community-based climate initiatives.

The study aims to achieve four goals related to the following variables in the context of Pakistan: community-based climate initiatives, CO_2 emissions, Gross Domestic Product (GDP) per capita, access to clean drinking water (ACD), yearly precipitation, and temperature anomalies:

(i) To comprehensively determine the present state of community-based climate projects in Pakistan.
(ii) To explore the interplay between environmental factors and the effectiveness of grassroots climate programs in Pakistan.
(iii) To examine how Pakistan's income per capita influences the accessibility to finance and participation in community-based climate projects, considering variations across different regions.
(iv) To assess the influence of yearly precipitation, temperature irregularities, and the availability of potable water on the establishment and maintenance of community-based climate initiatives in Pakistan.

The majority of empirical research on climate vulnerability in Pakistan has focused on macro-level indicators such as carbon emissions, economic growth, and environmental degradation, while ignoring community-level adaptive responses within a socio-economic and climatic framework. However, Pakistan remains one of the most susceptible nations to climate-induced environmental stress and hydrological unpredictability. The relationship between development-oriented characteristics, such as income growth and access to basic services, and environmental pressures in local populations' climate change adaptation has received minimal examination. This study addresses this requirement by proposing an empirical framework to evaluate Pakistani community-based climate change efforts from 1990 to 2022 in relation to climatic variability and socio-economic infrastructure. This study presents an interaction-based definition of the relationships among income dynamics, ACD, nonlinear precipitation impacts, and other variables to better understand how development conditions affect community resilience to climatic stress. This study contributes to policy adaptation to climate change by taking a long-term perspective of environmental and institutional elements that affect community-level climate responsiveness in vulnerable developing nations.

2. Literature review

2.1. Community-based climate initiatives

Community-based climate measures, including disaster management, treeplanting, and water conservation, have increased significantly over the past 30 years. These approaches promote local sustainable development and environmental resilience. Rural and resource-constrained areas have inadequate implementation and consistency, uneven coverage, and varied institutional support. Local climate action can be compared with community engagement to better understand its current state. Osuntuyi and Lean[20] examined the influence of education levels on the interplay between energy, economic growth, and environmental factors in Africa from 1990 to 2017. The results indicate that education contributes to environmental pollution, with the impact of energy consumption worsening as education levels rise. Economic growth, population growth, and trade openness have adverse environmental effects, while natural resources support environmental sustainability. The study provides evidence to researchers on how education levels affect energy, economic growth, and environmental factors in Africa. Oanh and Ha[21] examined the influence of human capital and income inequality on climate change in Asian countries from 2007 to 2020. Findings from the generalized method of moments estimator affirmed that rising income inequality and investments in human capital worsened environmental degradation in Asia. Notably, only tertiary school enrollment mitigated the impact of income inequality on carbon emissions. Huang *et al.*[22] analyzed the influence of student demographics on energy consumption in Ontario, Canada, using data from 3,672 schools. They found that factors such as the number of students with English as a second language, in special education, and from low-income households, and students' learning ability were inversely related to energy consumption, with learning ability having the greatest impact. Osabuohien-Irabor and Drapkin[23] used the extended Stochastic Impacts by Regression on Population, Affluence, and Technology framework and analyzed 86 developing countries. Results showed that strong national institutions enhanced the effectiveness of outward foreign direct investments in mitigating carbon emissions through eco-friendly technologies. High human capital levels improved home-country institutions, fostering spillovers from foreign direct investment that enhanced environmental quality. Overseas investment spurred human capital growth, encouraging green technology and cleaner production strategies. Environmental pressures affect community-based climate efforts. While severe and chronic pressures, such as rising CO_2 levels and unpredictable weather, might hinder program sustainability, moderate environmental issues can promote local adaptation through social action and resource-sharing.[24,25] Communities are more resilient and responsive when local climate monitoring is integrated into adaptation planning. Projects should account for seasonal rainfall and temperature extremes to protect agricultural productivity and water supplies, thereby boosting long-term outcomes.[26] These findings demonstrate the importance of ecological factors in the design and evaluation of grassroots climate initiatives, as environmental factors dynamically affect local adaptation capabilities.

2.2. Environmental determinants of community-based climate program effectiveness

Community-based climate efforts are affected by climatic unpredictability, temperature changes (TEMPs), and greenhouse gas emissions. Long-term or highly stressful events might make programs less resilient by increasing participants' vulnerability to damage and diminishing resources. Mild environmental shocks may motivate community-wide adaptations and cooperative efforts. The most effective adaptation strategies address short- and long-term ecological impacts on vulnerable people, and research suggests that community-based planning and local environmental monitoring are most effective. Zafar *et al.*[26] conducted a mixed-methods case study in northern Pakistan comparing two sites with differing levels of effectiveness in community-based conservation (CBC) and natural resource management. The proactive CBC in Khyber improved climate resilience through governance, practices, and knowledge, suggesting that integrating climate adaptation into existing CBC and natural resource management programs benefits vulnerable mountain communities. Madaleno andNogueira[27] conducted a study encompassing 27 European Union countries from 1994 to 2019. In the study, the impact of CO_2 emissions and renewable energy consumption on economic growth was investigated, along with various control factors. Results revealed positive contributions to economic growth from gross fixed capital, human development, and trade. However, the increased use of renewable energy came at the cost of higher CO_2 emissions, likely due to the region's reliance on fossil fuels. Economic considerations substantially influence community climate action.[28] More discretionary funds allow individuals to engage in local adaptation, training, and awareness activities.[29] Affluent, well-connected areas do better, as determined by regional education, infrastructure, and income. Hassan *et al.*[30] suggest that wealth and ACD are linked, as wealthier communities may use natural resources to support long-term adaptation efforts. The study emphasizes the need to incorporate socio-economic factors into climate adaptation programs to ensure equitable and effective community-based resilience measures.

2.3. Socio-economic influences: Income, finance, and regional disparities

Socio-economic variables, especially income per capita, impact communities' climate efforts. More discretionary income allows individuals to save money, engage in awareness and education campaigns, and build local adaptation strategies. Regional differences in infrastructure, institutional support, and income affect program sustainability and engagement in economically affluent areas. Thiede *et al.*[31] conducted a study from 1982 to 2017 across 23 sub-Saharan African countries, combining birth histories and historical climate data, and found that climatic variability affected childbearing in the short term. Women exposed to above-average temperatures and below-average precipitation experienced reduced fertility in the following year. The impact of precipitation anomalies on birth rates was notably strong, though the effects were modest in magnitude. Variations in temperature and precipitation effects were observed among demographic groups and across countries. Hydrological and climatic factors, including AP, temperature, and potable water supply, affect a community's capacity to adapt to climate change.[32] Temperature and rainfall variations affect agricultural productivity, water availability, and local community resilience, which in turn shape climate efforts.[33] Climate-mitigating initiatives demonstrate how targeted floodwater management and groundwater recharge can reduce environmental constraints.[34] Clean water promotes health, helps individuals earn a livelihood, and inspires climate change activism.[35] The study underscores the importance of safeguarding both urban and natural environments to mitigate the impacts of natural disasters and uncontrolled population growth. These studies collectively contribute to a deeper understanding of Pakistan's environmental challenges. They highlight issues such as water quality, extreme precipitation events, drought impacts on agriculture, and the urgent need for adaptive measures in the face of changing climatic conditions. These findings are crucial for policymakers and stakeholders to develop strategies for sustainable resource management, disaster prevention, and public health protection in Pakistan.

2.4. Climatic and water availability impacts on local climate adaptation

Annual precipitation, temperature anomalies, and potable water availability affect the takeoff and maintenance of community-based climate initiatives. Temperature and rainfall variations affect agricultural productivity, water security, and vulnerability, affecting communities' adaptation efforts. Safe drinking water is essential for public health and community engagement. ACD is vital for public health and well-being. AP is a critical component of the Earth's water cycle, impacting agriculture, ecosystems, and freshwater resources. Weather anomalies, such as extreme events, affect societies and economies, making accurate forecasting and preparedness crucial for resilience and safety. Ali and Muhammad[36] assessed the water quality of the Astore River for various uses, including domestic, drinking, and irrigation purposes. Samples were collected and analyzed for 17 physicochemical parameters. Findings revealed issues with turbidity, fluoride, and nitrate levels in some samples, affecting water quality. However, the river was suitable for agriculture and had a corrosive tendency. The study highlights that natural sources influenced hydrochemistry. Jamali *et al.*[37] conducted a study in Iran from 2001 to 2017 and analyzed the relationships among landscape indicators, including land surface temperature (LST), elevation, vegetation, and urban growth. Results showed rising LST across elevations and land uses, with the largest daytime LST anomalies occurring in forests, mountains, and populous metropolises. Positive trends in LST were observed during both summer and winter seasons in forest and mountain land uses. Additionally, all seasons exhibited positive trends in the Enhanced Vegetation Index (EVI) for mountain and desert land uses. The rising LST could heighten vulnerability to various natural disasters, while improvements in EVI reflect government efforts in green spaces and urban parks. Climate-vulnerable economies need water resource management. This is particularly true when hydrological fluctuation affects agricultural productivity, public health, and livelihood stability. The water security index links water accessibility, availability, and institutional management competence to socio-economic development outcomes, such as clean drinking water.[38] Prior research has demonstrated that water security reduces poverty, increases educational participation, and improves climate adaptability by making communities less vulnerable to environmental shocks.[39,40] Research shows that enhancing water accessibility infrastructure is a crucial public health intervention and a fundamental to the long-term sustainability of community-based climate initiatives in Pakistan. Komnino and Panori[41] and Istrate *et al.*[42] underscore the need for adaptable solutions that incorporate sociological and climatic factors and for combining local environmental monitoring with climate-neutrality policy.

Based on the discourse presented in the preceding sections, the following hypotheses were formulated:

(i) H1: The escalation of economic and environmental factors is anticipated to influence community-based climate change initiatives (CCIs) within a nation.
(ii) H2: Enhanced access to potable water is expected to benefit community-based CCIs.
(iii) H3: Alterations in climatic conditions are projected to sway community-based CCIs within a nation.

Drawing from the referenced literature, several critical factors previously overlooked in prior studies have been incorporated into the current research to bridge existing research gaps and enrich the field. Prior studies have predominantly focused on factors such as carbon emissions, globalization, industrialization, education, human capital, income disparity, governance practices, and climatic variations, while neglecting the significance of ACD—a vital determinant of population health and a pivotal factor influencing community-based CCIs.[43,44] Notably, it is uncommon to find studies integrating CO_2 emissions, income, and ACD within a unified model—an aspect identified as a novel contribution in this study. Secondly, previous research has primarily focused on water quality, pollution awareness, contaminants present in water, and its suitability for human health and agriculture[45,46] while overlooking the influence of AP on community-based CCIs. AP significantly impacts these initiatives by affecting accessibility, thereby influencing students' regular attendance. This study addresses this gap by introducing variables such as AP, income, and emissions in a unified model to assess their impacts on community-based CCIs. Thirdly, while numerous studies have explored variables such as LSTs, elevation, vegetation, and flood and drought incidents across varied contexts, they often overlook temperature anomalies, a crucial factor with substantial effects on variables such as agriculture and community-based CCIs.[47,48]

3. Methodology

The study collected data for the period 1990–2022 from the World Development Indicators published by the World Bank[49] and the Climate Change Knowledge Portal.[50] The following variables were used in the study for empirical illustrations:

(i) Dependent variable: Community-based CCIs (% gross). Information on the presence and scale of community-based projects and initiatives aimed at climate change adaptation. Data on the presence and scale of environmental education programs within the community suggest a grassroots effort to raise awareness and build capacity for climate adaptation. Secondary school enrollment (% gross) was used to assess community resilience to climate change, as communities with a higher percentage of individuals with higher levels of secondary education indicate greater potential for environmental awareness and participation in environmental education programs. The data was taken from the World Bank[49] database.
(ii) Independent variables:

a. CO_2 emissions (metric tons per capita): CO_2 emissions per capita as a measure of the community's carbon footprint. The data were collected from the World Bank[49] database.

b. GDP per capita (GDPPC; constant 2015 United States dollars [US$]): The economic well-being of the community, which can affect its capacity to implement resilience and adaptation strategies. The GDPPC data were collected from the World Bank[49] database.

c. ACD (% of population): The percentage of the population with access to clean and safe drinking water, as it impacts public health and disaster response. The data were collected from the World Bank[49] database.

d. AP (mm) (AP): Average AP levels are relevant for communities facing issues such as flooding or drought. The data on average precipitation were collected from the Climate Change Knowledge Portal.[50]

e. TEMP (°C): Deviations in annual temperature from historical averages, which can indicate changing climate patterns and their effects. Data on extreme temperatures are available on the Climate Change Knowledge Portal.[50]

(iii) Square term. APsquared (SQAP): This squared term helps account for nonlinear relationships between precipitation levels and community resilience, as extremely high or low precipitation levels may have disproportionate impacts.

(iv) Interaction term: GDPPC × ACD: This interaction term helps analyze how economic well-being and access to clean water interact to influence community resilience. It provides insights into the role of economic resources in improving water access and, subsequently, resilience.

The secondary school enrollment data, CO_2 emissions, and ACD were sourced from the World Bank[49] database, while data on AP and temperature anomalies were obtained from the CCKP[50] data portal. Examining Pakistan within the framework of resilience and adaptation to climate change yielded valuable insights into the challenges and opportunities of sustainable development in a rapidly evolving economy. This approach provided a distinctive viewpoint on the intersection of economic growth, environmental degradation, and policy interventions. Analyzing Pakistan's environmental policies, resource management practices, and their repercussions on local and global ecosystems can contribute to broader discussions on sustainable economic strategies.

The circular economy emphasizes sustainable production and resource efficiency in analyzing community-based climate initiatives.[51] Circular economy techniques maximize resource efficiency, minimize waste, and promote recycling and reuse to increase economic output and reduce environmental impact.[52] Georgescu *et al.*[53] showed that adopting circular economy models in the European Union enhanced economic efficiency and reduced resource use, helping the environment over time. Applying these principles to community-based climate programs in Pakistan ensures that local adaptation efforts address environmental and socio-economic issues, while advancing the long-term goal of reducing the negative effects of material consumption and building climate change resilience.

3.1. Augmented Dickey–Fuller unit root test

The augmented Dickey–Fuller (ADF) test is a commonly used statistical test for determining whether a time series has a unit root, which can indicate non-stationarity.[54] In a non-stationary time series, the statistical properties, such as the mean and variance, change over time, making it challenging to make meaningful inferences or predictions. The ADF test helps in identifying such non-stationarity.

This study tested for time-series stationarity using the ADF test, a prominent method for detecting unit roots. For strong inference on variables' integration characteristics, the ADF test allows for the modification of lagged differences to account for autocorrelation. In processes with moving-average components, the ADF test's restrictions may affect the distribution of the test statistic, leading to size distortions. Due to these limitations, Galbraith and Zinde-Walsh[55] advised caution when interpreting ADF results, especially for variables with strong autocorrelation or near-unit-root behavior. This study evaluated environmental and socio-economic determinants of stationarity using scientific methods and, based on these findings, proposed a framework for assessing stationarity. The ADF test was conducted based on the following autoregressive model (**Equation 1**):

$$\Delta Y_t = \alpha + \beta Y_{t-1} + \gamma t + \varepsilon_t \quad (1)$$

where Δy_t represents the differenced time-series data, which helps make the data more stationary, y_{t-1} is the lagged value of the time series, Δy_{t-1} is the first differenced lagged value of the time series, t is a trend term, and ε_t is the residual or error term.

The ADF test has several variants, including the ADF–generalized least squares test, which accounts for serial correlation and heteroskedasticity. Researchers and analysts use the ADF test and its variants to assess the stationarity of time-series data, a crucial step in time-series analysis and econometrics. **Equations 2–7** show the ADF unit root specifications:

$$\Delta(CCI)_t = \alpha + \beta(CCI) + \gamma(CCI)_{t-1} + \delta_1\Delta(CCI)_{t-1} + \ldots + \delta_{p-1}\Delta(CCI)_{t-p-1} + \varepsilon_t \quad (2)$$

$$\Delta(CO2)_t = \alpha + \beta(TIME) + \gamma(CO2)_{t-1} + \delta_1\Delta(CO2)_{t-1} + \ldots + \delta_{p-1}\Delta(CO2)_{t-p-1} + \varepsilon_t \quad (3)$$

$$\Delta(GDPPC)_t = \alpha + \beta(TIME) + \gamma(GDPPC)_{t-1} + \delta_1\Delta(GDPPC)_{t-1} + \ldots + \delta_{p-1}\Delta(GDPPC)_{t-p-1} + \varepsilon_t \quad (4)$$

$$\Delta(ACD)_t = \alpha + \beta(TIME) + \gamma(ACD)_{t-1} + \delta_1\Delta(ACD)_{t-1} + \ldots + \delta_{p-1}\Delta(ACD)_{t-p-1} + \varepsilon_t \quad (5)$$

$$\Delta(AP)_t = \alpha + \beta(TIME) + \gamma(AP)_{t-1} + \delta_1\Delta(AP)_{t-1} + \ldots + \delta_{p-1}\Delta(AP)_{t-p-1} + \varepsilon_t \quad (6)$$

$$\Delta(TEMP)_t = \alpha + \beta(TIME) + \gamma(TEMP)_{t-1} + \delta_1\Delta(TEMP)_{t-1} + \ldots + \delta_{p-1}\Delta(TEMP)_{t-p-1} + \varepsilon_t \quad (7)$$

3.2. Autoregressive distributed lag bounds testing approach

The autoregressive distributed lag (ARDL) bounds testing approach is a widely used econometric method for analyzing the long- and short-run relationships among variables in a time-series context. This approach is especially valuable when dealing with integrated time-series data and is commonly employed in econometrics and economics. It was introduced by Pesaran *et al.*[56], providing a framework for estimating and testing cointegrating relationships.

This study used the ARDL bounds testing method to examine the relationships among the variables in both the short- and long-term. To determine the optimal lag length, the study used established lag selection criteria, including the Akaike Information Criterion, Schwarz Bayesian Criterion, and Hannan–Quinn Criterion. This approach is essential for ensuring the model's robustness and preventing potential misspecification. After establishing the integration order of the variables, the ARDL framework was estimated, and the significance of the coefficients was assessed through probability values at the 5% significance level.

The ARDL approach distinguishes between short-run dynamics and long-run relationships within a set of time-series data. The primary models used in ARDL are shown in **Equation 8**:

$$\begin{aligned}\Delta ln(CCI)_t = \alpha_0 &+ \sum_{i=1}^{p}\varphi_i \Delta ln(CCI)_{t-i} + \sum_{i=0}^{q}\theta_i \Delta ln(CO2)_{t-i} \\ &+ \sum_{i=0}^{r}\theta_i \Delta ln(GDPPC)_{t-i} + \sum_{i=0}^{t}\phi_i \Delta ln(ACD)_{t-i} \\ &+ \sum_{i=0}^{u}\phi \Delta ln(AP)_{t-i} + \sum_{i=0}^{v}\phi \Delta ln(TEMP)_{t-i} n \\ &+ \delta_1 ln(CO2)_t + \delta_2 ln(GDPPC)_t + \delta_3 ln(ACD)_t \\ &+ \delta_4 ln(AP)_t + \delta_5 ln(TEMP)_t + \varepsilon_t \end{aligned} \quad (8)$$

where Δ shows the first difference operator.

Narayan's[57] critical values were used to either accept or reject the hypothesis related to the cointegration process in the given model. **Equation 9** extended the general ARDL equation and included an error correction term to analyze the short-run adjustment that occurs in the given model:

$$\begin{aligned}\Delta ln(CCI)_t = \alpha_0 &+ \sum_{i=1}^{p}\varphi_i \Delta ln(CCI)_{t-i} + \sum_{i=0}^{q}\theta_i \Delta ln(CO2)_{t-i} \\ &+ \sum_{i=0}^{r}\theta_i \Delta ln(GDPPC)_{t-i} + \sum_{i=0}^{t}\phi_i \Delta ln(ACD)_{t-i} \\ &+ \sum_{i=0}^{u}\phi \Delta ln(AP)_{t-i} + \sum_{i=0}^{v}\phi \Delta ln(TEMP)_{t-i} n \\ &+ \delta_1 ln(CO2)_t + \delta_2 ln(GDPPC)_t + \delta_3 ln(ACD)_t \\ &+ \delta_4 ln(AP)_t + \delta_5 ln(TEMP)_t + \lambda(EXT)_{t-1} + \varepsilon_t \end{aligned} \quad (9)$$

where λ shows the adjustment parameter.

The ARDL bounds test involves estimating an unrestricted error correction model and calculating the *F*-statistic to test for cointegration. The computed *F*-statistic was subsequently assessed against the critical value thresholds. The determination of cointegration relies on a 5% significance level. In this context, the null hypothesis, which posits the absence of a long-run relationship, is rejected when the *F*-statistic surpasses the upper-bound critical value.

3.3. Granger causality test

The Granger causality test is typically applied to two time series, denoted as Y and X. It tests the hypothesis that past values of X can predict current values of Y, and vice versa. The vector autoregression framework (**Equation 10**) was used for analysis, i.e.,

$$
\begin{bmatrix} ln(CCI)_t \\ ln(CO2)_t \\ ln(GDPPC)_t \\ ln(ACD)_t \\ ln(AP)_t \\ ln(TEMP)_t \end{bmatrix} = \begin{bmatrix} \tau_0 \\ \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \end{bmatrix} + \sum_{i=1}^{p} \begin{bmatrix} \sigma_{11t} & \sigma_{12t} & \sigma_{13t} & \sigma_{14t} & \sigma_{15t} \\ \sigma_{21t} & \sigma_{22t} & \sigma_{23t} & \sigma_{24t} & \sigma_{25t} \\ \sigma_{31t} & \sigma_{32t} & \sigma_{33t} & \sigma_{34t} & \sigma_{35t} \\ \sigma_{41t} & \sigma_{42t} & \sigma_{43t} & \sigma_{44t} & \sigma_{45t} \\ \sigma_{51t} & \sigma_{52t} & \sigma_{53t} & \sigma_{54t} & \sigma_{55t} \\ \sigma_{61t} & \sigma_{62t} & \sigma_{63t} & \sigma_{64t} & \sigma_{65t} \end{bmatrix} \times \begin{bmatrix} ln(CCI)_{t-1} \\ ln(CO2)_{t-1} \\ ln(GDPPC)_{t-1} \\ ln(ACD)_{t-1} \\ ln(AP)_{t-1} \\ ln(TEMP)_{t-1} \end{bmatrix}
$$

$$
+ \sum_{j=p+1}^{dmax \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix}} \begin{bmatrix} \theta_{11j} & \theta_{12j} & \theta_{13j} & \theta_{14j} & \theta_{15j} \\ \theta_{21j} & \theta_{22j} & \theta_{23j} & \theta_{24j} & \theta_{25j} \\ \theta_{31j} & \theta_{32j} & \theta_{33j} & \theta_{34j} & \theta_{35j} \\ \theta_{41j} & \theta_{42j} & \theta_{43j} & \theta_{44j} & \theta_{45j} \\ \theta_{51j} & \theta_{52j} & \theta_{53j} & \theta_{54j} & \theta_{55j} \\ \theta_{61j} & \theta_{62j} & \theta_{63j} & \theta_{64j} & \theta_{65j} \end{bmatrix} \times \begin{bmatrix} ln(CCI)_{t-j} \\ ln(CO2)_{t-j} \\ ln(GDPPC)_{t-j} \\ ln(ACD)_{t-j} \\ ln(AP)_{t-j} \\ \ln(TEMP)_{t-j} \end{bmatrix} \quad (10)
$$

Equations 11–16 show Granger causality for a multivariate system:

$$
\begin{aligned} CCI_t = c_1 &+ \sum_{i=1}^{2} \delta_1 CCI_{t-i} + \sum_{i=1}^{2} \delta_2 CO2_{t-i} \\ &+ \sum_{i=1}^{2} \delta_3 GDPPC_{t-i} + \sum_{i=1}^{2} \delta_4 ACD_{t-i} \\ &+ \sum_{i=1}^{2} \delta_5 AP_{t-i} + \sum_{i=1}^{2} \delta_6 TEMO_{t-i} + \varepsilon \end{aligned} \quad (11)
$$

$$
\begin{aligned} CO2_t = c_1 &+ \sum_{i=1}^{2} \delta_1 CO2_{t-i} + \sum_{i=1}^{2} \delta_2 CCI_{t-i} \\ &+ \sum_{i=1}^{2} \delta_3 GDPPC_{t-i} + \sum_{i=1}^{2} \delta_4 ACD_{t-i} \\ &+ \sum_{i=1}^{2} \delta_5 AP_{t-i} + \sum_{i=1}^{2} \delta_6 TEMP_{t-i} + \varepsilon \end{aligned} \quad (12)
$$

$$
\begin{aligned} GDPPC_t = c_1 &+ \sum_{i=1}^{2} \delta_1 GDPPC_{t-i} + \sum_{i=1}^{2} \delta_2 CO2_{t-i} \\ &+ \sum_{i=1}^{2} \delta_3 CCI_{t-i} + \sum_{i=1}^{2} \delta_4 ACD_{t-i} \\ &+ \sum_{i=1}^{2} \delta_5 AP_{t-i} + \sum_{i=1}^{2} \delta_6 TEMP_{t-i} + \varepsilon \end{aligned} \quad (13)
$$

$$
\begin{aligned} ACD_t = c_1 &+ \sum_{i=1}^{2} \delta_1 ACD_{t-i} + \sum_{i=1}^{2} \delta_2 CO2_{t-i} \\ &+ \sum_{i=1}^{2} \delta_3 GDPPC_{t-i} + \sum_{i=1}^{2} \delta_4 CCI_{t-i} \\ &+ \sum_{i=1}^{2} \delta_5 AP_{t-i} + \sum_{i=1}^{2} \delta_6 TEMP_{t-i} + \varepsilon \end{aligned} \quad (14)
$$

$$
\begin{aligned} GDPPC_t = c_1 &+ \sum_{i=1}^{2} \delta_1 GDPPC_{t-i} + \sum_{i=1}^{2} \delta_2 CO2_{t-i} \\ &+ \sum_{i=1}^{2} \delta_3 CCI_{t-i} + \sum_{i=1}^{2} \delta_4 ACD_{t-i} \\ &+ \sum_{i=1}^{2} \delta_5 CCI_{t-i} + \sum_{i=1}^{2} \delta_6 TEMP_{t-i} + \varepsilon \end{aligned} \quad (15)
$$

$$
\begin{aligned} TEMP_t = c_1 &+ \sum_{i=1}^{2} \delta_1 TEMP_{t-i} + \sum_{i=1}^{2} \delta_2 CO2_{t-i} \\ &+ \sum_{i=1}^{2} \delta_3 GDPPC_{t-i} + \sum_{i=1}^{2} \delta_4 ACD_{t-i} \\ &+ \sum_{i=1}^{2} \delta_5 AP_{t-i} + \sum_{i=1}^{2} \delta_6 CCI_{t-i} + \varepsilon \end{aligned} \quad (16)
$$

The Granger causality test was applied to examine the direction and existence of causal relationships among the selected variables. All statistical analyses are conducted using EViews software (version 9).

4. Results and discussion

Table 1 presents the descriptive statistics. CCI ranged from 19.911% of gross to 41.855% of gross, with a positively skewed distribution and a mean of 29.697%. The variable for CO_2 emissions had a standard deviation of 0.102 metric tons per capita, ranging from 0.918 to 0.505 metric tons per capita, and a positively skewed distribution with a mean of 0.700 metric tons per capita.

Furthermore, the GDPPC had a mean of US$ 1,118.979 and a standard deviation of US$ 200.503. Its range spanned from a minimum of US$862.416 to a maximum of US$1535.718. The ACD variable displayed a positively skewed distribution, with a mean of 88.512% and a range of 87.364% to 90.625%. Regarding the AP variable, it had a kurtosis of 2.215and a skewness of 0.149. The mean, maximum, and minimum values for AP were 293.588 mm, 442.880 mm, and 181.500 mm, respectively. Lastly, the TEMP variable ranged from 20.210°C to 22.240°C and exhibited a negative skew. It had a standard deviation of 0.551°C and a mean value of 21.386°C. Table 2 presents the results of the unit root tests. The variables CO_2, AP, and TEMP exhibited stationarity at the level, indicating that their datasets are relatively stable and not highly volatile. On the other hand, the variables CCI, GDPPC, and ACD were stationary at first differences, suggesting that changes occurred over time and that their datasets are more volatile.

Table 3 displays the lag length selection criteria. According to the results, all selection criteria recommended using data up to the first lag length when conducting an ARDL to examine both long- and short-run relationships. Thus, the study used the first lag of the variable and estimated short- and long-run effects using an ARDL model.

Table 4 presents the long and short-run relationships among the variables. The error correction term was significant, indicating that it self-corrected by 57% each year. Notably, there exists a negative relationship between the CCIs and carbon emissions in the long run. This suggests that an increase in carbon emissions leads to a long-term adverse change in CCI. This could be attributed to higher emissions, which contribute to overall climate change and result in more severe environmental challenges that hinder communities' ability to implement sustainable practices. Additionally, industrial activities that increase emissions may overshadow local efforts to reduce carbon footprints. Moreover, economic and social pressures

Table 1. Descriptive statistics

Parameters	CCI (% of gross)	CO_2 (metric tons per capita)	GDPPC (US$)	ACD (%)	AP (mm)	TEMP (°C)
Mean	29.697	0.700	1,118.979	88.512	293.588	21.386
Maximum	41.855	0.918	1,535.718	90.625	442.880	22.240
Minimum	19.911	0.505	862.416	87.364	181.500	20.210
Standard deviation	5.967	0.102	200.503	1.118	64.984	0.551
Skewness	0.556	0.023	0.571	0.471	0.149	−0.434
Kurtosis	2.440	2.288	2.087	1.817	2.215	2.423

Abbreviations: ACD: Access to clean drinking water; AP: Annual precipitation; CCI: Climate change initiative; CO_2: Carbon dioxide; GDPPC: Gross domestic product per capita; TEMP: Temperature change.

Table 2. Unit root estimates

Variables	Level		First difference		Decision
	Intercept	Intercept and trend	Intercept	Intercept and trend	
CCI	2.230 (0.999)	−2.194 (0.476)	−4.182 (0.002)	−5.012 (0.001)	I(1)
CO_2	−1.595 (0.473)	−4.715 (0.004)	−4.642 (0.001)	−4.415 (0.010)	I(0)
GDPPC	1.724 (0.999)	−1.360 (0.852)	−3.637 (0.010)	−4.043 (0.017)	I(1)
ACD	−0.072 (0.944)	−3.064 (0.132)	−3.716 (0.012)	−4.958 (0.001)	I(1)
AP	−6.184 (0.000)	−6.214 (0.000)	−6.457 (0.000)	−6.399 (0.000)	I(0)
TEMP	−2.694 (0.085)	−4.518 (0.005)	−7.726 (0.000)	−7.597 (0.000)	I(0)

Note: The reported values represent the augmented Dickey–Fuller (ADF) test statistics. Brackets show probability values
Abbreviations: ACD: Access to clean drinking water; AP: Annual precipitation; CCI: Climate change initiative; CO_2: Carbon dioxide; GDPPC: Gross domestic product per capita; TEMP: Temperature change.

Table 3. Lag length selection criteria

Lag	Log-likelihood	Likelihood ratio test	Final prediction error	Akaike information criterion	Schwarz criterion	Hannan–Quinn criterion
0	−396.2196	Not applicable	7498.998	25.94965	26.22720	26.04013
1	−263.1550	206.0356[a]	14.99431[a]	19.68742[a]	21.63024[a]	20.32073[a]
2	−231.1474	37.17009	25.74857	19.94499	23.55309	21.12114

Note: [a]indicates lag order selected by the criterion.

stemming from the consequences of climate change may divert attention and resources away from local initiatives.

An increase in GDPPC led to higher CCI in both the short and long runs. Economic growth can positively influence community-based CCIs by providing increased resources, awareness, and community engagement. With economic expansion, there is typically a rise in financial resources available for environmental initiatives. Additionally, higher income levels enable communities to invest in sustainable technologies, infrastructure, and education programs. Economic development also correlates with higher levels of education and awareness, empowering communities to understand the implications of climate change and adopt proactive measures. Moreover, economic growth fosters social cohesion and community resilience, providing stability and reducing vulnerabilities, which allows communities to focus on environmental concerns.[58-60]

The AP exhibited a negative short- and long-term relationship with CCI, implying that an increase in AP decreases CCI in both short- and long-term. Decreased precipitation can significantly affect community-based CCI by intensifying environmental stress and constraining sustainability efforts, whereas increased precipitation supports such initiatives by improving

Table 4. Autoregressive distributed lag estimates

Variables	Coefficient	Standard error	*t*-statistic	Probability
Selected model: Autoregressive distributed lag (1, 1, 1, 0, 0, 1)				
D(CO_2)	−2.040906	9.657111	−0.211337	0.8346
D(GDPPC)	0.321250	0.158336	2.028910	0.0547
D(ACD)	−2.191075	1.468699	−1.491847	0.1499
D(GDPPC×ACD)	−0.003549	0.001685	−2.106205	0.0468
D(AP)	−0.009544	0.004700	−2.030790	0.0545
D(SQAP)	−0.000019	0.000008	−2.487900	0.0209
D(TEMP)	−0.113447	0.744153	−0.152451	0.8802
Error correction term	−0.573742	0.124917	−4.592998	0.0001
Long-run coefficients				
CO_2	−33.564328	16.511376	−2.032800	0.0543
GDPPC	0.073172	0.020186	3.624910	0.0015
ACD	−3.818920	2.673418	−1.428478	0.1672
GDPPC×ACD	0.000783	0.000218	3.585361	0.0016
AP	−0.016634	0.008463	−1.965414	0.0621
AP square	−0.000042	0.000021	−2.022875	0.0554
TEMP	−3.200437	1.615922	−1.980564	0.0592
Constant	355.365764	212.918343	1.669024	0.1093

Note: Dependent variable: CCI.
Abbreviations: ACD: Access to clean drinking water; AP: Annual precipitation; CCI: Climate change initiative; CO_2: Carbon dioxide; GDPPC: Gross domestic product per capita; TEMP: Temperature change.

environmental conditions and resource availability. Water scarcity resulting from decreased precipitation can divert community resources away from CCIs toward immediate survival concerns. Moreover, altered precipitation patterns can disrupt biodiversity, ecosystem health, and agricultural productivity, hampering long-term planning and implementation of sustainable practices.[61,62]

In the long run, the TEMPs showed a negative relationship with CCI. This indicates that an increase in the rate of change in temperature decreases CCI. Rising temperature anomalies pose challenges to community-based CCIs by exacerbating environmental stressors, compromising ecosystems, and increasing vulnerability. Elevated temperatures contribute to shifts in weather patterns, leading to more frequent and intense heat waves, which strain local resources and impact agricultural productivity. Additionally, warmer temperatures amplify the occurrence of extreme weather events, disrupt water availability, and challenge community-based water conservation efforts.[63,64]

In the short and long run, the product of income and clean water availability significantly affects climate change mitigation efforts. Income-induced access to clean water may reduce community involvement in climate change projects. As economies grow and access to clean water improves, communities may prioritize economic development and living standards over environmental concerns. Previous research implies that economic growth reduces environmental advocacy and sustainability initiatives.[65,66] As societies get wealthier, they may prioritize economic growth over environmental protection, reducing climate change efforts. Access to clean water may also reduce environmental concerns, contributing to complacency about climate change. The findings also showed no inverted-U-shaped relationship between annual precipitation and climate change efforts. Both AP and its square term negatively affect climate change efforts. Thus, neither low nor high precipitation increases community participation in climate change. The disruptive impact of severe precipitation events on community stability and resilience may explain this result economically. Flooding, infrastructure damage, and population migration from high precipitation shift resources from climate change programs to disaster response and recovery.[67] Low-precipitation areas may confront water constraints and agricultural issues, limiting their ability to prioritize climate change activities.[68]

Table 5. Autoregressive distributed lag bounds estimates

Test statistic	Value	*k*
F-statistic	3.545	5
Critical value bounds		
Significance	I0 bound	I1 bound
10%	1.81	2.93
5%	2.14	3.34
2.5%	2.44	3.71
1%	2.82	4.21

Abbreviations: ACD: Access to clean drinking water; AP: Annual precipitation; CCI: Climate change initiative; CO_2: Carbon dioxide; GDPPC: Gross domestic product per capita; TEMP: Temperature change

The environmental Kuznets curve hypothesis suggests that as economies advance, technical efficiency, environmental awareness, and institutional maturity increase, reducing environmental damage.[69] The results that income dynamics affect community-based climate actions in the long run may signal a systemic shift toward sustainable development. The unfavorable environmental externalities of early economic development disappear as nations adopt cleaner technologies, expand educational attainment, and improve access to essential utilities, such as safe drinking water.[70] This move aligns with new circular economy concepts that promote more efficient resource use in manufacturing to reduce raw material consumption and boost environmental resilience. Recent studies, such as those by Masud and Khan[71] and Imran *et al.*[72], underline the importance of education, institutional coordination, and technical upgrading in Pakistan's community-level climate adaptation activities. This emphasizes the need to integrate socio-economic indicators with environmental sustainability methods.

Recent studies emphasize the role of education in sustainable development and the circular economy.[73,74] It can enhance environmental awareness, make institutions more responsive, and enable communities to adopt circular economy-aligned, resource-efficient behaviors by expanding participation in educational programs.[75] Community-based climate activities include social engagement and knowledge-based adaptation mechanisms that enhance resource efficiency and environmental stewardship.[76] Better education, greater technology, and stronger social and economic infrastructure reduce environmental stress and build more resilient societies.[77] These strategies, which improve community engagement through education to encourage climate-responsive behavior and facilitate the transition to more sustainable consumption and production, may assist Pakistan and other developing nations.

Table 5 presents the bound-testing estimates. The *F*-statistic value in the table is significant at the 5% level. This indicates the presence of a long-term relationship or cointegration among the variables.

Table 6 presents the results of the Granger causality test, revealing significant insights into the relationships among the variables under study. Firstly, the test indicated a unidirectional relationship between GDPPC and CCI. Economic expansion enables communities to access increased financial resources, facilitating investment in sustainable projects. These resources can fund the development of renewable energy infrastructure and promote environmentally conscious practices within communities. Moreover, economic growth fosters technological advancements, particularly in green technologies, making them more affordable and accessible for local implementation.[78] Job creation in green sectors empowers individuals to engage in climate initiatives, raise living standards, and contribute to a skilled workforce capable of sustaining eco-friendly projects.[79]

Secondly, the analysis suggested a unidirectional relationship between GDPPC and CO_2 emissions. Historically, economic growth has been correlated with increased CO_2 emissions, driven by heightened industrial activity and energy consumption. As economies expand, energy demand often surges, which is often met by burning fossil fuels, a significant contributor to CO_2 emissions.[80] Industrial processes and transportation associated with economic growth further exacerbate emissions. This phenomenon, known as the environmental Kuznets curve, suggests that environmental degradation initially rises with economic growth but may eventually decline as societies prioritize environmental sustainability.[81] Similarly, a unidirectional relationship was observed between ACD and CCI. ACD is crucial for community-based CCIs as it enhances resilience and supports adaptation efforts. Clean

Table 6. Granger causality estimates

Causality direction	*F*-statistic	Probability
CO_2 ≠ CCI	1.935	0.164
CCI ≠ CO_2	0.234	0.793
GDPPC →CCI	5.630	0.009
CCI ≠ GDPPC	0.377	0.689
ACD → CCI	11.059	0.000
CCI ≠ ACD	1.498	0.242
AP ≠ CCI	1.147	0.333
CCI ≠ AP	0.505	0.609
TEMP ≠ CCI	2.204	0.130
CCI ≠ TEMP	2.170	0.134
GDPPC → CO_2	3.751	0.037
CO_2 ≠ GDPPC	1.603	0.220
ACD ≠ CO_2	2.639	0.090
CO_2 ≠ ACD	2.443	0.106
AP ≠ CO_2	1.829	0.180
CO_2 ≠ AP	0.797	0.461
TEMP ≠ CO_2	0.091	0.913
CO_2 → TEMP	2.807	0.078
ACD → GDPPC	7.806	0.002
GDPPC ≠ ACD	0.768	0.474
AP ≠ GDPPC	0.657	0.526
GDPPC ≠ AP	0.907	0.416
TEMP ≠ GDPPC	0.100	0.904
GDPPC ≠ TEMP	2.082	0.144
AP → ACD	3.036	0.065
ACD ≠ AP	1.008	0.378
TEMP → ACD	3.860	0.034
ACD ≠ TEMP	2.073	0.146
TEMP ≠ AP	0.875	0.428
AP ≠ TEMP	0.438	0.649

Note: The symbol (→) indicates unidirectional causality running from one variable to another, while (≠) indicates the absence of causality between the variables.

Abbreviations: ACD: Access to clean drinking water; AP: Annual precipitation; CCI: Climate change initiative; CO_2: Carbon dioxide; GDPPC: Gross domestic product per capita; TEMP: Temperature change.

water is essential for maintaining health, particularly in the face of climate-related events such as droughts and floods. Moreover, communities with established water security are better positioned to implement sustainable practices, contributing to climate change mitigation.[39] Additionally, CO_2 emissions influence TEMP, indicating a unidirectional relationship. Increasing CO_2 emissions contribute to rising global temperatures, as evidenced by temperature anomalies. As anthropogenic activities increase CO_2 emissions, the enhanced greenhouse effect intensifies, leading to a warm climate.[82] This correlation underscores the urgency of reducing greenhouse gas emissions to mitigate the impacts of climate change.

Furthermore, there was a unidirectional relationship between ACW and GDPPC. ACD drives economic growth by improving public health, education, and productivity.

Communities with reliable access to clean water experience lower healthcare costs, reduced absenteeism, and enhanced overall well-being, contributing to a more robust workforce. Moreover, access to clean water positively correlated with educational outcomes, fostering innovation and sustainable development.[70] Finally, TEMP influenced ACW, indicating a unidirectional relationship. Changes in temperature patterns, including rising temperatures and altered precipitation, can affect the availability and quality of water resources. Extreme weather events associated with temperature anomalies, such as floods and storms, can compromise water infrastructure and disrupt access to safe drinking water. These climate-induced challenges underscore the importance of resilient water management practices to ensure continuous ACD amidst changing climate conditions.

Pakistani community-based climate adaptation mechanisms are dynamic; therefore, explanatory factors have varied short- and long-term impacts. Resource availability affects short-term reactions, while structural environmental circumstances affect long-term consequences. When income per capita and access to clean water increase, households may participate in education, awareness, and communal adaptation initiatives. This temporarily boosts community-based climate change activities. These improvements enable communities to engage in climate-responsive activities and reduce short-term livelihood risks. However, rising carbon emissions and climatic variability harm the environment over time. This applies notably to temperature and precipitation variations. Regular environmental stress undermines community-level adaptability and institutional continuity. Due to ongoing environmental degradation, the future of agricultural production, water availability, and public health is unclear, diverting community resources from long-term climate resilience planning. Long-term income and water benefits suggest that socio-economic infrastructure stabilizes adaptive capabilities to climatic shocks. These findings demonstrate that environmental pressures reduce community resilience over time. However, basic service accessibility and economic development may buffer these effects by strengthening the social and institutional roots of community-based climate action.

5. Conclusion

This study delved into the intricate dynamics of community-based climate initiatives, aiming to understand how various factors influence their adoption and success across diverse regions. By examining the impacts of carbon emissions, GDPPC, access to clean water, and climate conditions, the research seeks to provide insights into how to enhance climate resilience in Pakistan. Using data from 1990 to 2022, the study employed the ARDL model to examine the relationships among the variables. The ARDL analysis revealed several significant findings:

(i) A negative long-term relationship existed between CO_2 and community-based CCIs, suggesting that higher emissions over time negatively affect CCIs.
(ii) GDPPC emerged as a significant factor in both the short- and long-term, indicating its influential role in shaping climate initiatives.
(iii) AP exhibited a negative correlation with CCI in both short and long runs, highlighting the challenges posed by changing precipitation patterns on climate initiatives.

Community engagement and socio-economic infrastructure are needed to improve Pakistan's climate change adaptation. Policymakers should prioritize integrated programs that boost income and provide universal ACD, thereby improving a community's climate resilience. They must also invest in climate-resilient infrastructure, early-warning systems, and local adaptation education to mitigate the effects of rising carbon emissions and climatic unpredictability. Integrating socio-economic growth with environmental stability may help governments and local governments adapt to climate change. This will enable community-level adaptability over time. In light of these results, several policy recommendations can be made to support short-term, medium-term, and long-term climate action efforts:

(i) Short-term policy recommendations:
   a. Launch short-term awareness campaigns to educate communities on the immediate impacts of carbon emissions and promote sustainable practices.
   b. Develop short-term emergency response plans to address the adverse effects of increased precipitation on climate initiatives.
   c. Introduce short-term financial incentives for businesses and communities engaging in environmentally friendly practices.
   d. Initiate short-term water conservation projects to ensure sustainable water management practices.
   e. Conduct workshops to enhance local community capacity in regions with high-temperature anomalies.

(ii) Medium-term policy recommendations:
   a. Implement policies that promote sustainable economic growth and integrate environmental considerations into development plans.

b. Invest in infrastructure projects to enhance resilience to extreme weather events caused by temperature anomalies.

c. Allocate funding for research and innovation grants to support climate initiatives and economic growth.

d. Develop integrated water management strategies to address challenges in water access.

e. Introduce a carbon pricing mechanism to incentivize emission reductions and support climate initiatives.

(iii) Long-term policy recommendations:

a. Formulate a comprehensive national climate action plan integrating community-based initiatives into broader sustainability goals.

b. Implement educational reforms to embed climate consciousness into the curriculum and nurture a generation committed to climate action.

c. Strategically transition to renewable energy sources to mitigate emissions and support sustainable growth.

d. Invest in climate-resilient infrastructure projects to safeguard climate initiatives against future challenges.

e. Foster international collaborations to share best practices and enhance Pakistan's capacity to address climate challenges globally.

Policy suggestions align with Pakistan's sustainable development objectives, particularly the National Adaptation Plan and the Sustainable Development Goals framework. Supporting national climate adaptation, environmental protection, and equitable socio-economic development requires enhancing educational accessibility, water resource management, and climate-resilient infrastructure in community-based climate projects.[26,83] The Recharge Pakistan and Green Pakistan Upscaling Programme demonstrates how ecosystem restoration and coordinated floodwater management can support local adaptation.[84,85] Localized resilience plans that align with national policy frameworks may increase institutional coordination and help achieve national and international sustainability objectives. In conclusion, adopting these policy recommendations can bolster Pakistan's efforts to build climate resilience and sustain community-based climate initiatives amid evolving environmental challenges.

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Conflict of interest

The authors declare no conflict of interest.

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Availability of data

The data is freely available at World Development Indicators published by the World Bank at https://databank.worldbank.org/source/world-development-indicators, and the Climate Change Knowledge Portal at https://climateknowledgeportal.worldbank.org/

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