

Article

The Effectiveness of Climate Adaptation Finance and Readiness on Vulnerability in African Economies

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Abstract: Addressing climate vulnerability remains a priority for economies globally. This study used the panel-corrected standard error (PCSE) methodology to investigate the impact of adaptation financing on climate vulnerability. This analysis examined 52 African countries from 2012 to 2021 while considering their climate adaptation readiness. The impact was also assessed based on the Human Development Index (HDI) categories to reflect different levels of development. The findings showed that adaptation finance considerably influenced climate vulnerability reduction in Africa, particularly in nations with a moderate HDI. However, most countries still need higher levels of adaptation financing, resulting in a small impact on vulnerability reduction. Furthermore, the impact of readiness measures differed by HDI category. Economic and social climate readiness strongly impacted climate vulnerability in high-HDI nations, but governance preparedness was more critical in low-HDI countries. Based on the empirical facts, two policy proposals emerge. First, it is critical to reconsider the distribution of adaptation financing to reduce disparities and effectively alleviate climate vulnerability. Moreover, African economies should consider implementing innovative localized financing mechanisms to mobilize extra adaptation finance. Second, African governments should customize climate readiness interventions based on their HDI levels to improve the achievement of a positive impact on climate vulnerability.

Keywords: climate adaptation finance; climate readiness; climate vulnerability; panel-corrected standard error analysis; Africa



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1. Introduction

In light of the pressing issue of climate change, it is imperative to swiftly and consistently execute measures that address climate change adaptation on a continental scale [1]. The implemented adaptation measures' long-term effectiveness partly depends on the climate vulnerability of the respective regions [2]. Climate vulnerability, referred to as the susceptibility to adverse impacts caused by climate-driven hazards [3], remains a subject of considerable interest as policymakers work toward enhancing climate risk management [4]. The far-reaching consequences of climate change risks, which threaten economic and social advancement [5,6], have garnered significant attention across the globe, including in Africa.

The African continent, categorized as the most vulnerable to climate change [7], continues to experience disruptions, particularly in sectors susceptible to the adverse effects of climate change [8–10]. The need to address climate vulnerability remains an area of focus, given the crucial role these sectors play in the countries' socioeconomic landscapes. The agriculture sector, for example, significantly influences the macro- and micro-economies [11]. A considerable proportion of Africa's mixed economies notably rely on the rainfed agricultural sector for employment and livelihood, directly or indirectly.

In 2021, the agriculture sector employed 52% of the workforce, according to World Bank employment statistics [12].

Moreover, the sector's significant contribution to the gross domestic production, averaging nearly 20% across African countries, cannot be undermined [13]. The services sector, which is the highest contributor to the economic output of most African countries, is also sensitive to extreme climate-related events like drought and floods [14–16]. The impact of climate change across the key sectors has stimulated more discussion regarding proactive adaptation, notwithstanding the obstacles faced, particularly on confined financial, infrastructural, and technological resources [17].

Improving adaptation readiness toward tackling the complexities of climate change and strengthening resilience is crucial for Africa. Lagging in implementing proper coping measures will undeniably increase the number of Africans living in poverty by 2030 [18]. The Notre Dame Global Adaptation Index (ND-GAIN), an open-source index [19] adopted by scholars [20–22], defines readiness as the capacity to attract adaptation investment from various avenues. Its measurement is based on proxies that could encourage or discourage public and private sector investment.

A country's readiness is evaluated based on economic, governance, and social metrics. Economic readiness is assessed through the business environment since this is expected to attract or discourage investment in adaptation, particularly from the private sector. Governance readiness focuses more on the political risks and their possible impact on foreign capital flows. Social readiness proxies revolve around social attributes, including inequalities, education, access to knowledge, and innovation that could derail the community's ability to identify adaptation opportunities, invest, and yield returns. Adaptation readiness is pivotal in effectively habituating climate change's impacts [17,23]

In addition to readiness, actual progress in adaptation requires massive finance disbursement for related investments in Africa. The developed economies' commitment toward Africa's climate finance basket has seen more distributions toward mitigation than the adaptation course. This fact has been attributed to mitigation being considered a public good that directly benefits all nations, whereas adaptation indirectly benefits the fund contributors [24]. Disbursements on adaptation finance are also lagging compared to the commitments made [25]. The estimated deficit in financing based on the annual average is above 70% for 2020–2030 [26]. This sluggish adaptation financing trend attracts interest, given that climate adaptation financing initiatives have been laid out globally to support climate adaptation projects since the 1990s. The initiatives include the establishment of the Global Environment Facility in 1991, the Kyoto Protocol adaptation fund in 2001, and the Green Climate Fund in 2010. Generally, the formation of adaptation finance initiatives has mainly focused on vulnerable developing countries since adaptation finance has been acknowledged as having the potential to address climate vulnerability in these regions [27,28].

The influence of human development on climate adaptation and mitigation measures in different countries is significant [29]. Analyzing and understanding the disparities in countries' levels of development is crucial for effective policy design [30]. The Human Development Index (HDI) is a comprehensive metric systematically evaluating a country's development [31]. African countries exhibit a diverse range of HDI rankings and trends. Several African countries have achieved notable advancements in human development and exhibit relatively high HDI scores.

Nevertheless, a significant proportion of the HDI values in this region are relatively low compared to other areas. Specifically, more than 50% of the nations in this region have an average HDI below 0.55 (Figure 1), which falls within the low category according to the United Nations Development Programme (UNDP) classification ([32], p. 1). This results from countries with poverty, inequality, and limited access to quality education and healthcare. Countries with higher levels of human development are anticipated to possess the resources and capability to allocate and execute more ambitious adaptation readiness policies in contrast to countries with lower levels, owing to divergent priorities [33].

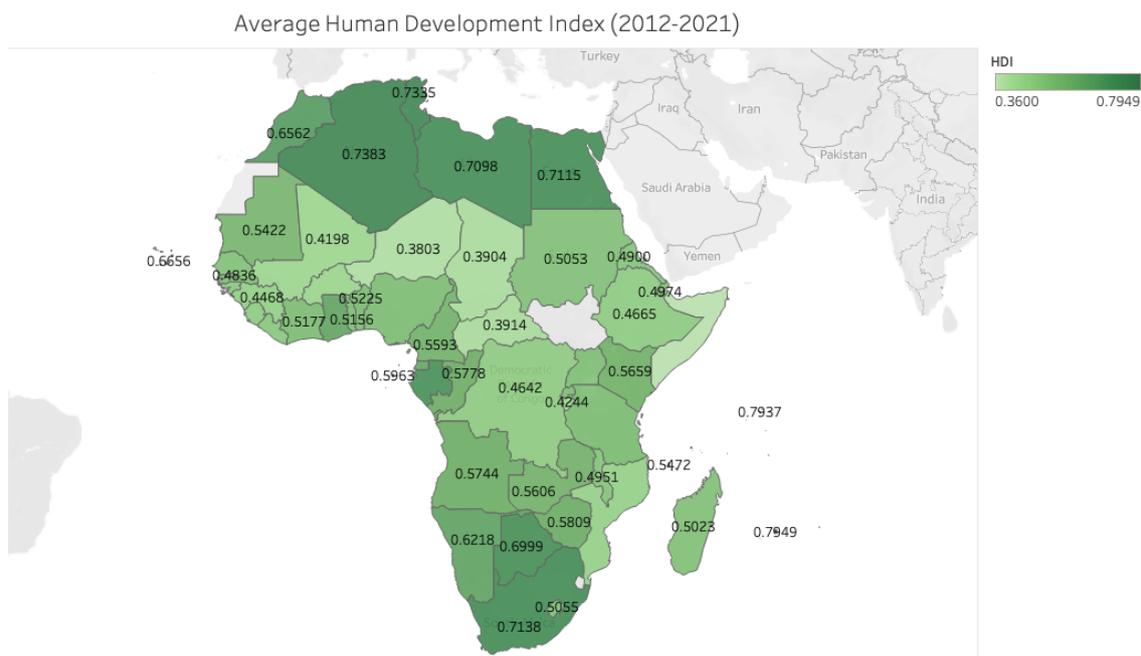


Figure 1. Average Human Development Index (HDI) of African countries for the period of 2012–2021. The Human Development Index is a United Nations country-ranking composite index comprising social and economic development indicators.

Given the interaction between adaptation financing, readiness, and vulnerability, we aimed to establish if the adaptation finance to Africa by bilateral, multilateral, and private philanthropic organizations has achieved the intended objective of reducing climate vulnerability while considering the various countries' readiness and HDI categories. The novelty of our research model is derived from the fact that we (i) evaluate the impact of traceable adaptation finance on Africa's climate vulnerability while taking into account the individual countries' readiness levels, (ii) employ the Prais–Winsten regression and panel-corrected standard error analysis (PCSE) to predict this impact, and (iii) analyze the impact across three African countries categories based on the level of development as measured by the Human Development Index (HDI). The rest of this paper is organized as follows: Section 2 discusses the relevant literature, Section 3 presents materials and methods, Section 4 presents the results and discussion of our findings, and we conclude the paper in Section 5.

2. Climate Vulnerability, Adaptation Readiness, and Adaptation Finance Literature

The climate vulnerability aspect has been examined through empirical research, resulting in interconnected themes defining the policy and scholarly investigations. The three main subjects of interest related to the topic are vulnerability assessment methodologies, factors influencing vulnerability, and their association with adaptation.

Climate vulnerability assessment entails modeling based on specific factors and risks to evaluate the levels at which climate impacts affect societies. The vulnerability assessment process of communities comprises the measurement of four components: climate change exposure, sensitivity to exposure, implications on points of sensitivity, and adaptive capabilities based on steps taken to address the impacts [34]. Moreover, it is imperative to acknowledge the importance of complex adaptive systems theory to assess vulnerability effectively. Considerations of community modulation, feedback mechanisms, redundancy, and susceptibility to change, extending from the theory, are essential incorporations in vulnerability models [35].

The approach adopted to assess vulnerability differs depending on the scale of analysis, emphasizing single risks impacting a specific industry or society or those affecting multiple sectors [36,37]. Integrating more indicators can strengthen the vulnerability indexes and

provide unique insights to guide the strategies adopted to reduce the vulnerability [38]. The efficacy of climate vulnerability assessment is crucial in informing and implementing suitable local strategies ([39], p. 12). Our study builds upon vulnerability measurement papers by going beyond assessment and determining the role of adaptability on the vulnerability trend using a preexisting ND-GAIN vulnerability measure.

The second broad category of researchers explores the factors influencing climate vulnerability, including socioeconomic and governance factors, considered components of adaptation readiness in ND-GAIN metrics [19,40]. A notable interaction between these factors and vulnerability is evident, though with mixed findings, as reported by [22,41–44]. One specific focus is the association between socioeconomic factors, including wealth and education levels, and climate vulnerability. Examining the correlation between wealth and vulnerability has established a clear negative relationship between low-income populations and those facing greater vulnerability risk. While assessing the dynamics of vulnerability to climate-related hazards, [45] reported a decreasing trend in global socioeconomic vulnerability, suggesting that societies worldwide have become less vulnerable to climate-related hazards over time. Moreover, the study revealed a strong negative relationship between population income levels and climate vulnerability.

Relatedly, wealth increases the sense of control, leading individuals to be climate change conscious and take climate action [46]. From the perspective of educational levels, there are two possible scenarios, especially for future generations [47]. Educational factors could improve the Human Development Index (HDI), a primary indicator of climate resilience, thus reducing vulnerability. However, population education attainments could increase energy consumption resulting from labor productivity and slow progress in reducing environmental pressures. Empirical evidence provided for the association between a country's economic level and climate vulnerability has indicated mixed findings. The contributors to a country's economic growth determine whether climate vulnerability reduces or accelerates [48]. Furthermore, there is a correlation between economic development and climate vulnerability [49]. The findings above underscore the significance of giving due consideration to socioeconomic factors in a bid to mitigate the impacts of climate change effectively.

The discussions on governance factors encompass political factors and institutional and societal frameworks that determine climate finance resource allocation and regulation. The efficacy of national and local governments, non-government institutions, and relevant international institutions in climate governance has been assessed [6,50–53]. While examining adaptation readiness from a climate governance perspective, [23] examined the effectiveness of governance across various countries and found that it impacts climate vulnerability. Participation, collaboration, and knowledge sharing among the various regulating bodies are essential to enhancing climate governance [54,55]. Regarding the influence of political factors, [56] acknowledges the possible self-interest of powerful political-economic institutions, politicians, and other interested actors in the vulnerability measurement and policymaking role. This creates challenges, including conflicting ideologies on the definition and indicators of climate vulnerability and implementing transformative and practical approaches that benefit the most affected.

Empirical studies on the adaptation readiness index comprising a combination of economic, social, and governance factors have indicated that countries with a high adaptation readiness, majorly the developed economies, are less vulnerable compared to their counterparts [17,57]. In essence, most studies on all the above factors focus on regions considered most vulnerable. This stems from the generally accepted ideology that climate vulnerability distribution is unequal [58,59], with developed economies being less vulnerable than developing economies [60]. The importance of reviewing the climate vulnerability influencing factors for our paper was the appreciation that they could contribute to aggravating or reducing climate vulnerability in addition to the distribution of adaptation finance [61,62]. This was a critical aspect to consider in our discussion of findings.

The climate adaptation topic has also been emphasized, with empirical evaluations focusing mainly on countries' adaptive capacities, adaptive interventions, and adaptation finance distributions. While developed countries have greater climate adaptation capacities due to their adaptation readiness, developing countries struggle to counter climate-related risks due to adaptation constraints [23,63]. The adaptive capacities of various communities have been assessed using different frameworks, with the strength varying across sectors and contexts [64–66]. For example, from the perspective of households, evidence suggests disparities in adaptive capacity scores across different age groups, genders, education levels, and locations. The technological, financial, social, infrastructural, governance, and human capital capabilities further determine the adaptive capacities [67–70].

Adaptation interventions to facilitate effective responses to climate change effects have been implemented from different levels, including national and local governments, international communities, and community-based initiatives. The intervention cruciality is highest in the most vulnerable regions [71,72]. Deep engagement with the communities in vulnerable regions to understand the different local contexts could lead to more adaptation success [71]. However, a lack of proper adaptation interventions may reinforce, redistribute, or create new vulnerabilities, thus hindering making substantial progress. From a related angle, [73] note that interventions may create losers and winners, just like the climate-related crisis. The main losers could be vulnerable communities if they are misrepresented, stereotyped, or excluded from adaptation discussions.

One essential adaptation intervention effort is the distribution of adaptation financing to fund essential adaptation projects. International funds are crucial in supporting adaptation for low-income states, given that adaptation finance is a significant constraint [74,75]. So far, examinations of adaptation finance have focused on the allocation levels across various sectors and countries, as well as the associated opportunities and challenges. The discrepancy between countries that need adaptation funding and those that are allocated exists [76,77]. The extent to which adaptation finance has reached vulnerable countries through the Green Climate Fund is low, particularly for the least developed countries that are stricken by conflict and have sluggish government institutions [78,79]. To this end, climate justice in adaptation financing has been explored, with inequities attributed to donors' use of aid to foster their political and economic interest in recipient countries [6,80].

Although scholars have explored the link between vulnerability and adaptation finance, focusing on whether vulnerability determines the adaptation finance received, [21, 81] the findings are still controversial. Moreover, while it is recognized that investing in adaptation measures is crucial for reducing vulnerability and building resilience to the adverse effects of climate change, scholarly emphasis on trends in achieving this goal is minimal. Accordingly, we expect climate vulnerability to decrease in countries with higher adaptation finance over time and a higher adaptation readiness index. We therefore formulate the following hypothesis:

Alternative hypotheses:

H1: *In the case of African economies, climate adaptation finance positively impacts the reduction of climate vulnerability when readiness factors are considered.*

Further, given the different levels of development across African countries, as measured by the HDI, we expect the impact of adaptation finance on vulnerability to be different across the low, moderate, and high HDI classifications. We hence formulate the second alternative hypothesis:

H2: *There is a significant difference in the impact of adaptation finance and climate readiness on climate vulnerability across Africa based on the Human Development Index (HDI) categories.*

In essence, testing the hypothesis and answering the questions could contribute to a deeper understanding of climate adaptation finance, readiness, and vulnerability dynamics and enhance evidence-based decision-making in policy formulation. This can, in turn,

promote the development of more effective policies and empower policymakers to fine-tune policy interventions relating to climate adaptation.

3. Materials and Methods

3.1. Scope

The first hypothesis, regarding whether adaptation finance reduces climate vulnerability in Africa, was evaluated using panel data analysis. We used panel data since it has several advantages, including controlling for cross-section heterogeneity and providing a greater capacity to find and quantify effects that are not discernible just through cross-sectional or time-series data [82]. We analyzed balanced panel data comprising 52 of 54 African countries over ten years (2012–2021) using a combination of R version 4.3.2, Stata/SE 17, and Microsoft Excel version 16.78.3. South Sudan and Eswatini were excluded from the analysis due to missing data cases.

To test the second hypothesis, we stratified African economies into three classifications based on their average HDI as reported by the UNDP data repository over ten years. According to the data, no African country has an HDI level that is significantly higher than 0.8. Further, less than five countries have an average high HDI above 0.7. Since most countries fall within the medium and low UNDP HDI classifications, we categorized the countries into three classifications [83]. The first category included countries with an average HDI of 0.6 or higher, indicating a relatively high level of human development. The second category encompassed countries with an average HDI ranging between 0.5 and 0.6, representing moderate human development. Lastly, the third category consisted of countries with an average HDI below 0.5, suggesting a lower level of human development.

The stratification allowed for a comprehensive analysis of the impact across varying levels of countries' development. We selected the ten years following the establishment of the Green Climate Fund, including 2015, the year that saw the ratification of the Paris Agreement. Focusing on this period, we aimed to capture the recent developments and advancements in climate finance adaptation and vulnerability.

3.2. Data

The data on climate adaptation finance originated from the Organization for Economic Cooperation and Development (OECD). OECD monitors climate finance using OECD DAC Rio Markers for Climate. This encompasses bilateral public climate finance from institutions in developed countries, multilateral public climate finance, climate-related officially supported export credits, and bilateral and multilateral private finance attributed to developed countries [84].

The climate vulnerability and adaptation readiness data were sourced from the University of Notre Dame Global Adaptation Index (ND-GAIN). This index serves as a comprehensive measure of countries' readiness and vulnerability to the impacts of climate change. It assesses various factors such as exposure to climate hazards, sensitivity to climate change, and adaptive capacity. The ND-GAIN index is widely recognized and used by researchers, policymakers, and organizations worldwide to understand climate vulnerabilities better and support effective adaptation strategies. Moreover, the HDI and greenhouse gas emissions (GHG) data, included as a control variable, were obtained from the World Bank Data Bank and UNDP databases [85]

Data Limitation

The challenges associated with establishing adaptation financing components and acquiring accurate data to differentiate commitments from disbursements hindered our ability to estimate adaptation finance requirements precisely. Nevertheless, the OECD has actively monitored climate development finance since 2000 and offers comprehensive data explorer tools and methodological documents. The distinction between adaptation financing and mitigation financing was of particular interest since our study focuses specifically on climate adaptation.

4. Findings and Interpretation

This section presents the empirical findings derived from the study’s data analysis. The results are then systematically discussed, providing insightful interpretations and implications.

4.1. Descriptive Statistic Analysis

The descriptive statistics below provide a comprehensive overview of the relevant data. The statistics play a crucial role in understanding the current state and trends in vulnerability to climate-related risks, adaptation finance, the adaptation readiness of different countries, and the classification based on levels of development as measured by HDI in Africa.

4.1.1. Climate Change Vulnerability

Climate vulnerability, as assessed by ND-GAIN, monitors a country’s exposure, sensitivity, and mechanisms to adapt to the negative impact of climate change. In the visualization presented in Figure 2, Somalia, Chad, Guinea Bissau, and Niger stand out as the most climate-vulnerable countries. At the same time, Algeria, Tunisia, Morocco, and South Africa are identified as among the least climate vulnerable. On average, the vulnerability across the entire continent is 0.513. Further analysis revealed that highly developed countries based on HDI exhibit an average vulnerability of 0.427, moderately developed nations average 0.524, and the least developed countries demonstrate an average of 0.574. This indicated that vulnerability averages are not significantly different across the development classifications, especially for the moderate and less developed nations.

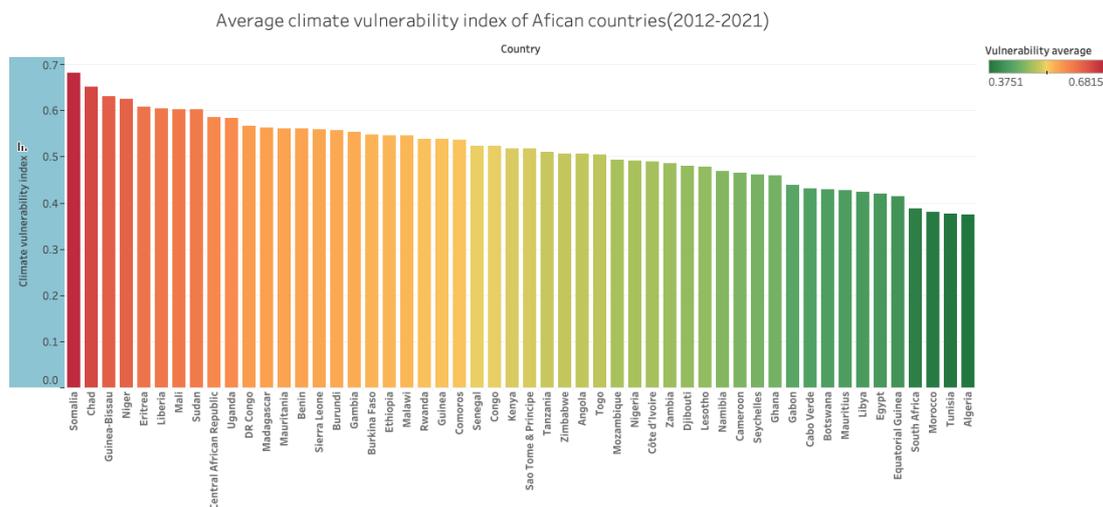


Figure 2. African countries’ climate vulnerability. The climate vulnerability averages for the 2012–2021 period are sourced from the University of Notre Dame Global Adaptation Index (ND-GAIN).

4.1.2. Climate Adaptation Development Finance

Climate Adaptation Development Finance reported by OECD comprises bilateral public climate funding from institutions in developed nations, multilateral public climate finance, climate-related publicly supported export credits, and bilateral and multilateral private financing attributed to developed countries.

To understand the level of climate adaptation finance across African countries, the study presents a map in Figure 3. The data are based on a scale of 28,018 to 10,035,018 USD thousand, with the blue color intensifying for countries with higher amounts of adaptation finance. Kenya emerged as the top African country in terms of total commitments in adaptation-related development financing recorded by the OECD within the period. Additionally, the Eastern Africa region has received more commitments than other regions, with Ethiopia, Somalia, Uganda, and Tanzania among the top ten countries in this category.

The West African countries have also received significant climate adaptation commitments. A comparison of the top ten most vulnerable countries and those that have received the highest commitments indicates that only two countries, Somalia and Niger, fall into both categories. This suggests there may be a disconnect between the level of vulnerability and the amount of adaptation support provided, highlighting a potential area for further analysis and targeted intervention.

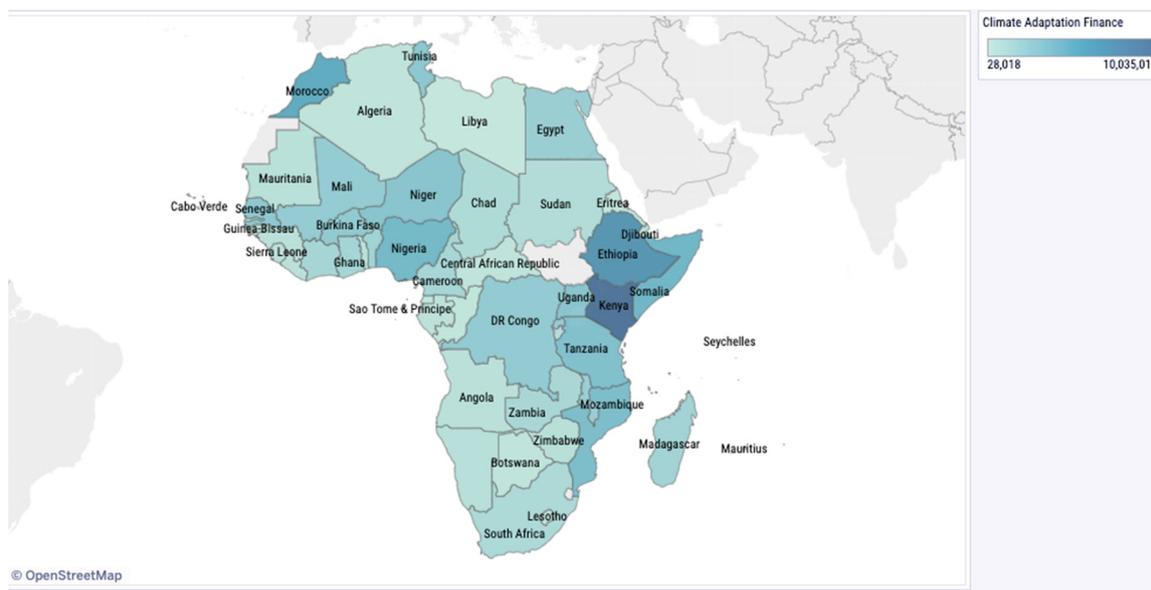


Figure 3. Africa Climate Adaptation Development Finance. The data are the totals in USD thousands from the period of 2012–2021 and are based on the OECD Climate-related Development Finance datasets.

On the other hand, the countries that have received minimum commitments include Libya, Seychelles, Equatorial Guinea, Sao Tome and Principe, and Guinea-Bissau. Of this, Guinea-Bissau is among the top ten most vulnerable countries. The other four countries are among the top 30% of countries in terms of HDI-measured development. There is a significant discrepancy in the distribution of commitment allocation, as the bottom 52% of countries' allocation is only 12% of the total share.

The global adaptation finance gap is increasing despite the increase in total climate finance [86,87]. Globally, the regions that are considered the most climate-vulnerable and thus might compete for climate adaptation finance include Africa, South Asia, the Pacific region, and Latin America [88,89]. A comparison of the adaptation finance across the regions during the period of 2021–2022 indicates that Asia and the Pacific region received 45% of global adaptation financing as compared to 20% in Africa and 10% in Latin America [90]. This means that there is an opportunity for enhancement to optimize the allocation of limited adaptation finance across vulnerable regions.

4.1.3. Climate Adaptation Overall Readiness

ND-GAIN measure of the overall climate adaptation readiness focuses on a nation's capacity to leverage investments and convert them to adaptation actions. The overall readiness comprises economic, governance, and social readiness.

The readiness of Mauritius for climate adaptation surpasses that of other African economies, as illustrated in Figure 4. The islands of Seychelles and Cabo Verde are also highly climate adaptation-ready from an overall perspective, along with Tunisia, Botswana, Morocco, and Rwanda. The least adaptation-ready economies include the Central African Republic, Chad, DR Congo, Zimbabwe, and Eritrea. Central African Republic and Chad's economic readiness was very low compared to the continent's average, leading to a low

overall readiness. Zimbabwe and Eritrea lagged on social readiness, contributing to their low overall readiness. This indicated a low community’s ability to tap into climate adaptation opportunities.

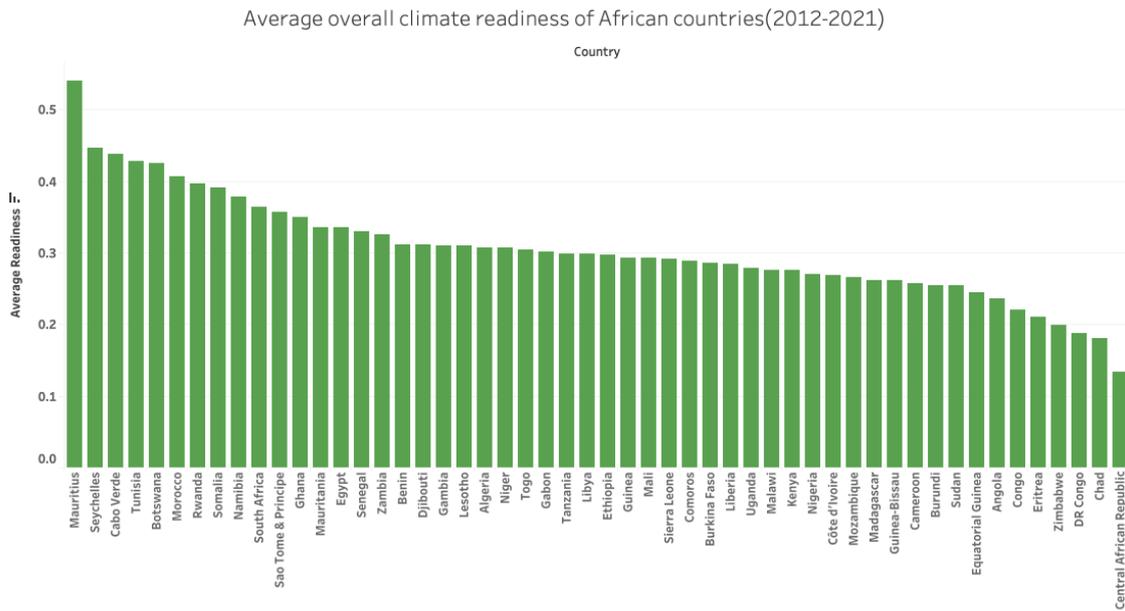


Figure 4. Africa’s overall climate adaptation readiness by country. The overall climate readiness index is an average of the period of 2012–2022 and is a factor of economic, social, and governance readiness as reported by ND-GAIN.

4.1.4. Time Trend of Variables Analysis

The visuals presented in this section illustrate African countries’ average governance, social, and economic readiness from 2012 to 2021. The ND-GAIN governance readiness, as illustrated in Figure 5, focuses on the institutional capabilities that enhance adaptation investment applications.

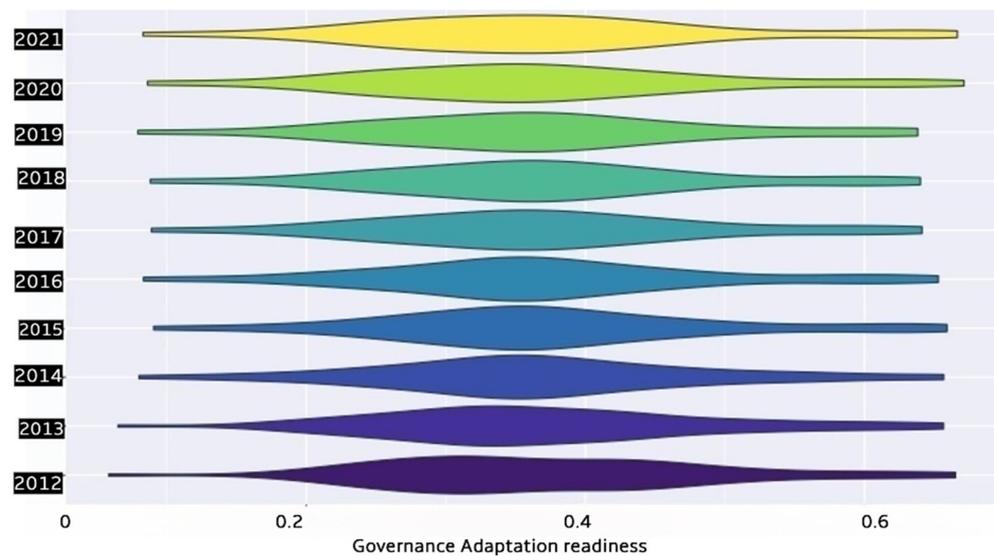


Figure 5. Average governance adaptation readiness of African countries for the period of 2012–2021.

The governance climate adaptation readiness metric has exhibited relative consistency over time. Throughout the years, certain countries constantly demonstrated high gover-

nance readiness, with index values exceeding 0.6, while others remained below 0.1, leading to an average index of 0.37

The social readiness index featured in Figure 6 incorporates indicators of the social and technological capabilities of the society that influence adaptation investment mobility and actions.

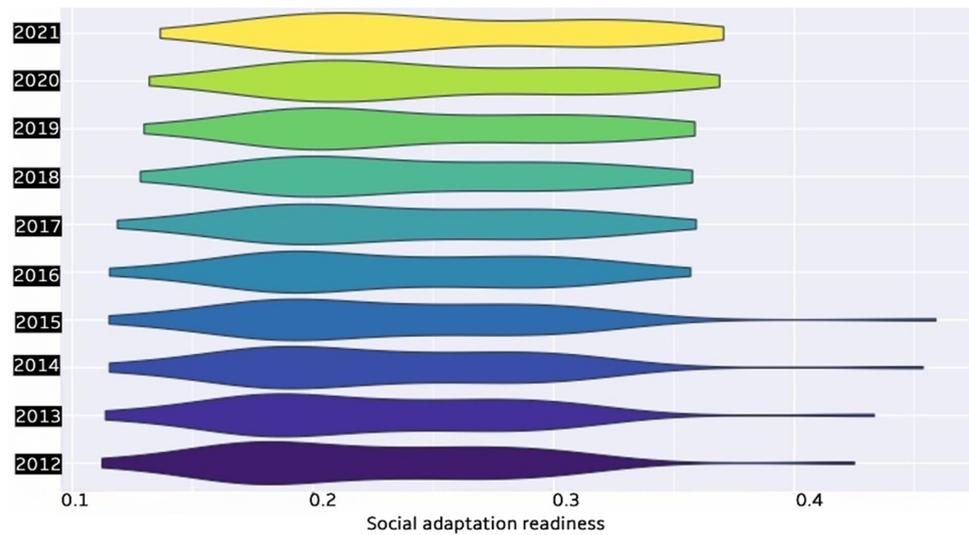


Figure 6. Average social adaptation readiness of African countries for the period of 2012–2021.

The social climate adaptation readiness, presents a skewed distribution, including notable positive outliers, particularly in 2012–2015. However, during the period from 2016 to 2021, the majority of indices are concentrated between 0.1 and 0.35 across countries. In the same period, some countries previously considered more socially prepared experienced a decline in readiness, resulting in a decreased overall mean index of 0.237, lower than the governance and economic readiness. Moreover, the countries with a lower index below 0.2 are still notable, but the trend has reduced over the years.

The economic readiness index presented in Figure 7 assesses a country’s business environment that could influence its adaptation investments. The economic readiness trend shows some similarity with the social readiness in the period from 2012 to 2015. However, in 2016–2021, the countries’ indices are more centered around the mean of 0.313, with some countries experiencing a decline from the previous years.

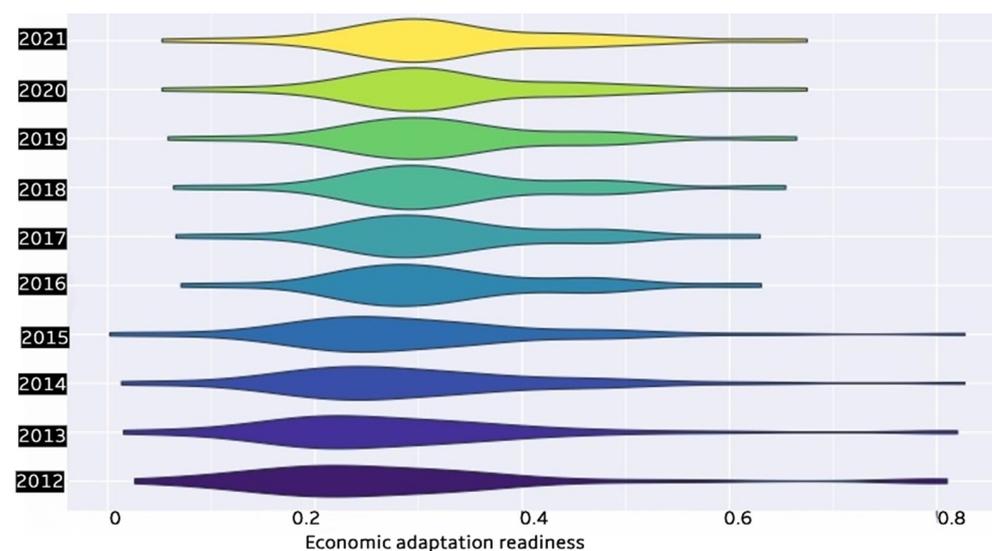


Figure 7. Average economic adaptation readiness of African countries for the period of 2012–2021.

The climate adaptation finance for most countries, depicted in Figure 8, has been very low averaging less than 500,000 USD thousand every year. However, the weight on the lower side has reduced over the years, with more countries receiving more adaptation funding recently.

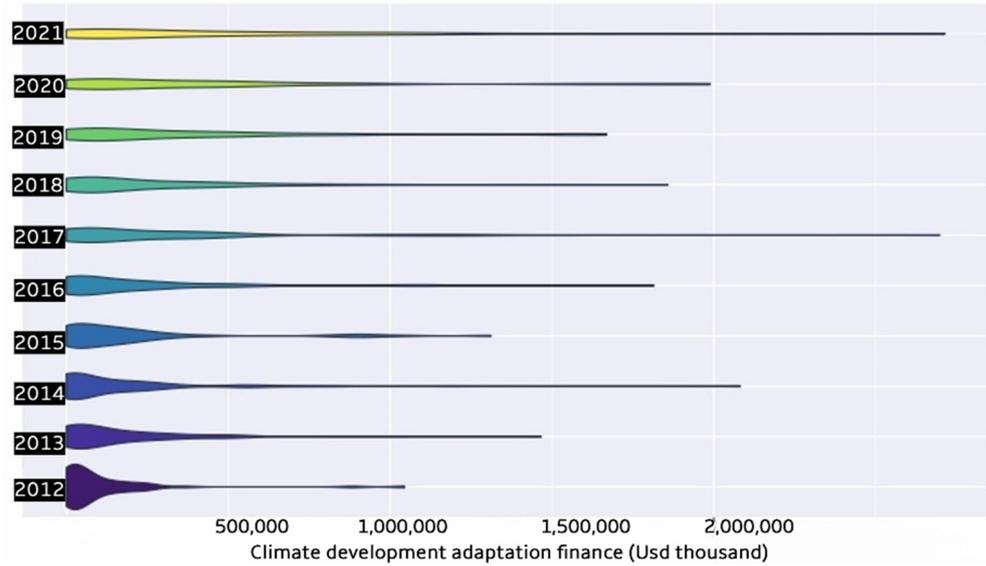


Figure 8. Climate adaptation finance of African countries for the period of 2012–2021.

Finally, Figure 9 shows the trend of overall climate readiness and vulnerability. The vulnerability has reduced as readiness has improved over the years. The increasing trend in adaptation readiness is notable as compared to the reduction in climate vulnerability.

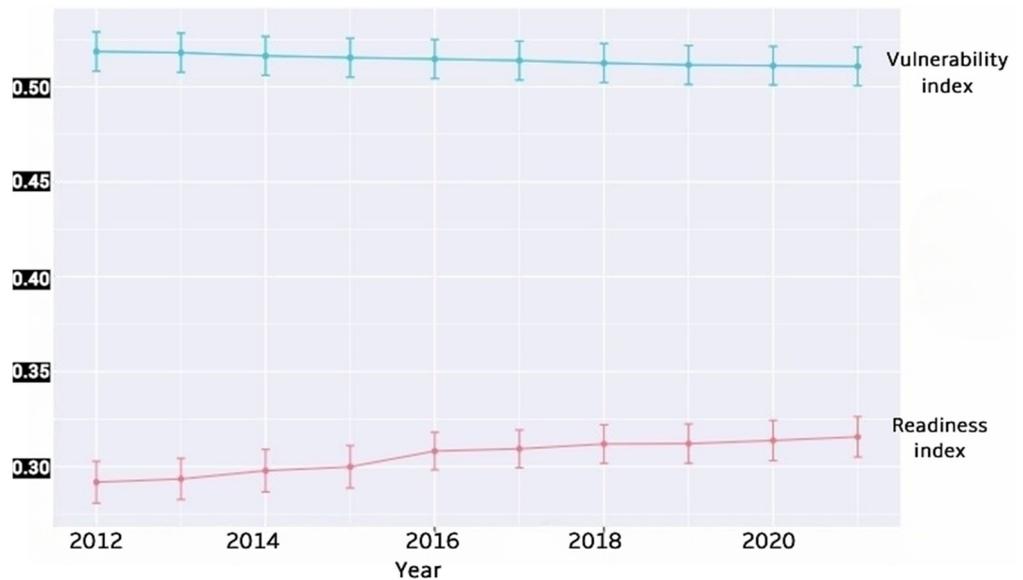


Figure 9. Overall African adaptation readiness vs. climate vulnerability trend.

4.2. Diagnostic Test

In this section, we discuss the results of five diagnostic tests. These tests played a crucial role in detecting potential issues in our panel data and, hence, selecting a robust analysis model in line with the problems identified.

4.2.1. Normality Test

Normal distribution of residuals is required for the test to be reliable while running a regression analysis [91]. The normality test on residuals was conducted at a 5% significance level. We utilized the sktest skewness and kurtosis normality test to test the null hypothesis that variable residuals were normally distributed against the alternative hypothesis that variable residuals were not normally distributed.

Table 1 indicates that the probability of skewness of the residuals is less than 0.05, meaning that the residuals are not normally distributed. Nonetheless, the probability of kurtosis implies that the residuals approach an asymptotic normal distribution with a 95% confidence level. Additionally, the joint test probability of Chi-square is less than 0.05, which provides sufficient evidence to conclude that the residuals are not normally distributed within a 5% level of significance. To address the non-normality issue, we use natural logs of the variables climate adaptation finance and GHG emissions that exhibited non-normality.

Table 1. Normality test output.

Skewness and Kurtosis Test for Normality Joint Test					
Variable	Obs	Pr (Skewness)	Pr (Kurtosis)	Adj chi2 (2)	Prob > chi2
resid	520	0.0000	0.6644	25.42	0.0000

4.2.2. Pesaran CD Cross-Sectional Dependence Test

Cross-sectional dependence of error terms could lead to biased test results and is problematic. Ignoring sufficient cross-sectional dependency in panel analysis could greatly diminish estimate efficiency because the panel estimator may not differ significantly from the single equation ordinary least squares estimator [92].

Using the Pesaran CD test, we ran the `pcdtest` R command to examine the possibility of cross-sectional dependence in the residuals across countries. This test was appropriate for our data set, given that the number of cross-sectional units was sizeable compared to the small number of periods. The CD test is advantageous when many cross-sectional units are recorded over periods, unlike the conventional Breusch–Pagan LM test of independence [93,94]. The null hypothesis assumes no correlation between cross-section residuals at a 5% significance level, while the alternative hypothesis assumes a correlation between cross-section residuals at a 5% significance level.

As shown in Table 2, Pesaran’s test probability of 0.0161 is less than 0.05; hence, we fail to accept the null hypothesis and conclude that the cross-section residuals exhibit contemporaneous correlation.

Table 2. Cross-sectional dependence test output.

Z Statistic	p-Value
2.4075	0.0161

4.2.3. Heteroscedasticity Test

Heteroscedasticity occurs when the errors do not exhibit a constant variance, meaning that $\text{var}(ut) = \sigma^2 < \infty$ [91]. Testing and tackling the heteroscedasticity of the residuals is vital since its presence may result in inadequate least squares estimates and inconsistent covariance matrix estimates. We used the Aod R package module by [95] to compute the Wald statistic for groupwise heteroskedasticity in the residuals of a fixed effect regression model. The test null hypothesis (H0) was that the residuals are derived from homoscedastic distributions, against an alternative hypothesis that the residuals are not derived from homoscedastic distributions, meaning they are expected to have unequal variance.

The results in Table 3 indicate the chi2 *p*-value of the test was 0.000, less than $\alpha = 0.05$; hence, we rejected the null hypothesis and concluded that heteroscedasticity was present in the panel regression model residuals.

Table 3. Heteroscedasticity test output.

Chi2	DF	<i>p</i> -Value
68.6	5	0.0000

4.2.4. Serial Correlation

Serial correlation is the correlation between matched data sets that are not obtained at a single point in time but rather observed progressively through time. Autocorrelation is a type of serial correlation where the second data set matches the first set, albeit with a temporal lag [96]. Testing and solving for serial correlation, also referred to as autocorrelation in panel data, are essential to avoid a false high R squared and erroneous more minor standard errors of the coefficients [97–99]. We utilized the pbgttest command of the Lm R package to run the Breusch–Godfrey–Wooldridge test on the null hypothesis of no serial correlation in idiosyncratic errors as proposed by [100]. The test is appropriate since it permits heteroscedasticity, which was present in our data.

The significant *p*-value of 0.000 in Table 4 below indicated the presence of serial correlation in the panels. Moreover, Figure 10 below further demonstrates a correlation between the temporal mean of the dependent variable, climate vulnerability.

Table 4. Serial correlation output.

Chi2	DF	<i>p</i> -Value
118.93	1	0.0000

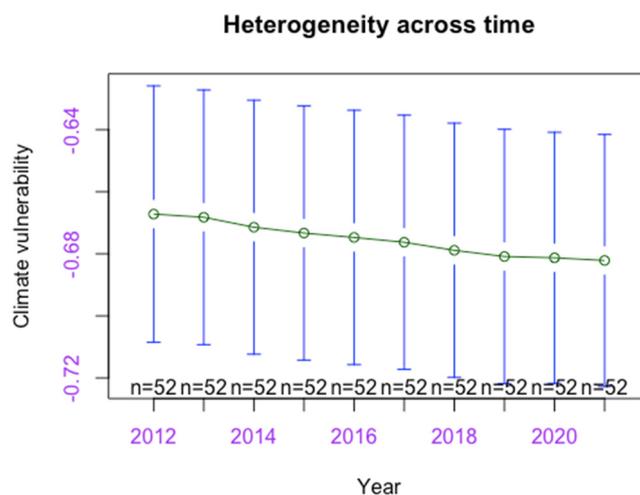


Figure 10. Heterogeneity of climate vulnerability across time.

4.2.5. Unit Root and Cointegration Tests

The unit root test is conducted to determine whether the panels are stationary. Stationarity is crucial to ensure no spurious relationships from the analysis [101,102]. We employed the Phillips–Peron test of the Tseries R package to examine the following hypothesis:

Null hypothesis (H0): *All panels contain a unit root.*

Alternative hypothesis (HA): *None of the panels have a unit root.*

The test yields more reliable results when dealing with disturbance processes that may exhibit heteroscedasticity and autocorrelation in our dataset [103,104]. Most panel unit root tests, including the Breitung and Das test and Levin–Lin–Chu unit root test, assume homoskedasticity [105] and hence were not applicable.

Table 5 shows that the p -values are not significant at 5%. We, therefore, fail to reject the null hypothesis and conclude that the panels contain a unit root, implying they are not stationary.

Table 5. Phillips–Perron unit root test output per variable.

Variable	Dickey–Fuller	p -Value
Climate vulnerability	−6.016	0.01
Climate Adaptation Finance	−7.2769	0.01
Economic readiness	−6.3659	0.01
Governance readiness	−5.4711	0.01
Social readiness	−5.3766	0.01
GHG emissions	−5.8296	0.01

Consequently, we conducted the Kao cointegration test to ascertain the existence of a long-run association between the non-stationary variables. Cointegration is crucial for avoiding spurious outcomes in variables that lack stationarity [106]. The test results, presented in Table 6, support the alternative hypothesis that panels are cointegrated. Therefore, we conclude that there is a long-term relationship between the variables and hence proceeded with regression analysis.

Table 6. Kao-cointegration test results.

	Static	p -Value
Modified Dickey–Fuller t	−5.0399	0.0000
Dickey–Fuller t	−11.9640	0.0000
Augmented Dickey–Fuller t	−6.2431	0.0000
Unadjusted modified Dickey–Fuller t	−11.8750	0.0000
Unadjusted Dickey–Fuller t	−14.7455	0.0000

From the diagnostic tests conducted, the standard error estimates exhibit the problems of non-normal distribution, cross-sectional dependence, heteroscedasticity, and autocorrelation. To solve the non-normality issue, we transformed the data into logs. Additionally, we ran and interpreted the panel-corrected standard error (PCSE) estimation models. This error-corrected model introduced by [107] solves for standard error estimates that are not robust due to the disturbances above in panel models. The advantages of using the model include its accountability for serial correlation, heteroskedasticity, and contemporaneous correlation. The model was also appropriate given that the data comprised many cross-sections (n) compared to the periods (t), a pre-requisite of using the model. The model employment has limitations in cases where the cross-sections are fewer than the periods [107,108].

4.3. PCSE Empirical Outputs

This study estimated four panel-corrected standard error (PCSE) econometric models to answer the research hypothesis. The results of Model 1 relating to hypothesis 1 are presented in Section 4.3.1 below, while those of Model 2–4 testing hypothesis 2 are presented in Section 4.3.2.

4.3.1. Hypothesis 1 Estimation Results

We applied the first PCSE regression model (Equation (1) below) to test the null hypothesis that climate adaptation finance does not positively impact the reduction of climate

vulnerability in Africa when readiness factors are taken into account. We examined the effect of adaptation finance; economic, governance, and social readiness; GHG emissions; and vulnerability, the value of which was lagging in terms of climate vulnerability. The output is presented in Table 7 below.

Table 7. Overall Prais–Winsten regression output with panel-corrected standard error (PCSE): Dependent variable: climate vulnerability.

Variable	Coefficient	Std. Err.	Z	p > Z	[95% Conf. Interval]	
CAFlog	−0.0207	0.0004	−2.07	0.039	−0.0014	0.0003
Economic readiness	−0.1282	0.0170	−7.52	0.000	−0.1616	−0.0948
Governance readiness	−0.1878	0.0285	−6.59	0.000	−0.2437	−0.1319
Social readiness	0.1198	0.0181	6.62	0.000	0.0843	0.1552
GHGlog	0.0044	0.0008	5.25	0.000	0.0028	0.0060
LagV	0.3883	0.0697	4.86	0.000	0.2022	0.4755
Constant	0.3560	0.0363	9.82	0.000	0.2849	0.4271
rhos=	1	−0.2923	0.4447	−0.3651	1	−0.0269
Wald chi2(6)=	2810.32					
Prob > chi2=	0.0000					

CAF log is the natural log of the climate adaptation finance. GHG log is the natural log of greenhouse gas emissions. Lag V is the lagged value of the vulnerability index.

Equation (1): PCSE estimation output

$$\begin{aligned}
 Xtpcse \text{ Climate vulnerability}_{it} &= \text{Climate adaptation finance}_{it} + \text{Economic readiness}_{it} + \text{Governance readiness}_{it} \\
 &+ \text{social readiness}_{it} + \text{GHG}_{it} + \text{Lag vulnerability}_{it} + \epsilon_{it}
 \end{aligned}
 \tag{1}$$

At a 95% level of confidence, all the variables were statistically significant. Climate adaptation finance, economic readiness, and governance readiness had a statistically negative relationship with the vulnerability index, while social readiness, GHG emissions, and the lagged value of the vulnerability index had a positive relationship. These results imply that climate adaptation finance has a positive impact on reducing vulnerability, given the negative relationship. However, based on the beta coefficient, the decrease is minimal since a 1% increase in climate adaptation finance led to an average reduction of 0.02% in climate vulnerability. The slight decline may be attributed to most nations’ insufficient aggregate adaptation funds. According to the data depicted in the adaptation finance map, 52% of the nations have received total commitments of less than 1,000,000 USD thousands. The disparity in financing between the highest- and lowest-ranking countries is also substantial.

Concerning adaptation readiness, countries’ economic and governance readiness reduces climate vulnerability, with governance readiness exhibiting a higher impact. This inferred that a good adaptation investment environment that defines the economic readiness and governance factors contributing to political stability and stability is important in minimizing climate vulnerability. Unexpectedly, contrary to prior research [17], the social readiness variable exhibited a positive relationship with vulnerability, implying that as the overall African social structures of communities become more solid, the climate vulnerability is likely to increase. The Notre Dame social readiness indicators include social inequality, innovation, information communication technology (ICT), and education.

Prior research suggests that the impact of ICT on the environment could be two-way, depending on the ICT quality and interventions [109,110]. This could suggest a possible explanation for this relationship, considering that African nations have had a higher rate of ICT technology adoption over the past decade compared to previous years. Furthermore, as argued by [111] innovation can potentially increase climate challenges, depending on the nature of the innovation, its accessibility, and its environmental implications. A significant impact of green technological innovations on carbon productivity in developing economies is difficult to find [112]. Moreover, education enhancement is expected to result in improved HDI but could also increase emissions resulting from economic growth that negatively

impact the environment in the short run [47]. The results further imply that prioritizing the reduction of GHG gas emissions and addressing climate vulnerability from previous years are essential steps toward achieving overall climate vulnerability reduction.

In summary, we reject the null hypothesis 1 and conclude that at a 95% confidence level, climate adaptation finance positively influences the reduction of climate vulnerability in Africa. Nevertheless, it is important to take note of the minimal nature of the decrease and the unique characteristics of individual countries in the African continent.

4.3.2. Hypothesis 2 Empirical Output

Given that African countries vary in development, we tested the null hypothesis 2 that there is no significant difference in the impact of adaptation finance and climate readiness on climate vulnerability across African economies based on HDI 3 classifications. The results of the three empirical models are presented in Tables 8–10 below based on low HDI, average HDI, and high HDI ranking.

Table 8. Low-HDI countries' PCSE empirical output. Dependent variable: climate vulnerability.

Variable	Coefficient	Std. Err.	Z	$p > Z$	[95% Conf.	Interval]
CAFlog	−0.0106	0.0005	−1.24	0.214	−0.0015	0.0003
Economic readiness	−0.0735	0.0125	−5.87	0.000	−0.0980	−0.0489
Governance readiness	−0.2219	0.0161	−13.74	0.000	−0.2536	−0.1903
Social readiness	0.0561	0.0435	1.29	0.198	−0.0293	0.1415
GHGlog	0.0174	0.0016	11.23	0.000	0.01438	0.0205
Lag V	0.3033	0.0545	5.57	0.000	0.1966	0.4101
cons	0.1805	0.0153	11.82	0.000	0.1506	0.2105
rhos=	1	1	1	−0.3687	1	−1
Wald chi2(6)=	9692.34					
Prob > chi2=	0.0000					

Table 9. Average-HDI countries' PCSE empirical output. Dependent variable: climate vulnerability.

V	Coefficient	Std. Err.	Z	$p > Z$	[95% Conf.	Interval]
CAFlog	−0.0322	0.0005	−4.48	0.000	−0.0031	−0.0012
Economic readiness	0.0328	0.0119	2.75	0.006	0.0094	0.0561
Governance readiness	−0.0856	0.0222	−3.86	0.000	−0.1291	−0.0421
Social readiness	0.0544	0.0297	1.83	0.067	−0.0039	0.1127
GHGlog	0.0038	0.0007	−5.57	0.000	−0.0052	−0.0025
lagV	0.1556	0.0570	2.73	0.006	0.0438	0.2674
cons	0.5394	0.0371	14.53	0.000	0.4667	0.6122
rhos=	0.4035	0.0303	1	0.0454	0.5301	1
Wald chi2(6)=	73.82					
Prob > chi2=	0.0000					

Table 10. High-HDI countries PCSE empirical output. Dependent variable: climate vulnerability.

Variable	Coefficient	Std. Err.	Z	$p > Z$	[95% Conf.	Interval]
CAFlog	−0.0107	0.0003	−2.43	0.015	−0.0013	−0.0001
Economic readiness	−0.0960	0.0188	−5.09	0.000	−0.1329	−0.0590
Governance readiness	−0.0704	0.01732	4.07	0.000	0.0365	0.1044
Social readiness	−0.0180	0.01769	−1.02	0.039	−0.0527	0.0167
GHGlog	0.0044	0.0020	2.18	0.029	0.0004	0.0084
lagV	0.4693	0.0800	5.87	0.000	0.3126	0.6261
cons	0.1678	0.0494	3.40	0.001	0.0711	0.2646
rhos	0.4749	1	1	0.3313	0.7167	0.6119
Wald chi2(6)=	705.5					
Prob > chi2=	0.0000					

Results in Table 8 were based on African countries whose average HDI index was below 0.5, which signifies a lower level of human development. These countries include

Somalia, Niger, Chad, Central African Republic, and Mali. All the variables except social readiness were statistically significant at a 5% level of significance. A 1% increase in climate adaptation finance is expected to reduce vulnerability by 0.01% in low-HDI African countries. From the readiness perspective, a unit increase in economic preparedness might lower climate vulnerability by 0.07, whereas a unit increase in governance readiness could reduce climate vulnerability by 0.22. Similar to the overall continent results, the findings also suggest that it is crucial to tackle climate vulnerability from past years and prioritize the decrease of greenhouse gas emissions in low-HDI economies to effectively reduce overall climate vulnerability.

Table 9 presents the output of category 2, comprising countries with an average HDI between 0.5 and 0.6. Some countries in this category included Senegal, Uganda, Nigeria, Rwanda, Zambia, Kenya, and Angola. Similar to the low HDI category, all the variables except social readiness were statistically significant at a 95% level of confidence. Climate adaptation finance was negatively related to climate vulnerability, with a 1% increase in the finance expected to lower the vulnerability by 0.03%. The reason for the greater influence, in comparison to other categories, may be attributed to the fact that countries with an average HDI, including Kenya and Nigeria, ranked among the top nations in terms of climate adaptation finance.

In contrast to the lower HDI group, the economic readiness variable exhibited a positive relationship with climate vulnerability. This finding revealed that as the ease of doing business index improves in the middle-developed countries, the climate vulnerability is likely to increase. The ease of doing business in middle-HDI countries, the economic readiness indicator, is associated with the prospect of infrastructure development, industrial growth, and increased energy intensity [113,114] as the countries expand. These activities may heighten climate vulnerability if not well planned out. Vulnerability was still positively related to the GHG and lagging vulnerability variables. However, the beta coefficients indicated a lesser potential impact on vulnerability.

The third classification was comprised of countries categorized as high-HDI countries with a value higher than 0.6. These countries included Mauritius, Seychelles, South Africa, Egypt, Namibia, and Ghana. The findings, as depicted in Table 10 above, indicated that all variables were statistically significant at 5%, similar to the overall continent's output presented in Table 7. The relationship of climate adaptation finance, economic readiness, and governance readiness with climate vulnerability was negative, signifying a positive impact similar to that of the low HDI category. The social readiness variable exhibited a statistically significant negative relationship in this category, indicating that social readiness is essential in reducing the climate vulnerability of highly human-developed African countries. The GHG emissions and lagged value of vulnerability maintained the same results as previous models.

In summary, the impact of variables across the various HDI categories is different. The relationship between the readiness variables and climate vulnerability and the magnitude of change in the climate vulnerability index caused by change in the independent variables varied across the classifications, indicating that the influence of the variables varies with HDI levels. According to the findings, the impact of adaptation finance is higher among average HDI countries than the lower and higher HDI countries. Economic and social readiness has more influence in high-HDI countries, while governance readiness is more important in low-HDI countries.

As a result, we rejected the null hypothesis 2. We concluded that the impact of adaptation funding and climate preparation on climate vulnerability varies significantly among African economic classifications based on the Human Development Index.

5. Conclusions and Policy Recommendations

The cruciality of promptly and consistently implementing actions to minimize climate vulnerability cannot be undermined in aiding the prevention and alleviation of the detrimental impacts of climate change [115]. African countries' socioeconomic, political,

geographical, and environmental processes contribute to their heightened vulnerability to climate impacts [116]. In recent years, the continent has experienced a growing number of climate-related calamities, prompting increased discourse on the significance of adaptation.

Using Prais–Winsten regression and panel-corrected standard error analysis, this study empirically tested the effect of adaptation finance on climate change vulnerability while factoring in adaptation readiness in 52 African countries over the 2012 to 2021 period. Further, the paper explicitly assessed the effect across three different HDI categories, given the various levels of development across African countries. The empirical findings from all models validate the contribution of adaptation finance in reducing climate vulnerability to climate change in Africa. The influence is more significant in countries with average HDI than those with lower and higher HDI. However, the levels of adaptation finance are still low, with significant disparities across African countries leading to a small vulnerability reduction impact between 0.01% and 0.03% across the various HDI categories. On the other hand, the effect of adaptation readiness indicators varies across the categories. Economic and social preparedness significantly impacts vulnerability in countries with high HDI, while governance preparedness plays a more critical role in countries with low HDI.

Utilizing the empirical data, we make the following two policy recommendations. First, adaptation funding needs to be reassessed. While recognizing the critical role of adaptation finance in reducing climate vulnerability, it is essential to tackle the notable disparities in the allocation across African countries. Given that just 12% of the overall adaptation funding share to Africa is allocated to the 52% of bottom-HDI-ranked nations, it is crucial to prioritize improving the equitable distribution of funds to maximize its effectiveness in reducing vulnerability. The effective allocation process requires collaboration from stakeholders to conduct a comprehensive adaptation investment needs assessment of all countries while factoring in their risk susceptibility. Subsequently, the allocation can be carried out equitably while factoring in the assessment findings and the available resources.

Bridging the climate finance gap requires African countries' innovation of localized adaptation financing mechanisms, continuous international cooperation, and related partnerships. The establishment of adaptation project financing mechanisms at both the national and local government levels could ensure a comprehensive reach. To foster a sense of inclusivity and community engagement, these mechanisms should aim to provide favorable terms to attract contributory financing, even from local residents and corporations in vulnerable areas. By structuring financing mechanisms in this way, a wider range of adaptation projects can be supported, contributing to greater resilience across diverse geographic and demographic contexts.

To enhance international cooperation and partnerships, especially with private investors, African countries should focus on adaptation projects that have clearly defined and measurable outcomes. Further, maintaining consistent and high-level transparency and accountability in the usage of the adaptation finances is crucial. The assurance will not only reinforce existing partners' trust but could also encourage new international partnerships, attracting a wider pool of adaptation finance.

Second, African countries' governments should continue enhancing their adaptation readiness. Given the varying impact of readiness indicators on vulnerability across different HDI categories, adaptation readiness interventions should be tailored to the specific needs of countries based on their HDI levels. For countries with high HDI, the focus should be on strengthening economic and social preparedness, which has been shown to have a more significant impact. This entails enhancing the business environment to attract additional investment in adaptation and leveraging societal preparedness capabilities, such as education and technology adoption. For countries with low HDI, improving governance preparedness first is crucial. This may involve capacity building, institutional reforms, and policy frameworks to enhance governance readiness, specifically in these countries.

We acknowledge that obstacles to implementing policies may arise as a result of factors such as political will, institutional capacity, and resource constraints, which may impact the effectiveness of proposed interventions. Political will plays a pivotal role in

facilitating coordination among key players involved in the implementation process and in establishing important legal frameworks. Conversely, the absence of the will could pose implementation challenges. Moreover, strong and effective institutions are critical in implementation coordination and management. The absence of such institutions in African countries could challenge the implementation. Additionally, the policy recommendations also necessitate resources, particularly financial resources, and therefore, limited resources could derail the process.

This study's conclusions are limited to a certain extent. First, this study focused on the effect of adaptation financing, readiness, and the country's classification of HDI on climate vulnerability. Other variables outside this scope were not included in this study, which determined the overall explanatory level of the model. Other researchers could further investigate other factors to enhance knowledge of their impact on the climate vulnerability aspect, especially in regions considered to be the most vulnerable.

Second, this study excluded South Sudan and Eswatini due to the lack of sufficient data, which impacts the generalizability of our findings to these countries. The exclusion, however, was not very significant since it represented 3.85% of the sample. The limitation highlights the need for improved data collection and reporting standards in Africa to ensure more inclusive and accurate research outcomes.

Third, the research was based on Africa, a continent mostly composed of developing and low-income nations with unique socioeconomic and developmental features. The findings may, therefore, only apply to other regions with relatable similar characteristics. It is hence important to exercise caution when extrapolating the results to developed nations or regions with different socioeconomic systems and development levels.

The assumptions underlying the analysis and which might have influenced the results included a presumption that data reported for the various variables from the sources was accurate. Given that biases in data collection could influence the robustness of results, validation of data sources and collection methods is important. Further, this study assumed a causal relationship where the independent variables impact climate vulnerability. The possible reverse causation of climate vulnerability influencing the independent variables was not tested and can be considered in future research.

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