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Climate philanthropy as a catalyst for advancing the renewable energy transition and climate resilience in Africa

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Introduction: Africa faces the dual challenges of energy poverty and climate change, necessitating urgent solutions to ensure sustainable development. While renewable energy offers a viable alternative to fossil fuels, its adoption is hindered by financial constraints. Philanthropic funding has emerged as a crucial catalyst for accelerating renewable energy transitions and enhancing climate resilience. The main aim of this study was to investigate the role of philanthropic funding in renewable energy to address climate change in Africa.

Methods: This study employed a bibliometric analysis combined with a systematic literature review guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, with relevant peer-reviewed journal articles published between 2014 and 2024 identified and screened using the Scopus database. The Population, Intervention, Comparison, Outcome, and Context (PICOC) framework. The SALSA framework was used to guide Search, Appraisal, Synthesis, and Analysis of the selected literature to ensure a structured and transparent review process.

Results: Findings indicate an increasing focus on climate-smart technologies, low-carbon development, and climate adaptation strategies, with South Africa and Kenya leading research output in Africa, followed by the USA and the UK. Environmental science was the primary subject area, and Nature was the most influential journal, followed by Climate Policy. Four key thematic areas were identified: adaptation and resilience building, low-carbon transition, governance and financial flows, and agriculture and food security. Despite increasing scholarly attention, significant funding gaps persist, particularly in adaptation-focused initiatives and renewable energy infrastructure, while challenges such as inadequate regulatory frameworks and coordination issues continue to hinder effective philanthropic interventions.

Discussion: Future research should examine the socio-economic implications of climate philanthropic funding to maximise impact, assess its effectiveness in different regions, and develop context-specific climate adaptation strategies. Strengthening governance structures, fostering multi-stakeholder collaborations, and aligning philanthropic investments with national climate policies are critical to enhancing the sustainability of renewable energy projects. This study underscores the need for increased philanthropic engagement in Africa's energy transition to address energy poverty, mitigate climate vulnerabilities and promote long-term resilience, which will all go a long way in addressing SDG 7. It highlights that, once gaps are identified, climate philanthropy can complement public finance and drive inclusive and long-term

climate action across vulnerable sectors such as agriculture, energy, and food security.

KEYWORDS

climate change, philanthropic financing, energy access, climate adaptation, green energy, green growth and low-carbon

1 Introduction

Africa is the second largest and the most populous continent after Asia, home to over 1.5 billion people (United Nations Economic Commission for Africa, 2024). Given its population size, the continent is grappling with challenges such as energy poverty and climate change (Mabunda Lioko, 2023). Energy poverty is when a household has no access to adequate energy levels, thus failing to meet its basic needs (Simcock et al., 2021; MacDowell, 2023). Nearly 620 million Africans (two-thirds of the population) do not have access to electricity (Mukhtar et al., 2023), thus restricting economic growth and development (Alex-Oke et al., 2025). Climate change is a severe change in weather patterns across all regions and is a global phenomenon that has caused challenges in various sectors (Abbass et al., 2022; Sharifi et al., 2024).

Climate change and its effects are more severe and rampant on the continent than in most other parts of the world, despite Africa being the least responsible for the problem (IEA, 2023; Fonjong et al., 2024). With nearly one-fifth of the world's population today, Africa accounts for less than 3% of the world's energy-related carbon dioxide (CO) emissions to date. It has the lowest emissions per capita of any region (World Meteorological Organization, 2023). The increase in natural disasters and extreme weather events on the continent, as well as the lack of access to electricity, has resulted in high unemployment, loss of livelihoods, displacement, and illness, all fueling mass migration and regional instability (Kwanhi et al., 2024; Nhamo et al., 2025). The UNEP (2023) Adaptation Gap Report notes that Africa's adaptation financing needs are 8 to 10 times greater than current flows, and funds needed for adaptation per year in developing countries, including Africa, are between US$215 billion and US$387 billion. This highlights the urgency for innovative funding approaches.

Climate finance encompasses all public and private financial flows for climate mitigation and adaptation (Freitas and Mwaniki, 2024). Climate philanthropy, by contrast, is a voluntary, non-commercial subset of this finance, involving strategic allocations from individuals, foundations, or corporations to support environmental sustainability, renewable energy, climate advocacy, and related research (Bajwa and Gopalakrishnan, 2023). Globally, climate philanthropy is recognised as a catalyst for renewable energy transitions and climate resilience. In Africa, its role is becoming more visible. At the 2025 Mission 300 Africa Energy Summit, the Global Energy Alliance for People and Planet (GEAPP) and The Rockefeller Foundation announced nearly two dozen energy access projects across 11 countries and the Common Market for Eastern and Southern Africa (COMESA). With an initial US$10 million commitment, the initiative focuses on decentralised renewable energy and mini grids, complementing African Development Bank and World Bank Group goals to connect 300 million Africans to electricity by 2030 (Rockefeller Foundation, 2025; Global Energy Alliance for People and Planet, 2025).

Other notable contributors include the IKEA Foundation, which has invested hundreds of millions in climate justice and clean energy, such as through its partnership with the Access to Energy Institute (A2EI) to promote solar-powered livelihoods (IKEA Foundation, 2021), and the Bill & Melinda Gates Foundation, which supports clean cooking technologies. The Sustainable Energy Fund for Africa (SEFA), managed by the AfDB, offers catalytic financing and technical assistance under its Green Baseload, Green Mini-Grids, and Energy Efficiency pillars (Development Aid, 2023). The African Climate Foundation (ACF) supported the $500 million Renewables Investment Platform for Limitless Energy (RIPLE), part of the ReNew2030 initiative to increase solar and wind capacity fivefold by 2030 (African Climate Foundation, 2024).

Philanthropic climate funding to developing countries is increasing. For Africa, it tripled over 5 years to $112 million in 2022 but still represents only 6% of total foundation climate funding (World Resources Institute, 2023). The Climate Policy Initiative (2024) estimates that climate flows must increase fourfold annually until 2030 to meet Nationally Determined Contributions (NDCs). Most foundation funding supports climate mitigation, especially renewable energy, low-carbon cities, methane reduction, and capacity-building. Adaptation funding remains comparatively small, despite growing initiatives such as the Adaptation and Resilience Collaborative for Funders (ARC), launched at COP28 in 2023. ARC now includes over 60 philanthropic organisations globally, coordinating investments in adaptation and resilience (Esmaeili et al., 2024).

Research gaps remain. As Kim and Park (2023) highlight, few studies assess how African renewable energy transitions incorporate climate adaptation objectives. Furthermore, philanthropic giving for climate mitigation is less than 2% of global philanthropic giving (Desanlis et al., 2023), revealing significant untapped potential (Roeyer et al., 2020). The intersection of climate philanthropy, renewable energy, and adaptation in Africa remains underexplored in academic literature. Therefore, this study analyses research trends on philanthropy funding and renewable energy as a climate adaptation strategy in Africa, focusing on publication outputs, subject areas, sources, and country-level contributions. Using bibliometric analysis, it maps keyword patterns and research clusters, which are then synthesised through a systematic review to identify key themes. By integrating these methods, the study fills a gap in understanding how philanthropy and renewable energy intersect in advancing climate resilience across the continent. The study begins with a review of existing literature to establish the background and theoretical foundation. This is followed by a description of the research methodology, leading to the presentation and discussion of the findings. Finally, the conclusion highlights the

implications of the results and offers recommendations for future research.

2 Literature review

2.1 Conceptualising climate philanthropy

Philanthropy broadly includes all voluntary action undertaken for the public good (Payton, 1988). Daly (2012) argues that the meaning of philanthropy has changed over time and differs between different contexts. In Africa, philanthropy is described as 'gifting' with horizontal and vertical typologies (Fowler, 2022). According to Jung and Harrow (2015), governments worldwide welcome philanthropic acts such as donations and/or giving to solve the numerous problems facing societies, including responding to climate change (Mogotsi, 2025). However, Fowler (2022) cautions against dependency on philanthropy to address systemic inequalities, like energy poverty and the effects of climate change.

Climate philanthropy has been identified as a means of promoting renewable energy globally and as one of the primary strategies for climate change mitigation and adaptation (Suman, 2021). A substantial body of literature supports the fact that renewables not only help climate mitigation due to their carbon reduction effect but also promote climate adaptation, contributing to building the capacity to address climate change (Kim and Park, 2023; Long and Steinberger, 2016; Suman, 2021; Maulida, 2024). The sustainable nature of renewables in coping with climate change drives the global promotion of renewable energy transition (Kim and Park, 2023). According to the International Energy Agency (IEA), renewables supplied nearly 27% of global electricity in 2019 and could become the primary electricity source by 2030, providing 40% of the world's electricity supply (IEA, 2020). Energy is the key to development in Africa and the foundation for industrialisation [International Renewable Energy Agency (IRENA), German Development Bank (KfW), and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2020]. This is echoed by Nkoa and Fonguen-Kong-Ngoh (2024), who state that a shift towards renewable energies on the continent makes achieving the dual objective of industrialisation and environmental preservation possible. By choosing sustainable energy sources over fossil fuels, Africa can create new jobs, experience greater economic growth and harvest social and health benefits (Jaiswal et al., 2022; Gielen et al., 2019). SDG 7 of the 2030 Agenda speaks to access to affordable, reliable and sustainable energy for all (Shyu, 2021). The international community, multilateral organisations and bilateral donors are ready to partner. They are partnering with African countries on their path towards sustainable growth and work with them to develop and implement solutions to attain that goal (Saidi and Wolf, 2011).

The share of Africans with access to electricity in their homes increased from 36% in 2018 to 54% in 2000 (IEA, 2019). This is notable progress, especially considering the significant population growth during that period and the large investments required to connect people, particularly in rural and peri-urban areas. While philanthropic resources alone cannot match the trillions of dollars in investment needed to decarbonise the global economy, it has a unique and critical role in achieving this target (Roeyer et al., 2020). Philanthropy can increase global ambition, support innovative solutions, scale proven mitigation strategies, and drive collaborative actions (Roeyer et al., 2020). Furthermore, Roeyer et al. (2020) add that it allows for risks that the public and private sectors cannot or will not take. Philanthropy can also support frontline advocacy, emerging but unproven breakthrough technologies, and unique collaborations that bring together public, private, and civil society voices to solve the climate crisis (Desanlis et al., 2023).

2.2 Philanthropic funding trends and emerging practices

Philanthropy can help catalyse the trillions of dollars of public and private sector funding required to enable the transition toward a low-carbon global economy. The 2022 Global Philanthropy Environment Index (GPEI) reveals that the philanthropic environment showed modest improvement at the global level, but not uniformly so. Country and regional reports suggest that a consistent and enabling regulatory environment, state collaboration, and strong philanthropic traditions and societal values are essential to nurturing philanthropy (Indiana University Lilly Family School of Philanthropy, 2022). GPEI measures the philanthropic environment using 5 factors, including ease of operating a philanthropic organisation, tax incentives, cross-border philanthropic flows, political environment, and socio-cultural environment. An additional factor, the economic environment, was added to the 2022 GPEI. The Sub-Saharan Africa region contains 53 countries with an estimated total population of 1.2 billion (United Nations Statistics, 2017; World Bank, 2016). Kenya, Nigeria, Senegal, South Africa, Tanzania, and Zimbabwe account for 36.5% of the population. The Global Philanthropy Environment Index (GPEI) "Sub-Saharan Africa" region includes Eswatini, Ethiopia, Ghana, Kenya, Liberia, Nigeria, Senegal, South Africa, Tanzania, Uganda and Zimbabwe. Figure 1 summarises the philanthropic landscape in selected sub-Saharan African countries over the period 2014 to 2020.

Figure 1 shows that the sub-Saharan Africa average score was 3.21 from 2014 to 2017, then increased to 3.31 from 2018 to 2020, and slightly dropped to 3.31 from 2021 to 2023. The growing inflation has negatively affected the growth of African philanthropy, especially formalised HNWI-based giving (Murisa, 2025). Table 1 compares the sub-Saharan region with other regions in the world regarding the Global Philanthropy Environment Index (GPEI) Scores for 2025. As shown in Table 1, sub-Saharan Africa is the worst-performing region compared to Canada, the USA, Latin America, and Western Europe. Tax incentives and the economic environment are the lowest indices for Sub-Saharan Africa, whilst operating a philanthropic organisation seems easy in the region.

The last two decades (2002–2022) have witnessed a growth in high-profile Africans giving to significant causes across the continent. As of June 2025, Africa had 21 billionaires worth an average of USD 4.1 billion (Forbes, 2025). These billionaires are spread across the continent but concentrated in Nigeria, Egypt, Kenya and South Africa. They have established foundations that give towards different causes.

Philanthropy is vital in meeting development challenges and mitigating crises in sub-Saharan Africa (African Youth Philanthropy Network, n.d.; Organisation for Economic Co-operation and Development, 2024). Formalised philanthropy has a more extended history in South Africa than in other sub-Saharan African countries (Murisa, 2022). While giving in Africa by both internal and external

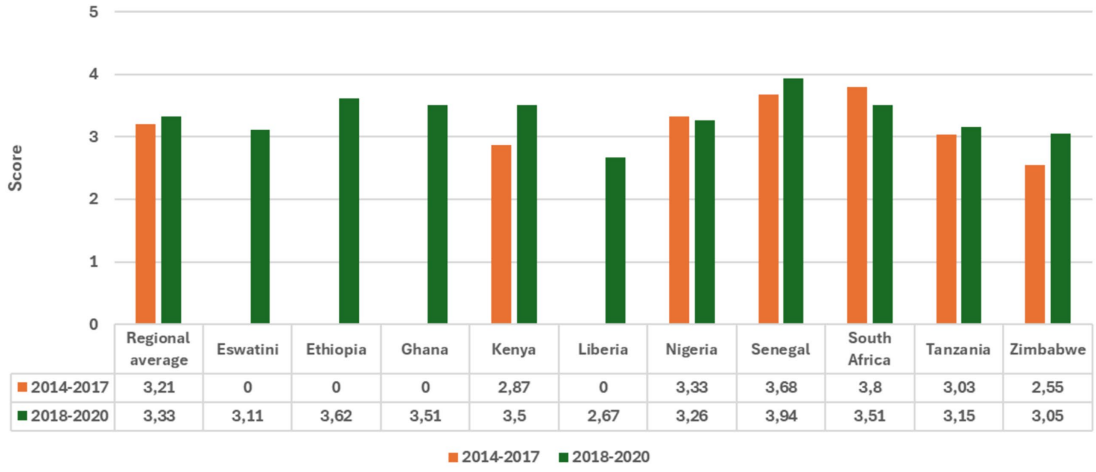

FIGURE 1
Global Philanthropy Environment Index (GPEI) overall score—sub-Saharan Africa. Source: Indiana University Lilly Family School of Philanthropy (2022).

TABLE 1 Regional comparison: Global Philanthropy Environment Index (GPEI) scores 2025.

Region	Global Philanthropy Environment Index (GPEI) scores						
	Ease of operating a philanthropy organisation	Tax incentives	Cross-border philanthropic flows	Political environment	Economic environment	Socio-economic environment	Overall score
Canada and USA	3.83	5	4	4.5	4.5	4.75	4.33
Latin America	3.66	3	2.83	2.84	2.6	3.38	3.05
West Europe	4.81	4.64	4.42	4.52	4.49	4.6	4.58
Sub-Saharan Africa	3.75	2.88	3.25	3.21	2.99	3.8	3.31

groups is on the rise, such efforts still encounter obstacles in cases where national policies constrain the ease of operating (such as in Zimbabwe) or the ability to send or receive funds across borders (as in Kenya).

2.3 Climate change financing

Through its Climate Promise, the United Nations Development Program (UNDP) is committed to working with governments and local communities to increase access to clean and affordable energy for 500 million Africans (UNDP, 2023). Attention must also be given to innovative financing mechanisms. Diaspora communities have contributed philanthropic flows and volunteer talent in key areas such as education, health, and climate mitigation (Osili, 2022). As has been widely noted, China, Europe, and the United States bear the most responsibility for greenhouse gas emissions. Prioritising the transition to renewables and imposing higher emission reduction requirements on the EU, U. S., and China will ease the burden on those nations that still need various power generation methods to increase energy access. Another big challenge is the lack of access to electricity, whereby nearly 600 million Africans lack access to electric power (IEA, 2023). In sub-Saharan Africa, 12 million new people enter the workforce annually (ISS African Futures, 2025). Prosperity and peace on the continent are incumbent on powering economic development and creating enough gainful employment opportunities for the growing population (Brookings Institution, 2023). That is not something that can be done in the dark. Without universal access to electricity, we will be vulnerable to underdevelopment, high unemployment, a migration crisis, and instability. Given the close interplay of these challenges and their threat to the overall region, we must find a way to solve both if our continent is to realise a peaceful and prosperous future (Brookings Institution, 2023). To narrow the energy access gap as quickly as possible, Africa must employ a variety of power sources already utilised by the U.S., EU, and China while simultaneously phasing out coal. Such a shift requires mobilising development financing, which requires a robust climate financing architecture.

2.4 Theoretical framework: climate finance architecture

Climate finance architecture refers to the structured ecosystem of financial mechanisms, institutions, and governance systems designed

to mobilise and allocate capital for climate change mitigation and adaptation (Watson et al., 2021) Establishing a robust global climate finance architecture can facilitate technology transfer, knowledge exchange, and financial support flows to assist developing countries in addressing climate change (Chen et al., 2024) Within the context of philanthropic financing for climate change mitigation in Africa, this framework provides a critical lens to analyse how charitable funding interacts with broader financial flows, policy interventions, and socio-economic disparities. This section elucidates the components of climate finance architecture, its relevance to climate philanthropy, and its inherent limitations, while analytically linking core concepts such as climate resilience and renewable energy transition.

The United Nations Framework Convention on Climate Change (UNFCCC), 1992 defines climate finance as "local, national or transnational financing-drawn from public, private and alternative sources of financing that seeks to support mitigation and adaptation actions that will address climate change." Zhang et al. (2019) note that this definition is narrow and requires further extensions to capture the complexity the world has encountered. According to Cheng et al. (2023), the climate finance architecture is a complex system involving multilateral and bilateral channels, with many countries setting up national climate funds. The types of climate finance available vary from grants and concessional loans to guarantees and private equity. The architecture has differing governance structures, modalities, and objectives. While the transparency of climate finance programmes through multilateral initiatives is increasing, detailed information on bilateral initiatives, regional and national funds is often less readily available (Watson et al., 2021). Bhattacharya et al. (2023) note that the complex multilateral financing architecture has led to concerns regarding the coherence and effectiveness of these funds' different roles and the adequacy and predictability of their financing. According to Phadtare et al. (2021), climate financial architecture must enable easy access to finance for climate action and avoid placing frontline nations into further debt stress. It should enhance climate action and guarantee a better future for all.

Climate finance architecture includes public funding, private capital, and blended finance mechanisms to mitigate climate change and enhance adaptation. Its relevance to climate philanthropy lies in bridging funding gaps for vulnerable regions, fostering climate resilience through infrastructure and community-based projects, while accelerating the renewable energy transition via investments in clean technologies. However, inherent limitations include fragmented governance, overlapping initiatives diluting accountability, and asymmetric allocation, as low-income nations face barriers in accessing finance despite disproportionate climate risks. Additionally, greenwashing risks undermine credibility, with some instruments prioritising profit over genuine decarbonisation. Analytically, while climate finance theoretically strengthens resilience by funding adaptive agriculture or flood defences, its efficacy depends on equitable disbursement, often sidelined by geopolitical interests. Similarly, renewable energy transitions rely on sustained capital flows, yet short-termism in private investments may stall systemic shifts. Thus, while climate finance architecture is pivotal, its structural biases and operational inefficiencies constrain its transformative potential, necessitating reforms in transparency, inclusivity, and alignment with justice-based climate action. Using climate finance architecture, the paper analyses climate philanthropy as a catalyst for advancing Africa's renewable energy transition and climate resilience.

3 Methodology

This study investigates the role of philanthropic funding in renewable energy to address climate change in Africa. A bibliometric analysis (Donthu et al., 2021) was conducted to analyse existing scholarly articles on the topic. A systematic review was used to synthesise the literature identified through bibliometric analysis. This allowed for an in-depth understanding of the key themes, strategies, gaps, and opportunities related to philanthropy funding, renewable energy adoption, and African climate resilience. To guide the literature identification, selection, and analysis process, this study employs the PICOC (Population, Intervention, Comparison, Outcome, Context) framework to define and refine the research scope, the SALSA (Search, Appraisal, Synthesis, Analysis) framework to screen and analyze relevant studies systematically, and the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to transparently report the literature review process. Together, these frameworks provide a comprehensive approach for systematically answering the research question and ensuring the reliability of the findings. This methodology section details the research approach, participant selection, data collection methods, and data analysis techniques to achieve research objectives.

3.1 Population, intervention, comparison, outcome, and context (PICOC) framework

To begin with, the study employs the PICOC (Population, Intervention, Comparison, Outcome, Context) framework to define and refine the research scope. This framework helps identify the key components of the research question, ensuring that the literature search is focused and relevant (Booth et al., 2021). Table 2 illustrates the PICOC framework together with the definition of each concept.

3.2 Data collection method

3.2.1 Search, appraisal, synthesis and analysis (SALSA) framework

The SALSA framework, a structured approach used in literature reviews (both bibliometric analysis and systematic reviews) to ensure a comprehensive and systematic data collection process, was applied. The acronym SALSA stands for Search, Appraisal, Synthesis and Analysis. Originally adapted from evidence-based medicine, it is widely used in bibliometric and systematic literature reviews to maintain rigour and transparency. The SALSA framework emphasises the synthesis and analysis of existing research to reveal novel insights, challenge assumptions, and identify gaps for future studies (Andriuškevicius and Štreimikiene, 2022). Additionally, exploration, interpretation, synthesis, and analysis are fundamental to rigorous scholarly inquiry (Major and Savin-Baden, 2010). SALSA is considered particularly effective for literature identification, evaluation, and synthesis because of its structured approach, which minimises subjectivity (Fernández del Amo et al., 2018). Moreover, this method is widely adopted to ensure methodological precision, thoroughness, and breadth in systematic reviews and bibliometric analyses (Grant and Booth, 2009). Below is a detailed breakdown of each SALSA component in the context of the bibliometric review conducted.

TABLE 2 PICOC framework.

PICOC element	Description
Population (P)	African countries, with a focus on stakeholders involved in climate philanthropy, renewable energy transition, and climate resilience (e.g., philanthropic organisations, policymakers, renewable energy developers, local communities).
Intervention (I)	Climate philanthropy as a mechanism for funding, promoting, and supporting renewable energy projects and climate adaptation/resilience initiatives.
Comparison (C)	Situations with limited or no climate philanthropy engagement in renewable energy and resilience-building efforts, or comparison between regions/sectors with high vs. low philanthropic involvement.
Outcome (O)	Advancement of renewable energy adoption, strengthened climate resilience, increased innovation in sustainable energy solutions, and improved adaptive capacity in vulnerable communities.
Context (C)	The African continent, with a temporal scope focusing on literature and developments from 2014 to 2024, in the context of global climate change mitigation and adaptation goals.

TABLE 3 Key words.

Search string	
	(charit* OR philanthrop* OR fund*) AND ("climate change" OR "global warming" OR "climate adaptation" OR "climate mitigation") AND afr*

Source: Researcher's compilation, 2025.

3.2.2 Search: search strategy

This step entails systematically identifying all relevant literature. This was done through database selection, creating a search strategy and a search string, and defining the inclusion and exclusion criteria. Whilst many relevant databases exist (Web of Science, Science Direct, Dimensions), this study focused on SCOPUS. SCOPUS provides broader coverage as it indexes more journals than WoS and includes better coverage of interdisciplinary research. SCOPUS also provides Open-Access Integration by including preprints and gold open-access journals, which WoS often misses. ScienceDirect is a publisher database (Elsevier), meaning it only includes Elsevier journals, while Scopus is a multi-publisher index (covering Elsevier, Springer, IEEE, etc.). Dimensions include preprints and grants, which do not align with the in bibliometric analysis requirements (Herzog et al., 2020). Scopus has better manual curation, reducing duplicate and erroneous entries (Visser et al., 2021).

The exact search terms and Boolean operators used were: charit*: captures "charity," "charitable," and related terms philanthrop*: captures "philanthropy," "philanthropic," etc., fund*: captures "fund," "funding," "funded," etc., climate change" OR "global warming" OR "climate adaptation" OR "climate mitigation": ensures inclusion of studies addressing various aspects of climate change and adaptation/mitigation strategies, afr*: captures "Africa," "African," and other variations referring to the continent Boolean operators used OR was used to include synonyms and related terms within each concept. AND was used to combine the three main concepts: philanthropy/funding, climate change/adaptation/mitigation, and Africa. Although the initial search string did not explicitly include "renewable energy," the selection process focused on studies relevant to climate adaptation and philanthropy. During the screening and eligibility stages, articles discussing renewable energy projects, initiatives, or strategies were identified and included, as renewable energy is a key mechanism for climate mitigation and adaptation in Africa. This approach ensures that the review captures literature at the intersection of philanthropy, climate change, and renewable energy, even if the exact term was not in the original search string. Table 3 provides an overview of the search terms employed in the bibliometric and systematic review, detailing the key concepts, synonyms, and Boolean logic used to identify relevant publications.

3.2.3 Appraisal: inclusion/exclusion criteria

The study applied specific inclusion and exclusion criteria to ensure the literature selected was relevant, comprehensive, and suitable for bibliometric analysis. Document types included journal articles, reviews, conference papers, and book chapters, while short surveys, notes, editorials, and letters were excluded, as they provided limited bibliometric information. The temporal scope was set between 2014 and 2024 to capture recent research trends. Language was restricted to English, reflecting the researcher's proficiency and ensuring accurate interpretation. The database used was Scopus, chosen for its extensive coverage of peer-reviewed publications and bibliometric data. Geographically, the focus was limited to Africa to track philanthropic initiatives' contribution to renewable energy and climate resilience; publications from other continents were excluded. These criteria were applied consistently during the screening process to produce a relevant and representative dataset of the study objectives (see Table 4).

3.2.4 Synthesis: systematic review

The systematic review was built on the results of the bibliometric analysis. Keywords identified and clustered through VOSviewer's co-occurrence analysis were used to develop preliminary thematic areas. These thematic clusters guided the formulation of research questions and categorising relevant literature. Using a systematic review approach, studies were retrieved, screened, and synthesised according to the inclusion and exclusion criteria. The SALSA (Search, Appraisal, Synthesis, and Analysis) framework, alongside PRISMA guidelines Figure 2, was applied to ensure transparency and rigour in the review process. The bibliometric themes were further refined through qualitative synthesis, allowing for insights from individual studies into broader conceptual narratives. This process enabled the

TABLE 4 Inclusion and exclusion criteria.

Criteria	Inclusion	Exclusion	Justification
Document type	Articles, Reviews, Conference Papers and Book Chapters	Short Surveys, Notes, Editorials, Letters	To have a clear picture of the analysis
Timeline	2014–2024	Any document that is before 2014 and after 2024	
Language	English	Languages in English	Researcher's language of understanding
Database	Scopus	Preferred database	
Region	Africa	Any other continents	Keeping track of the contribution of philanthropy in Africa

Source: Researcher's compilation, 2025.

identification of recurring patterns, gaps in knowledge, and emerging areas of interest, which collectively informed the overall thematic framework of the study.

3.2.5 Analysis: bibliometric analysis

Bibliometric analysis was conducted to map and evaluate the scientific literature relevant to the study. Data analysis and visualisation were then carried out using VOS viewer, which supported the keyword co-occurrence analysis. VOSviewer was chosen because it is solid in creating visual representations of bibliometric data, such as co-authorship networks, keyword co-occurrence maps, and citation networks (Braun and Clarke, 2016; Bukar et al., 2023). This makes it easier to understand complex relationships and trends in the data. A minimum threshold of five keyword occurrences was applied to ensure inclusion of only the most significant terms while reducing noise. The resulting clusters were visualised and colour-coded based on their temporal distribution, enabling the identification of major research themes, emerging hotspots, and evolving trends. These clusters further informed the thematic synthesis by consolidating related concepts into broader themes.

3.2.6 PRISMA (preferred reporting items for systematic reviews and meta-analyses)

The study selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021), ensuring a transparent and replicable approach to identifying and screening relevant literature. The PRISMA checklist was applied to guide each stage of the systematic review, from identification through inclusion, ensuring that all critical steps, such as duplicate removal, eligibility assessment, and final inclusion, were rigorously documented, which was also done by Rethlefsen et al. (2021)

As illustrated in Figure 2, 3,300 records were initially identified across multiple databases. After removing duplicates, records deemed ineligible by automation tools, and other irrelevant entries, 1,034 records remained for screening. Screening based on title and abstract led to the exclusion of 245 records, and retrieval of 789 full-text reports was attempted, with five reports not retrieved. Of the 789 reports assessed for eligibility, 424 were excluded due to irrelevance or failing to meet the inclusion criteria. Following these steps, 360 documents were included in the dataset for analysis, and 20 reports were selected for the final synthesis. This systematic and iterative process, guided by the PRISMA checklist, ensures that the selected literature is comprehensive and relevant, supporting the reliability of the subsequent thematic analysis.

3.3 Results

The subsequent analysis delves into the research landscape by examining publication trends, identifying prolific sources, delineating subject area distribution, and mapping geographic research output. This bibliometric exploration serves as a foundation for understanding the evolution of research within the field.

3.3.1 Document by year

The study analysed publications from 2014 to 2024, revealing a consistent increase in the number of documents per year on the related topic. The highest number of publications was observed in 2023, with 137 papers indexed in Scopus, while 2014 had the lowest, with just 36 documents. Notably, 2024 already has 87 papers, surpassing the totals from 2014 to 2020. It also indicates a correlation between climate change and global events, which has led to increased policy changes and technological advancements over time. Over the 10 years, the average number of documents per year was 78.

3.3.2 Relevant documents per year by source

Table 5 presents Cite Score trends for various journals related to philanthropy funding, climate change adaptation, renewable energy policy, sustainability, and environmental science from 2014 to 2024. Over this period, most journals have experienced a notable increase in their Cite Scores, reflecting growing research output and impact in these areas. Climate Policy saw a consistent rise from a Cite Score of 3.1 in 2011 to 12.9 in 2023, indicating a significant increase in the journal's influence over the years. Nature, a leading multidisciplinary journal, maintained a high Cite Score, increasing from 53.1 in 2011 to 90 in 2023, peaking notably in the early 2020s. Climate and Development also showed considerable growth, with its Cite Score rising from 1.5 in 2011 to a peak of 9.3 in 2022 before slightly declining to 8.9 in 2023. Sustainability (Switzerland) steadily climbed, starting at 1.4 in 2011 and reaching 6.8 in 2023. Environmental Science and Policy maintained an impressive performance, with its Cite Score growing from 4.7 in 2011 to 10.9 in 2023. Regional Environmental Change experienced fluctuations but generally increased, peaking at 8.2 in 2022 before a slight drop to 6.8 in 2023. Newer or smaller journals like Climate Change Management entered the Cite Score listings later, gradually increasing from 0.6 in 2020 to 1.5 in 2023. Climate Dynamics fluctuated but remained robust, peaking at 10.2 in 2022 before a slight decrease to 8.8 in 2023. Lastly, Renewable and Sustainable Energy Reviews exhibited the most dramatic increase, starting at 7.9 in 2011 and reaching an impressive 31.2 in 2023, reflecting its growing importance in renewable energy. Despite minor fluctuations, the

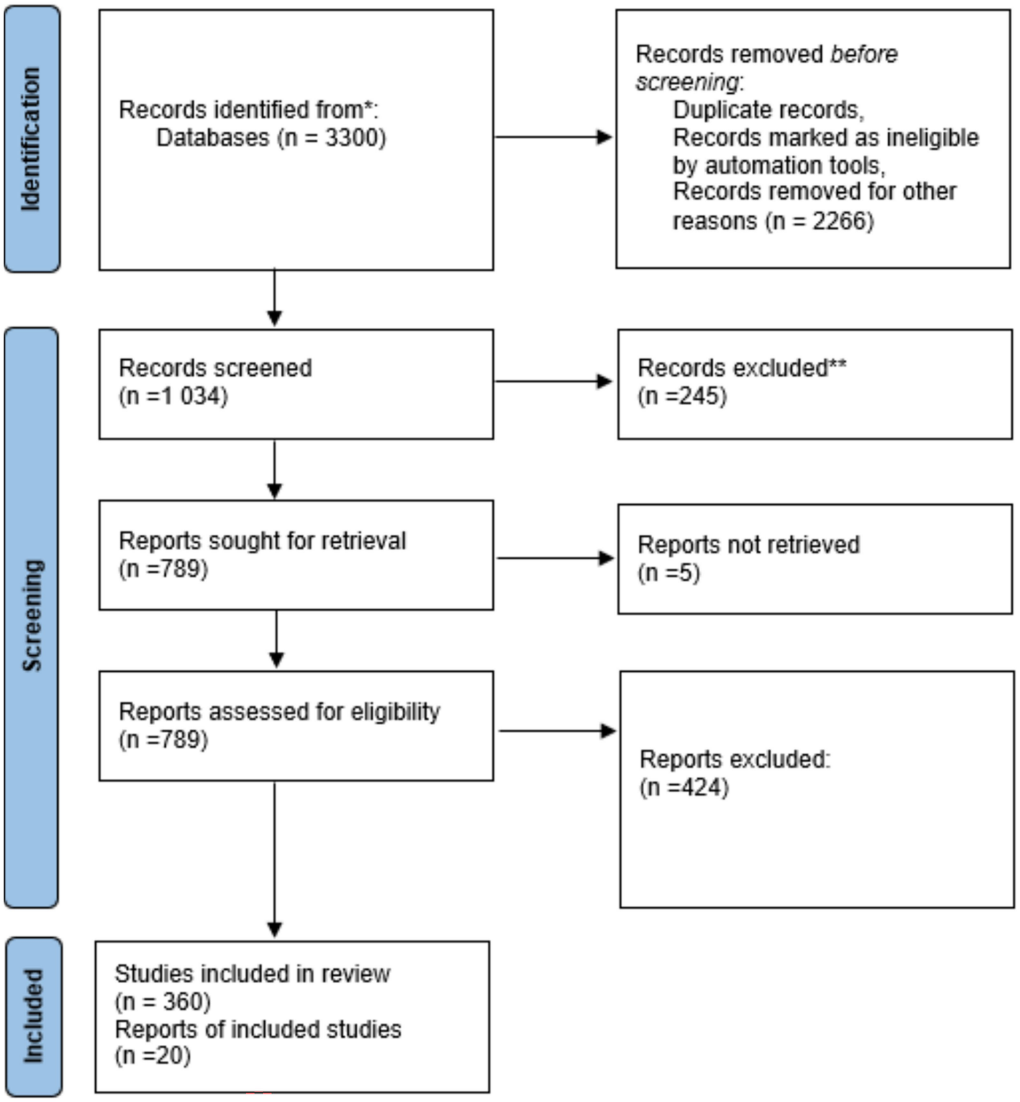

FIGURE 2
PRISMA diagram. Source: Researcher's compilation, 2025.

Journal of Climate showed consistent performance, with its Cite Score increasing from 7.1 in 2011 to 9.3 in 2023.

3.3.3 Document per subject area

This section of the results shows the documents per subject area. It provides a snapshot of where research efforts and funding are being concentrated and identifies gaps or opportunities in the literature. This breakdown offers several insights in the context of philanthropy funding renewable energy and climate adaptation. Eleven categories were identified in terms of documents per subject area. Environmental Science had the highest share, accounting for 22.2% of the documents. Environmental Science, having the highest percentage of documents, suggests that the field is at the forefront of research on renewable energy and climate adaptation. This aligns with the fact that these topics are inherently tied to environmental issues such as sustainability, climate change, and ecosystem management. This could indicate strong academic and philanthropic interest in addressing environmental challenges. However, it could also suggest that other important aspects, like social impacts, might be underrepresented. Social Sciences had 18.3%, a significant share of documents in Social Sciences highlights the importance of understanding the human, societal, and policy dimensions of renewable energy and climate adaptation. This includes examining the role of public perception, behaviour change, and policymaking in facilitating or hindering the adoption of these technologies. This indicates that social sciences are critical in ensuring that technological solutions are feasible, acceptable, and effective within different societal contexts. Philanthropic funding in this area could support research that bridges the gap between technology and society. Agricultural and Biological Sciences represented 11.9%. This percentage reflects the importance of agriculture in the context of climate adaptation. Agricultural and biological sciences are crucial for developing climate-smart agricultural practices and understanding the biological impacts of climate change. A substantial portion of research in this area emphasises the need for integrated approaches that combine renewable energy with sustainable agricultural practices to enhance

TABLE 5 Cite score publication per year.

Source	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Climate Policy	3.1	2.8	2.7	3.8	4.6	4.5	5.6	5.6	6.9	7.6	9.8	11.9	12.9
Nature	53.1	51	50.9	49.9	51.6	49.2	53.7	55.7	51.1	56.9	70.2	83.4	90
Climate and Development	1.5	2.1	1.8	2.6	2.6	3.2	4.1	3.7	4.1	4.8	7.3	8.9	8.9
Sustainability (Switzerland)	1.4	1.4	1.9	1.6	1.7	2.1	2.5	2.8	3.2	3.9	5.5	5.8	6.8
Environmental Science and Policy	4.7	5.8	5.5	6.4	5.7	6.2	7.3	8.4	8.4	8.7	10.4	10.5	10.9
Regional Environmental Change	2	3	3.5	4.4	4.7	5.3	5.6	5.6	6.5	7.4	8.1	8.2	8.8
Climate Change Management	–	–	–	–	–	–	0.6	0.9	1.3	1.5	–	–	–
Climate Dynamics	5.8	6.2	7.3	7.9	8.5	8.3	8.3	6.8	6.7	7.6	8.9	10.2	8.2
Renewable and Sustainable Energy Reviews	7.9	9.4	10.4	10.5	11	12.9	15.9	19.2	25.5	30.5	28.5	26.3	31.2
Journal of Climate	7.1	7.3	7.6	8.3	9	9.3	9.6	8.5	8.3	9.2	8.5	8.7	9.3

Source: Researcher's compilation, 2025.

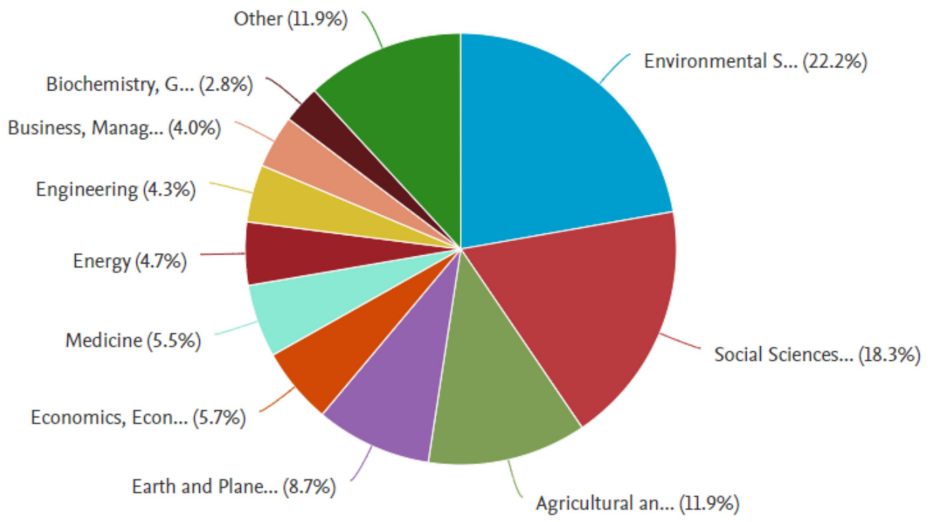

FIGURE 3
Document per subject area. Source: Researcher's compilation, 2025.

resilience in food systems. While Biochemistry, Genetics, and Molecular Biology had the fewest documents, contributing only 2.8%. The results are shown in Figure 3.

3.3.4 Document per country

The analysis of documents per country in philanthropy funding in renewable energy to mitigate climate change reveals (Figure 4) that South Africa leads with 221 documents, followed by the United States with 153, and the United Kingdom with 143. Kenya, another African country, ranks seventh with 53 documents. The many documents from South Africa suggest that the country is a significant hub for research and initiatives related to philanthropic funding in renewable energy. This may reflect strong academic interest, active policy development, or considerable philanthropic investments to address climate change in the region. The substantial contributions from the United States and the United Kingdom indicate their ongoing leadership in global climate initiatives, particularly in renewable energy and philanthropy. These countries often set trends and influence policies that have international implications. Despite having fewer documents than South Africa, Kenya's presence in the top 10 highlights its emerging role in renewable energy research within the African context. This is significant as it shows growing

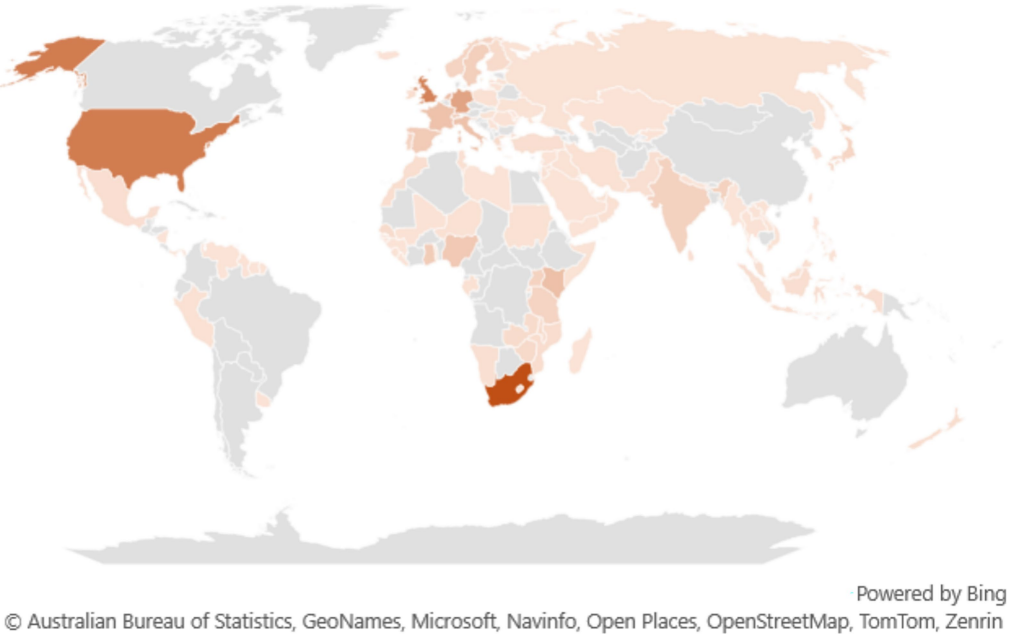

FIGURE 4
Documents per country. Source: Researcher's compilation, 2025.

attention and investment in renewable energy in countries particularly vulnerable to climate change. The distribution of documents per country helps identify where philanthropic funding is most concentrated and where it might be lacking. For instance, while South Africa is a leader in this field, other African countries might benefit from increased philanthropic attention to boost their renewable energy initiatives. Countries with a high volume of research outputs, like South Africa, the United States, and the United Kingdom, are likely to influence the direction of global climate strategies. Understanding this distribution can help philanthropists strategically channel funds to regions where they can have the most impact. The prominence of African countries in this analysis underscores the importance of directing philanthropic funding to regions highly vulnerable to climate change. Supporting research and initiatives in these areas can lead to more effective mitigation and adaptation strategies tailored to local needs.

3.3.5 Key words and themes

A VOS Viewer analysis clustered the keywords into six distinct groups, visually represented by different colours. The largest cluster, denoted by red, encompassed 30 items, primarily focused on adaptation, biodiversity, capacity building, and urban resilience strategies in the context of climate change. The green cluster, consisting of 26 terms, is centred on mitigation efforts, including alternative energy sources, carbon emissions, and climate finance. A geographical focus emerged from the blue cluster (23 items) with keywords like Southern Africa, Brazil, China, and economic development. The yellow cluster (20 items) highlighted agriculture, climate modelling, and drought as key concerns. The purple cluster (15 items) emphasised demographic factors, including gender and geographic distribution. A final cluster, represented by green, delved into participant demographics. From these clusters, themes were developed that were linked to the study topic (see Figure 5).

3.3.5.1 Climate change adaptation and resilience building

This theme focuses on the impacts of climate change, particularly in Africa, and strategies to adapt to these challenges. It emphasises the importance of building resilience in ecosystems, communities, and economies. Climate-smart agriculture has prospects for enhancing agricultural productivity and resilience in Africa. Some of the Climate-smart agriculture practices identified by Khumalo et al. (2024) are crop diversification, crop rotation, mulching drought-tolerant crops and organic manure. Boudalia et al. (2024) and Benaly et al. (2024) also stated that Africa has adopted climate-smart technologies, including forest and cropland regeneration practices, water resources, and weather and climate information services. Kenya has also adopted climate-smart technologies such as irrigation, agroforestry, soil conservation, changing animal breeds, and supplementary feeds (Ngigi and Muange, 2022).

Countries like Ghana and Nigeria emphasise crop rotation as a climate-smart method to mitigate the impact of climate change on agriculture (Antwi and Antwi-Agyei, 2023). To enhance climate resilience in agriculture, technological solutions such as the Internet of Things (IoT) are being explored, and in South Africa, climate change is being mitigated using a digital twin as a technological solution for monitoring and controlling temperatures in a greenhouse tunnel (Hull et al., 2024). Kwanhi et al. (2024) also observed that most African farmers are affected by climate change and have adopted migration to mitigate climate change impacts. Countries like Ghana, Uganda, Tanzania, and Ethiopia have had the most migration cases. It can also be noted that due to the climatic diversity in the African Continent, the impact of climate change from one country to another may vary; thus, the adaptation and mitigation strategies may also differ (Chari and Ngcamu, 2022; Oyawole et al., 2021). Climate change adaptation and resilience building require financial support, which can be met through climate philanthropy from foundations, companies and individuals (World Resources Institute, 2023).

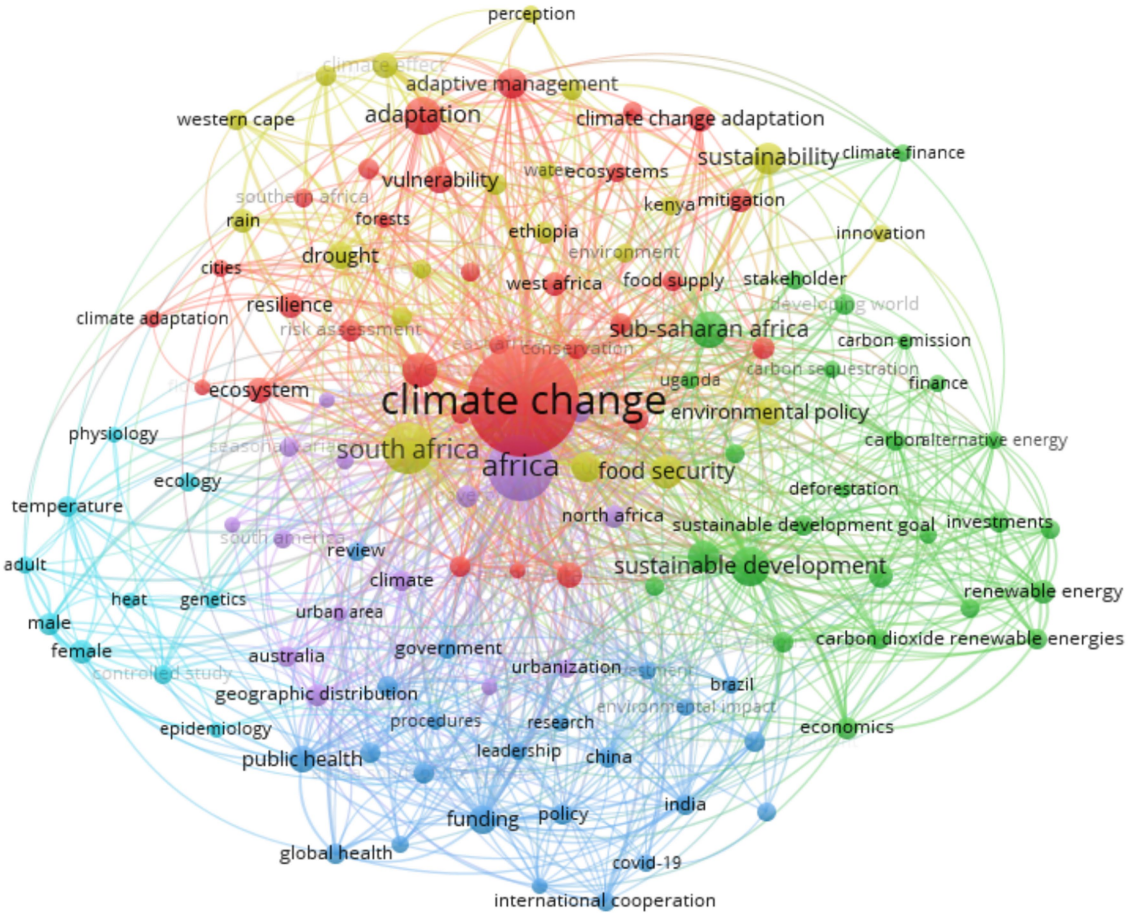

FIGURE 5
Network visualisation Vos viewer keywords into clusters. Source: Researcher's compilation, 2025.

3.3.5.2 Climate change and low-carbon transition

This theme highlights the need to reduce greenhouse gas emissions and transition to a low-carbon economy. It also emphasises the role of finance and investments in supporting this transition. Opoku-Mensah et al. (2024) mentioned that transitioning to sustainable energy is crucial for climate change mitigation. However, achieving net-zero emissions remains challenging in Africa, and West African countries have proven to have a low structural change level, limited energy access, and weaker institutional capacity. A study by Rweyendela et al. (2023) in Tanzania on oil and gas showed that if a proper strategic environmental assessment can promote low-carbon development in energy planning, this can be an excellent method to mitigate climate change. In a study conducted in Ghana, Nyasapoh et al. (2023) indicated that the transition from fossil fuel-based sources to low-carbon sources has significantly impacted climate mitigation. The results further suggest that renewables and nuclear energy to meet emissions have been adopted and have met a significant way of reducing high carbon emissions, thus increasing sustainable development; despite the higher investment cost associated with the additional installed capacity, the mitigation measures deployed in the electricity system reduced CO2 emissions by 15% (4,142.2 kilotons). However, Kenya is still struggling to meet the global community's target. Global climate change is very little, as the country's greenhouse gas (GHG) emissions represent less than 1% of total global emissions (Kibugi, 2021). Low-carbon transition needs a substantive financial injection. According to the University of Cambridge Institute for Sustainability Leadership (CISL) (2024), African states must spend around US$2.5 trillion by 2030 to meet climate commitments. Emission reduction makes up nearly 80% of spending, with plans for adaptation to climate change costing US$418 billion [University of Cambridge Institute for Sustainability Leadership (CISL), 2024]. A just transition to a low-carbon economy is expected to drive economic growth, create jobs and increase energy security.

3.3.5.3 African climate change governance and financial flows

This theme focuses on the broader context of climate change, including international cooperation, policy development, and financial mechanisms. It also touches on the role of governments and other stakeholders in addressing climate change. According to the literature, various African organisations have invested in climate change and have come up with policies to mitigate climate change. African climate governance encompasses complex policies, institutions, and practices to address climate change challenges. Key actors include the African Development Bank (AfDB), a pivotal institution in mobilising climate finance, and the Green Climate Fund (GCF), a global fund supporting adaptation and mitigation efforts. National climate action plans (NAPs) provide

country-specific roadmaps, while regional climate centres offer essential data and services. Investments in climate-smart agriculture and renewable energy projects are crucial to enhance resilience and low-carbon development. Africa faces substantial adaptation costs, estimated at USD 7–15 billion annually by 2020 (Schaeffer et al., 2013). The African Development Bank (AfDB) further quantifies this need, suggesting near-term adaptation costs of USD 7.4 billion per year based on Intended Nationally Determined Contributions (INDCs), acknowledging that these only partially capture adaptation needs (AfDB, 2019). A stark disparity in funding priorities is evident, with African, incredibly, Least Developed Countries (LDCs) demanding significantly more adaptation than mitigation. Zhang and Pan (2016) highlight this imbalance, reporting a 2:1 adaptation-to-mitigation finance ratio in 16 African INDCs, with Eritrea and Uganda exhibiting an even stronger preference for adaptation funding.

3.3.5.4 Climate change impact on agriculture and food security

This theme highlights the vulnerability of agriculture to climate change and the importance of finding adaptive strategies to ensure food security. Climate change has significantly affected agriculture, especially smallholder farmers in South Africa, and the welfare of the farmers has become a worrying situation due to the lack of nutritious food and income (Khumalo et al., 2024). In a study carried out by Naazie et al. (2024) on the Characterisation of urban agriculture and farmers' climate change adaptation: the case of Urban Wa, Ghana, the study revealed that Ghana is also facing climate change issues and it has become a significant threat to urban Agriculture as the weather patterns change which lead to draught, floods and extreme weather conditions and significant damage is seen on crops and livestock.

4 Discussion

The increase in research over the years go by between 2014 to 2024 can be linked to significant global policy events, such as the 2015 Paris agreement, which emphasised the collaboration of developed countries to assist with resources for mitigation and adaptation in climate change through climate finance (UNFCCC, 2015) coincided with global climate negotiations (e.g., COP28 in Dubai), heightened debates addressed climate change impact on the global community the attendance of key philanthropic foundations such as Gates Foundation and Bezos Earth Fund gave more attention to climate philanthropy. It formed grants for climate mitigation and resilience, as well as funding collaboration. The results also showed the significance of South Africa and Kenya as leading countries in Africa in terms of climate philanthropy research. These results are similar to those of Mthembu and Nhamo (2022), Ngigi and Muange (2022), which state that these two countries have a strong institutional framework and active philanthropy engagement. The pattern of wealth distribution of about USD 4.1 billion in South Africa and Kenya linked to philanthropy funding might also have caused the significance of these 2 African Countries (Forbes, 2025). It also proves a growing engagement of African countries towards climate change adaptation through renewable energy (Ngigi and Muange, 2022). The appearance of countries like the United States of America and the United Kingdom shows a collaboration link between research and philanthropy funding in Africa, as these two countries host the leading philanthropy organisations (Esmaeili et al., 2024). The results show that research outputs are closely linked to policy and funding, which shows the need for contextual and institutional factors in shaping the global climate.

Four interrelated themes were identified from this study: adaptation and resilience building, low-carbon transition, governance and financial flows, and agriculture and food security, which underscore the pivotal role of renewable energy and philanthropy in Africa's climate response. Adaptation strategies such as diversification, agroforestry, and drought-tolerant crops, among other methods, have proved effective in enhancing climate-smart agriculture. Practices like irrigation systems and digital innovation require reliable energy, emitting less carbon. Thus, renewable energy solutions such as solar irrigation and biogas mini grids have been funded by philanthropy organisations, which played a catalytic role (World Resources Institute, 2023). These results align with the ones by Esmaeili et al. (2024), which stated that Philanthropic contributions have grown substantially, tripling to US$112 million in 2022 and reaching US$9.3–15.8 billion in 2023, with US$600 million explicitly dedicated to climate adaptation. A case study of philanthropy operationalises adaptation and resilience strategies by 10 The Global Energy Alliance for People and Planet (GEAPP) which is trying to eliminate the spending of $2 billion annually on diesel-powered pumps by farmers in Africa by introducing Sun Culture solar powered irrigation systems that offer cost effective and clean alternatives to diesel pumps, increasing irrigation by 10% could result in a 50% increase in agricultural production. Sun Culture has developed a range of solar-powered irrigation systems that offer a clean, cost-effective alternative to diesel pumps, which have funded solar mini-grid projects in Kenya and Tanzania, supporting climate-smart agriculture through solar-powered irrigation and cold storage (Global Energy Alliance for People and Planet, 2025). Through capacity-building and technical support, the RIPLE initiative enhances renewable energy adoption in Southern African smallholder farming systems. The IKEA Foundation, through the Access to Energy Institute (A2EI), integrates renewable energy with community resilience interventions, such as solar-powered water pumps. This initiative strengthens resilience by reducing crop losses, improving food security, and empowering communities to adapt to climate variability (IKEA Foundation, 2021).

Transitioning to low-carbon energy systems is essential for achieving Africa's sustainable development and mitigation goals (Nyasapoh et al., 2023; Kibugi, 2021). Renewable energy adoption reduces emissions while expanding energy access; however, high costs and weak institutional capacity remain barriers. With an estimated US$2.5 trillion required by 2030 to meet climate targets, philanthropy complements public and private investments by mobilising risk-tolerant capital, supporting just transitions, and accelerating deployment [University of Cambridge Institute for Sustainability Leadership (CISL), 2024]. The Sustainable Energy Fund for Africa (SEFA) under the Africa Development Bank, working together with philanthropic organisations through interventions by expanding access to clean energy and supporting low-carbon transitions, to date, it has mobilised approximately USD100million (Development Aid, 2023; AfDB, 2025). The Bill & Melinda Gates Foundation have supported clean cooking technologies that reduce biomass reliance and associated emissions. The results showed that Governance and financial flows influence resource mobilisation and allocation. Multilateral

instruments such as the Green Climate Fund and African Development Bank prioritise renewable energy, yet disparities persist, particularly in Least Developed Countries. Philanthropy can fill these gaps while enhancing governance mechanisms (Zhang and Pan, 2016; AfDB, 2019). The African Power Platform (APP) supports African-owned enterprises deploying off-grid solutions and powering local economic activities, complementing multilateral finance and strengthening sector governance. African Climate Foundation (ACF) RIPLE / ReNew2030. The African Climate Foundation supported the $500 million Renewables Investment Platform for Limitless Energy (RIPLE) under the ReNew2030 initiative. This program aims to increase solar and wind capacity fivefold by 2030 by providing funding, technical support, and risk mitigation instruments.

However, although there is significant progress, there are systemic barriers that hinder philanthropic effectiveness. Philanthropic organisations encounter regulatory hurdles, coordination challenges, and sustainability concerns, which can be exacerbated when policies limit equitable partnerships with grantees. Such policies, e.g., in South Africa's Renewable Energy Independent Power Producers Procurement Programme (REIPPPP), sometimes fail to meet local empowerment targets, limiting benefits for vulnerable communities (Todd and McCauley, 2021). Addressing these requires policy reform, capacity building, inclusive planning, and fostering relational partnerships that pool resources and expertise, ensuring sustainable and context-sensitive interventions (Petzinger and Jung, 2024). Broader barriers, such as regulatory inconsistency, unclear land tenure, and insufficient incentives, create uncertainty for long-term investments. Funding gaps remain, 6% of total foundation climate funding, which often favours mitigation over adaptation (World Resources Institute, 2023). On the other hand, some communities face additional obstacles, including limited awareness, technical skills, high upfront costs, and cultural resistance. Uneven distribution of philanthropic funds has become a common challenge in most communities, with more emphasis given to large projects, which might not address the local needs of the community (Wo, 2023; Efendi and Khomairoh, 2024).

5 Conclusion

This study used a bibliometric and systematic approach to analyse the role of philanthropy in encouraging the transition to renewable energy and boosting climate adaptation in Africa based on the body of available literature. This study offers a thorough assessment of the body of current knowledge, identifies significant trends, gaps, and influencing factors, and evaluates the effects of philanthropy support on the renewable energy industry and attempts to adapt to climate change in African contexts. This analysis aimed to shed light on the best ways to maximise charitable donations to promote resilience-building and sustainable energy initiatives across the continent.

5.1 Limitations

The bibliometric analysis relied exclusively on the Scopus database, thereby limiting the scope of the study to peer-reviewed literature. Consequently, the investigation may have overlooked crucial insights from grey literature, such as the intricate relationship between philanthropic funding and renewable energy as catalysts for climate change mitigation. A more comprehensive systematic literature review encompassing a broader spectrum of sources could have yielded richer and more nuanced findings.

5.2 Future directions and policy recommendations

Given the lack of research on this subject, the study also lays the groundwork for future investigations and the formulation of policies. This will facilitate funding climate change adaptation and mitigation efforts by donors and other interested parties. Additional research is necessary on the policies that control philanthropy in Africa and the success stories of climate funding in philanthropy on the continent. From the discovered themes, the study moved on to correlate the themes with Philanthropy funding and came up with five links, which are gaps that academics can uncover and investigate. Philanthropic funding for adaptation and resilience development could include assistance with early warning systems, disaster preparedness, and ecosystem restoration. Philanthropic funding in low-carbon technology and projects: Examples include renewable energy projects, energy efficiency programs, and sustainable transportation. Philanthropic support for global climate governance may consist of funding for climate research, policy development, and capacity building in developing nations. Philanthropic contributions to agriculture and food security could include financing for climate-smart agriculture, drought-resistant crop types, and agricultural extension programs.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TK: Formal analysis, Visualization, Writing – original draft, Methodology, Validation, Data curation, Software, Investigation, Conceptualization. AK: Formal analysis, Resources, Data curation, Writing – original draft, Visualization, Investigation, Conceptualization, Validation, Methodology, Software. AB: Supervision, Writing – review & editing, Project administration, Validation, Resources. SM: Visualization, Resources, Project administration, Validation, Writing – review & editing, Supervision. JM: Project administration, Validation, Visualization, Writing – review & editing, Supervision, Resources.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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