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Nature-based solutions for water resource management in Africa's arid and sem-arid lands (ASALs): A systematic review of existing interventions

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ABSTRACT

Arid and Semi-Arid Lands (ASALs) in Africa, covering 66 % of the continent and are home to around 200 million people, face significant water scarcity challenges due to harsh climatic conditions. This systematic review assesses the effectiveness, socio-economic impacts, and implementation challenges of Nature-based Solutions (NbS) for water resource management in these regions. Analysing 9906 research articles narrowed to 143 studies, the review identified critical NbS interventions, including water conservation, soil moisture and conservation, water harvesting, conservation agriculture, agroforestry, and afforestation. The studies focused on biophysical aspects (31 %), socio-economic issues (39 %), or both (30 %), with an emphasis on water quantity (96 %) over quality (3 %). These interventions' direct (43 %) and indirect (55 %) impacts were examined. Findings show that 52 % of the studies meet all effectiveness criteria: socio-economic benefits, sustainable resource use, resource enhancement and conservation, and infrastructure sustainability. Stakeholder engagement in co-designing NbS significantly enhances their effectiveness and the integration of indigenous knowledge. Geographic distribution highlights concentrated research in eastern, southern, and western Africa, particularly in Ethiopia, Kenya, and South Africa, with underrepresentation in northern and central regions. The review identifies gaps in water quality interventions and calls for more comprehensive approaches. The review highlights NbS' potential to improve water availability, ecosystem resilience, and socio-economic development in ASALs. However, challenges such as limited stakeholder involvement, inadequate integration of indigenous knowledge, and regional research disparities need addressing. The study recommends prioritising the participation of local communities and stakeholders from the planning stages to implementation to enhance the effectiveness and sustainability of future NbS projects.

1. Introduction

Arid and Semi-Arid Lands (ASALs) are prevalent across Africa, encompassing ecosystems ranging from the Sahelian grasslands to the savannahs of East and Southern Africa. While ASALs cover about 40 % of the earth's surface and are inhabited by approximately 20 % of the world's population, they cover 66 % of Africa's total land area. They are home to approximately 200 million people [1,2]. These landscapes are defined by their harsh climate, infrequent and unpredictable rainfall, high evapotranspiration rates, and extended dry seasons [3–5]. The environmental conditions of these regions shape the physical landscape and greatly influence the biodiversity they support. Despite these harsh climatic conditions, ASALs are home to high species biodiversity. These ASALs receive limited amounts of precipitation that exhibit significant variability in both spatial and temporal distribution [6–9]. As a result, runoff and drainage systems that delineate the arid or semi-arid zones are inhabited by biota uniquely adapted to survive under water stress [10–12]. For example, plants such as baobabs, acacias, and various

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succulents have evolved deep root systems and water storage capacities alongside other adaptations like small, waxy leaves to minimise water loss [13–15]. Similarly, the fauna, for example, the Addax antelope and the African wild dog, have developed behavioural and physiological traits enabling them to thrive under water-limited and high-temperature conditions [16–20].

This unique biodiversity is not only restricted to terrestrial species but extends to aquatic biota in the ephemeral water bodies and intermittent rivers of these drylands [21]. These environments support complex ecosystems where water flows can be perennial or intermittent, creating significant environmental filters that challenge aquatic life. The remnant water bodies of dryland rivers serve as critical refuges for aquatic biota, sustaining species adapted to survive under intense water stress [22–24]. However, terrestrial and aquatic biodiversity in these arid and semi-arid regions is severely threatened due to overexploitation, habitat fragmentation, and the broader impacts of climate change, such as altered temperature and precipitation patterns. According to the most recent Living Planet Report by the World Wildlife Fund (WWF) [25], the abundance of monitored freshwater vertebrate species has declined by 83 % since 1970. This is the most significant decrease in the three primary domains of land, seas, and freshwater, underlining the disproportionate threat to freshwater biodiversity and giving rise to the need to address this declining biodiversity. Further, the IPCC's Fifth Assessment Report [26] highlights that agricultural systems in Africa's ASALs are increasingly vulnerable due to the combined effects of climate change and non-climatic stressors such as land degradation, poor soil health and ineffective agricultural practices. This increased vulnerability threatens agricultural production, directly impacting the livelihoods of rural communities, predominantly supported by smallholder farmers with limited resources and adaptive capacity [27–29]. Various ASALs have already been recognised as threatened biodiversity hotspots due to these multiple stressors, including human-induced changes, which contribute to the decline of species populations [30–32]. Addressing these challenges is crucial and requires conservation efforts informed by global sustainability goals like SDG 15, which promotes the sustainable use of terrestrial ecosystems and aims to halt biodiversity loss through strategic habitat conservation and sustainable management practices [33–36].

Water scarcity in ASALs is a common and critical challenge that extends its impact beyond mere ecological disruptions to profound societal ramifications [37,38] because the freshwater available is often insufficient to meet human and environmental needs. This water scarcity affects every aspect of life, from agriculture and food production to basic human necessities [39]. Chronic drought conditions exacerbate these challenges as water sources become increasingly stressed or depleted [40,41]. For example, the predominant reliance on rain-fed agriculture in ASALs makes these systems especially susceptible to fluctuations in water availability, often resulting in crop failures, loss of livestock, and a severe reduction in food security [42]. Such agricultural vulnerabilities exacerbate malnutrition and deepen poverty, making sustainable water resource management a critical priority. Crop failures become more frequent due to inadequate irrigation, reducing food security and increasing prices, particularly affecting the most vulnerable populations [39,43,44]. The competition for the limited water resources available in ASALs often leads to social and economic tensions. Communities and sectors, such as agriculture, industry, and domestic use, compete to access this scarce resource, sometimes resulting in conflict further exacerbated by the abstraction and diversion of waterways [45–47]. Moreover, water quality in these regions can deteriorate due to the overuse and contamination of dwindling sources [48–50], posing significant health risks as populations rely on these compromised water sources for drinking, cooking, and sanitation [51]. This makes the need for effective water management strategies very critical, which involve both local adaptations and broader policy implementations to be effective. Such strategies must include enhancing water use efficiency in agriculture, investing in technology for water reclamation, and implementing strict regulations on water pollution to ensure that the available water can meet the needs of both people and the ecosystems. Sustainable management of water resources, as advocated by SDG 6, is therefore crucial, encompassing modern practices and traditional water conservation techniques [52–54].

Nature-based Solutions (NbS) are increasingly recognised for their multifaceted potential to bolster ecosystem services while addressing critical socio-economic challenges. NbS are strategies and actions that leverage natural processes and ecosystems to address various environmental, social, and economic challenges. By working with and enhancing nature, these solutions benefit biodiversity, human well-being, and sustainable development [55]. These strategies involve the protection, restoration and sustainable management of ecosystems to mitigate the impacts of water scarcity, both directly and indirectly. For instance, planting trees is more than a conservation effort; it stabilises the soil, enhances water infiltration, boosts groundwater recharge, and reduces surface runoff [56,57]. Such efforts are pivotal for climate regulation and providing vital habitats for local wildlife, thereby supporting biodiversity. Moreover, NbS extends to agricultural practices through agroforestry, contour ploughing, cover cropping, etc. These methods improve soil health, augment water retention, and increase agricultural productivity. Such enhancements are crucial for sustaining the land, the biodiversity and the people who rely on it for their livelihoods [58–63].

Conventional water management approaches in ASALs have been primarily based on engineering solutions, such as dams, boreholes, and canals [64,65]. However, these solutions are often expensive, environmentally damaging, energy-intensive and unsustainable for many communities [66–68]. NbS can provide an alternative to traditional grey infrastructure as they are often low-cost, sustainable, and effective. NbS are particularly relevant for water resource management in ASALs due to their potential for dual benefits, including providing or safeguarding ecosystem services such as water regulation, purification, and storage, which enhance water availability and quality while supporting biodiversity and ecosystem services [55,69]. Additionally, interventions such as the restoration of wetlands serve as a critical component of NbS, vastly improving water purification, buffering against flooding, and aiding in groundwater recharge, all of which are especially vital in ASALs where water scarcity is a prominent challenge [69–71]. In this way, NbS can also improve the resilience of ecosystems and communities to climate change and extreme weather events. These solutions are often more cost-effective and adaptable to local contexts than conventional water management approaches [72]. The implementation of NbS is closely aligned with international environmental directives, notably the United Nations Convention to Combat Desertification (UNCCD), which promotes sustainable land management to combat desertification [73–75]. The support for these projects often comes from global initiatives and funding mechanisms, such as the Global Environment Facility (GEF), which ensure that local efforts are effective but also scalable and sustainable. This external support indicates the global recognition of integrating NbS into broader environmental and development strategies.

This nuanced NbS approach highlights the complex interplay between the ecological characteristics of ASALs, the pressing challenges posed by water scarcity, and the transformative potential of NbS to foster sustainable and resilient ecosystems. By marrying global environmental goals with local conservation and management practices, stakeholders can significantly enhance the sustainability of these vulnerable landscapes. This integrated strategy is crucial for effectively managing ASALs and promoting a balanced coexistence between human needs and environmental conservation [55]. It encourages water resource management and aquatic biodiversity conservation [76]. Such efforts contribute significantly to global biodiversity, enhance climate resilience (enabling us to meet our Global Biodiversity Framework (GBF) goals and climate goals outlined in the Paris Agreement), and improve human well-being, embodying a holistic approach to environmental and societal challenges.

Despite the growing interest in NbS, there is a need for a comprehensive systematic review of existing interventions for water management, particularly in the unique context of Africa's ASALs. Such a review is crucial to understanding these interventions' biophysical and socio-economic impacts while exploring their effectiveness and scalability. It can also provide valuable insights into the challenges faced in implementing NbS and identify areas for future research and policy development. This systematic review aims to synthesise existing literature on NbS for water resource management in Africa's ASALs. It evaluates the effectiveness of these interventions in improving water availability, quality, and sustainable use and analyses the socio-economic impacts of NbS on local communities in ASALs. Finally, it identifies challenges and gaps in current NbS practices and suggests areas for future research and policy development.

2. Methodology

2.1. Search Criteria

This systematic literature review utilised Web of Science, Scopus, and Dimensions as the primary databases due to their comprehensive coverage of scholarly articles across various disciplines. The search strategy involved defining a set of keywords and search queries tailored to the research topic. The initial search was conducted across the selected databases using predefined search queries (Table 1). These queries were designed to be broad enough to capture a wide range of relevant studies but specific enough to ensure relevance. No particular timeframe for publication dates was established because, although NbS is a relatively new term (first coined in 2009), many activities and interventions associated with the concept have been carried out for longer than it has existed. All search results were recorded and compiled. Articles were filtered using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) strategy [77]. PRISMA is a strategy designed to help authors enhance their reporting of systematic reviews and meta-analyses. The PRISMA flow diagram illustrates the flow of information through the various phases of a systematic review. It details the number of records identified, included, and excluded and the reasons for exclusion. All recorded search results were sorted in Rayyan AI [78] based on the screening process described below.

2.2. Screening process

This study followed a pre-defined screening process to ensure the selection of relevant, high-quality studies to answer the research question. This systematic and rigorous screening process is essential to minimise bias and ensure that the review accurately reflects the available evidence related to the research question. Before the screening began, explicit inclusion and exclusion criteria were established (highlighted in the section below). Screening of articles was done in three steps: The first level of screening involved reviewing the titles and abstracts of identified articles. At this stage, articles that did not meet the inclusion criteria were excluded. At least two reviewers did this step independently to minimise bias and errors. Articles that passed the initial screening were then subjected to a full-text review. In this stage, reviewers read the complete articles to determine if they fully complied with the inclusion criteria. Reasons for the exclusion of articles at this stage were documented for transparency. The articles that met all the inclusion criteria underwent a quality assessment, which involved evaluating the methodological rigour in each study. Data was then extracted from articles that passed the quality assessment. This included categories of interventions, areas of focus (biophysical vs socioeconomic, type of study (qualitative vs quantitative), efficiency and sustainability of interventions, and impacts and outcomes. Data extraction was done using a standardised form in Excel to ensure consistency. Any discrepancies between reviewers are resolved throughout the screening process through discussion or consultation with a third reviewer. This consensus approach ensured objectivity and reliability in the screening process. The final set of articles that passed through all the screening stages formed the basis of the systematic review. The screening process was thoroughly documented, including the number of articles screened at each stage and the reasons for exclusion. This was represented in a PRISMA flow diagram, which provided a transparent and systematic presentation of the screening process (Fig. 1).

Table 1
Summary of predefined search queries and keywords used in the three databases to capture the relevant studies.

Ecosystem/ Focal Area	"Arid and Semi-Arid Lands" OR "Semi-desert" OR "Desert" OR "Dry savannah" AND "Africa" OR "Every African Country Name"
Challenge addressed	"freshwater" OR "water resources" OR "groundwater" OR "surface water" OR "water basin" OR "watershed" OR "catchment area" AND "water security" OR "water scarcity", "water balance", "water availability",
Nature-based Approach	"Nature-based solutions" OR "ecological restoration" OR "ecological engineering" OR "landscape restoration" OR "green infrastructure" OR "natural infrastructure" OR "ecosystem-based" OR "climate adaptation" OR "area-based conservation" OR "nature-based" OR "rehabilitation" OR "ecological resilience" OR "risk reduction"

2.3. Inclusion and exclusion criteria

To be considered for inclusion in the review, papers were required to adhere to several specific criteria. Each study needed to focus geographically on Africa's ASALs, with studies concerning other regions automatically excluded. The subject had to address nature-based solutions for managing water resources, encompassing water conservation, sustainable water use, natural water purification, flood management, and drought resilience. Only studies describing specific interventions or practices were included, excluding conceptual (and model-based) papers that did not focus on practical interventions. A preference was shown for empirical research, including case studies, comparative analyses, longitudinal studies, and intervention evaluations, while purely theoretical papers, review articles, or opinion pieces were excluded. Eligible publications included peer-reviewed scientific articles and conference proceedings, excluding unpublished theses, non-peer-reviewed articles, personal blogs and other grey literature. Additionally, only studies published in English were considered unless an English translation was available.

Any studies not focusing on ASALs, those concentrating solely on technological or infrastructural solutions without a nature-based component, or general studies on water management in Africa without specific relevance to ASALs or nature-based solutions were excluded. Non-empirical studies, such as theoretical discussions, opinion pieces, and reviews that did not present new empirical data or analysis, were also excluded. Lastly, non-peer-reviewed sources, including grey literature, unpublished theses, and personal blogs that hadn't undergone rigorous peer review, were not considered.

2.4. Effectiveness criteria

The study evaluated the effectiveness and sustainability of NbS for water resource management, using criteria adapted from [79] and aligned with the IUCN Global Standard. The effectiveness of NbS was assessed based on their support for ecological integrity, socio-economic enhancement, and project sustainability. The criteria included:

1. *Criterion 1. Socio-economic aspects and impacts on growth, resilience, stability, public health, safety, and well-being:* The criterion examined NbS impacts on economic growth, resilience, community stability, public health, and safety. It assessed how NbS contribute to

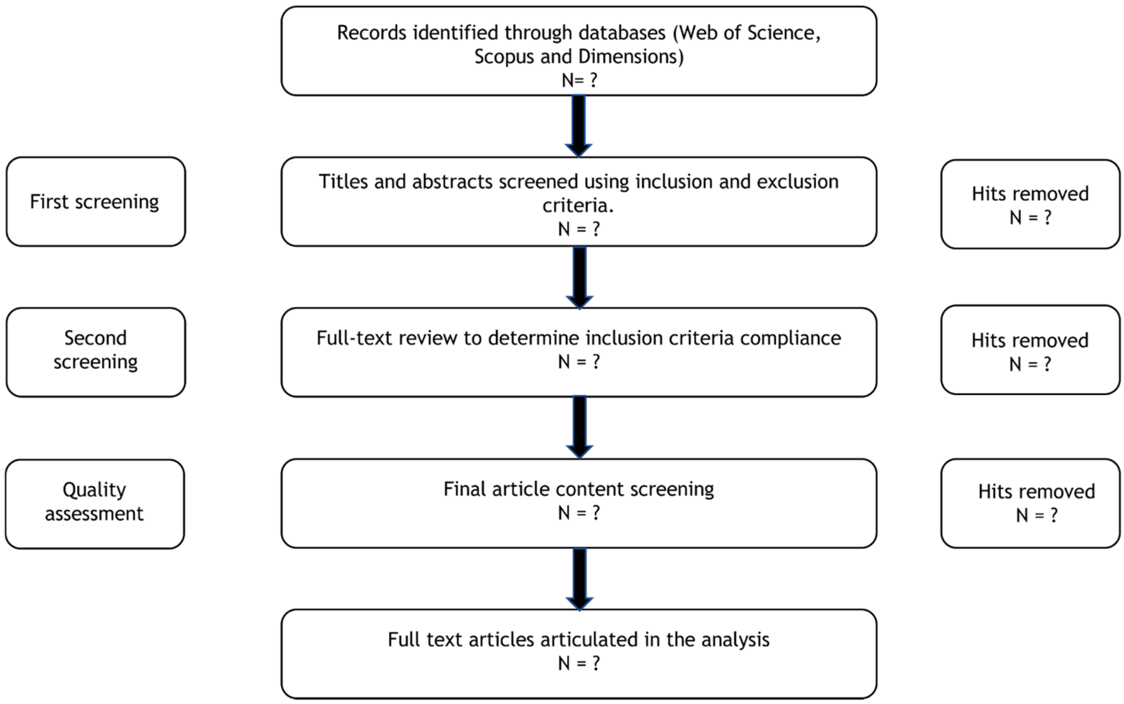

Fig. 1. A PRISMA flow diagram representing the systematic presentation of the article selection process.

sustainable development goals, including poverty reduction and enhanced community resilience to water-related challenges like droughts and floods. The criterion also considered improvements in water quality and safety from water-related disasters.

2. *Criterion 2. The sustainable use of natural and environmental resources for NbS is fundamental:* This criterion focuses on the efficiency of NbS in using water and other ecological resources. It evaluated whether NbS provide eco-efficient water management that minimises waste and optimises water usage across sectors through innovative approaches like rainwater harvesting and wetland restoration.
3. Criterion 3. Enhancement and conservation of natural and environmental resources and improving their carrying capacity: The extent to which NbS enhances and conserves natural environments crucial for water management was assessed. This included the role of forests, wetlands, and rivers in regulating water cycles and purifying water, supporting biodiversity, and providing clean water sources for human use.
4. Criterion 4. Flexibility and sustainability of infrastructure works, management opportunities for multifunctional use, and opportunities to adapt to changing circumstances: The flexibility and sustainability of NbS infrastructure were evaluated in terms of adaptability to environmental and socio-economic changes, including climate variability. The criterion also considered the multifunctional benefits of NbS, such as enhancing urban landscapes while managing stormwater.

These criteria ensured that NbS addresses immediate water management needs and supports broader environmental and social sustainability goals.

2.5. Data synthesis and analysis

The descriptive analysis in the systematic review was conducted by summarising and synthesising the extracted data from selected articles to understand the trends, themes clearly, and overall findings relevant to the research question. Initially, the data were organised into meaningful categories such as study characteristics, intervention details, outcomes measured, and critical findings, aiding in identifying patterns and trends across studies. The organised data were then presented in tables or figures to facilitate easy comparison and highlight important data points, such as the types of interventions used. A narrative synthesis was written to describe the context and results of the included studies, explaining how the findings related to the broader research question and discussing any consistent or divergent trends observed among the studies. Furthermore, findings were compared with existing literature or theoretical frameworks to assess alignment or contradictions, providing insights into areas needing further research or potential biases.

Frequency counts and percentages for each level/category summarised categorical variables. A graphical presentation was also included to visualise the data. The Chi-square test of independence was used to determine whether there was an association between any two categorical variables. This test was used because it is an excellent statistical test to determine if the difference between the observed and expected data is due to pure chance or if an association exists between the categorical variables. It is very versatile in handling categorical variables with two or more categories. Fisher's exact test was used instead of the Chi-square test when the expected values were small. The Fisher's exact test performs better than the Chi-square, where the sample size is small because the deviation from the null hypothesis is calculated exactly rather than relying on an approximation method. Cramer's V test was used to determine the strength of the association in cases where the Chi-square or Fisher's exact test showed an association between two variables. It indicates how strong or weak the association between categorical variables is. The Cramer's V values range from 0 to 1, where 0 indicates no association, and 1 indicates a perfect association between the categorical variables. Logistic regression was used to estimate the probability of meeting the effectiveness criteria based on the independent variables that showed association from the Chi-square/ Fisher's exact test. Logistic regression was also used to determine the effect of co-designing the NbS with stakeholders on incorporating indigenous knowledge. The logistic regression/modelling technique enables one to predict the probability of an event occurring based on predictor variable (s). It provides both a measure of quantifying the association between the dependent and independent variables, that is, the coefficient size and the direction of the association, whether negative or positive. R Version 4.4.0 was used for the analysis because R is open-source and facilitates good scientific practices by supporting the reproducibility of the results.

3. Results and discussion

A total of 9906 papers (N) were first found through an initial search, using basic information such as the title, abstract, and authors. Subsequently, the papers underwent an initial screening process, wherein the titles and abstracts of the initial 9906 papers were reviewed. This screening aimed to eliminate articles that were unrelated to the study subject. Papers that satisfied the inclusion criteria or necessitated additional assessment were kept. Following this stage, 526 articles met the criteria for further evaluation. However, only 180 articles focused on NbS interventions. These articles underwent a second screening and were meticulously scrutinised in their entirety. The screening process was more stringent and concentrated on assessing the content based on the specific inclusion criteria. Subsequently, the remaining articles underwent quality assessment. Upon conclusion of the process, 143 articles satisfied all the inclusion criteria and were chosen for the final evaluation (Fig. 2). This is relatively low compared to many NGOs working on conservation across Africa. This could be attributed to most African conservation projects not reporting their findings in academic journals [80].

3.1. Data extraction and analysis

The data extraction and organisation were done after meticulously reading through the 143 selected articles for the study. Each article's content was systematically dissected, with relevant information categorised into distinct variables. Excel served as the primary tool for data organisation, where the data was organised in two tables. Key variables such as type of intervention, the country where intervention was carried out, focus area (biophysical vs socio-economic), category of intervention (protection, restoration or extension), direct vs indirect impact of intervention of water resource management, study type (qualitative vs quantitative), and involvement of local communities were identified and assigned respective columns. Binary variables were coded as 1 for "yes" and 0 for "no," ensuring consistency and ease of analysis. However, a unique approach was adopted for study type classification: qualitative studies were denoted as "L," quantitative studies were denoted as "N," and studies employing both methodologies (mixed methods) as "B." This coding process laid the groundwork for both descriptive and statistical analysis. The data regarding the effectiveness and sustainability of the interventions were organised in another datasheet. Each intervention was evaluated based on these predefined criteria and systematically assessed. Each was coded with '1′ for "yes" if the study met the criterion effectively and '0′ for "no" if it did not. This binary coding allowed for a clear, visual representation of which articles covered successful and sustainable interventions according to the study's benchmarks. This method facilitated an easy comparison across different interventions, highlighting areas where each succeeded or needed improvement.

3.2. Descriptive analysis

3.2.1. Geographical distribution

The results show that most studies were in eastern, southern and western Africa (Fig. 3). Ethiopia had the highest number of studies (43), indicating a robust focus on environmental management strategies. Kenya followed with 30 studies and South Africa with 22, highlighting significant research activities related to NbS in these countries. Other countries like Burkina Faso, Ghana, Nigeria, Rwanda, Uganda, and Zimbabwe have moderate numbers ranging from 2 to 9 studies, reflecting varying degrees of investment in researching nature-based solutions. In contrast, several countries like Botswana, Democratic Republic of Congo, Niger, Senegal, South Sudan, The Gambia, Togo, Tunisia, and Zambia each report only a single study, suggesting a much lower level of research engagement, although the focus on English language articles could have affected these numbers by excluding studies from Francophone countries. Only one collaborative study among African states (between Nigeria and Ethiopia) was found, indicating limited cross-border research collaborations. Similar results of a few cross-collaborations between African countries in NbS were reported by Olago et al., 2024 [81].

The distribution of scientific articles can be attributed to environmental, socio-economic, and academic factors. Each of these countries presents unique characteristics that make them focal points for NbS

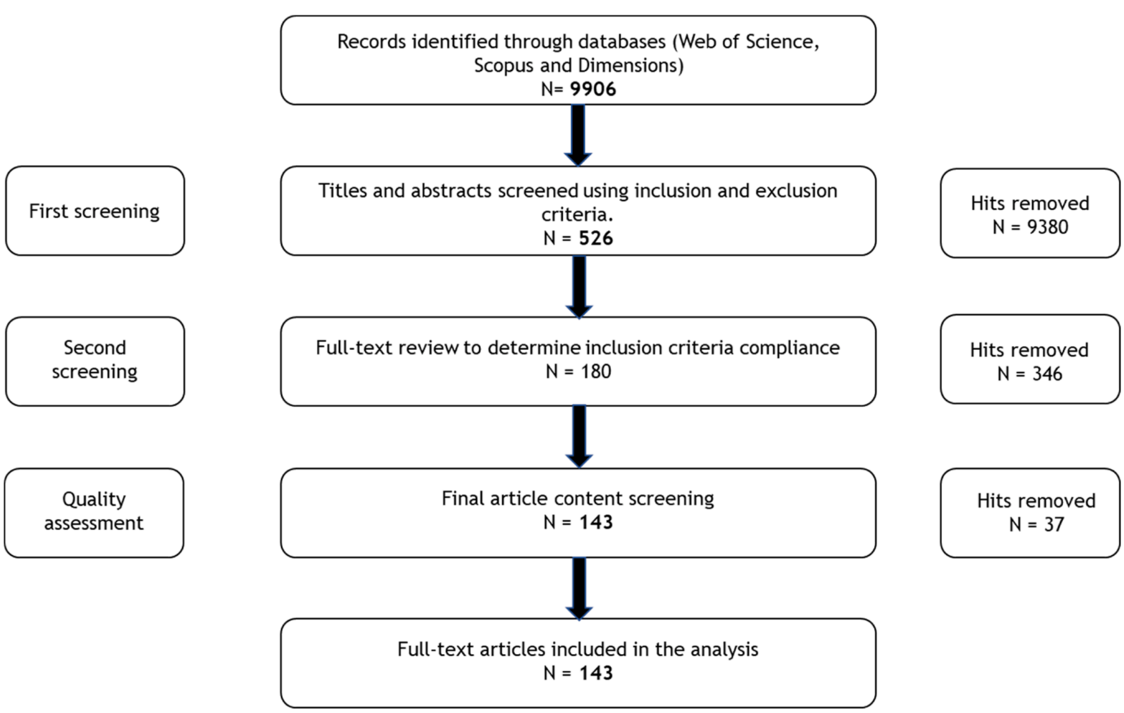

Fig. 2. A PRISMA flow diagram representing the systematic presentation of the article selection process with the number of articles filtered out at each stage.

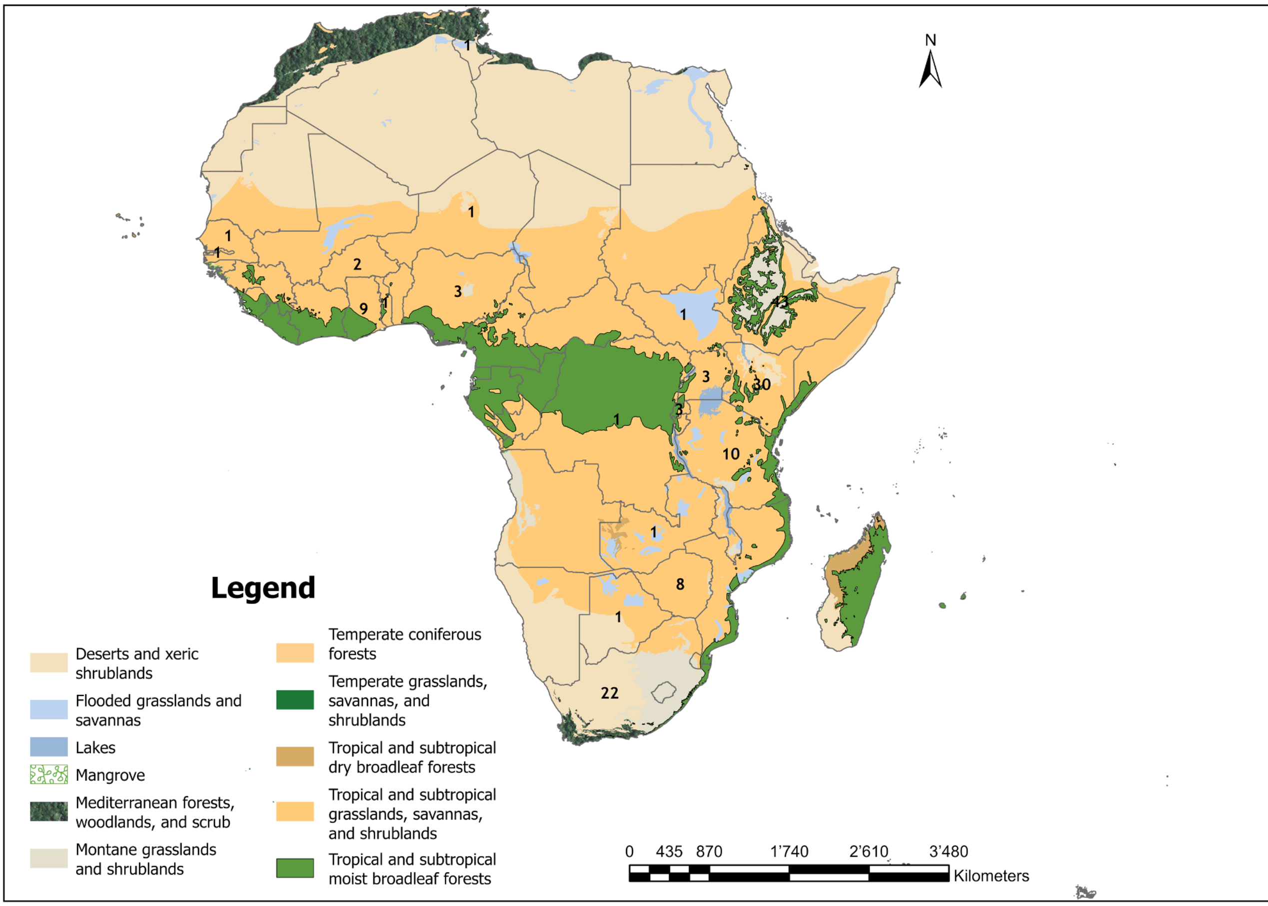

Fig. 3. Map showing the geographical distribution of articles identified in this study across Africa superimposed over a map highlighting the location of ASALs in Africa, i.e., deserts, semi-deserts and dry savannahs.

research in ASALs. Kenya, Ethiopia, Tanzania, and Zimbabwe share significant ASAL regions. For example, over 80 % of Kenya's surface area is classified as ASALs, characterised by water scarcity, periodic droughts, and environmental degradation [82,83]. These challenges necessitate innovative approaches like NbS for sustainable water and land management. In many African countries, rural and indigenous communities heavily depend on natural resources for their livelihood [84–86]. This dependency creates a strong impetus for researching and implementing NbS that supports ecosystem health and community well-being. Countries like Zimbabwe and Tanzania face socio-economic pressures from land degradation and water scarcity, driving research towards sustainable solutions [87]. Furthermore, some countries, such as Kenya and South Africa, have robust academic and research infrastructures (such as the National Research Fund in both these countries) compared to the rest of the continent [88], facilitating extensive studies and pilot projects in NbS. International collaborations and funding are more accessible in these countries, especially in Ethiopia and South Africa, enhancing their research output [89]. South Africa, Kenya, Ethiopia, Nigeria, Uganda and Ghana, all with fair to good representation among the studies here, rank among the top 10 African countries in terms of research output [90]. The presence of articles from these countries in the scientific literature can also reflect the global academic community's interest and the availability of data from these regions.

Conversely, the limited representation from other African countries might be due to less developed research capacities or lower prioritisation of NbS in national policies. The absence of literature from Northern Africa, where the Sahara Desert is, and Southern Africa, where the Kalahari Desert is, was noted in this study (Fig. 3). Northern African countries, predominantly desert, might face environmental challenges that differ from those in sub-Saharan ASALs. While water scarcity is a common issue, the specific environmental conditions and socio-economic contexts might lead to different priorities in research and policy. For example, Northern African countries may focus more on desertification control or oasis management rather than the types of NbS commonly applied in sub-Saharan ASALs. Another possible explanation could be a publication bias where studies from these regions, especially those from developing countries or non-English speaking nations, are underrepresented in international scientific literature. More than 95 % of the research papers in natural and social sciences disciplines are published in English [91], and nearly 80 % of all indexed journals are published in English [92]. Additionally, language barriers and limited access to international publishing platforms can further reduce the visibility of research from these regions [92]. This would impact Northern and Western African countries where Arabic and French are spoken predominantly. The focus of this study on English could have led to the exclusion of papers from these regions. These regions' environmental management and sustainable practices are often rooted in cultural and historical contexts. Communities in these regions have traditional or indigenous practices for managing water resources that are not labelled as NbS or documented in scientific articles [70], which could also play a role in the underrepresentation of these regions in the literature. Furthermore, the availability of data and the specific focus of researchers play a crucial role. If there is limited data availability or if researchers in these regions are focused on different aspects of environmental management, this would result in a gap in the literature, specifically about NbS. Notably, the absence of literature does not necessarily imply the absence of NbS practices in these regions. Instead, it could indicate a gap in documentation, research, or international recognition of such practices. This uneven distribution underscores the importance of enhancing research capabilities and fostering NbS initiatives across other African nations facing similar ASAL-related challenges.

3.2.2. Distribution by year

The studies reviewed were conducted each year from 1998 to 2024. The distribution of studies over the years showed a gradual increase in research activity, particularly noticeable from 2010 onwards, coinciding with the development of the NbS terminology. Only one research article was recorded for 1998 and 1999, suggesting a nascent interest in the NbS studies. The early to mid-2000s show low but slightly increasing activity, with the number of studies fluctuating between one and three per year. A noticeable surge occurred from 2010, when studies increased to five, indicating a growing interest and possibly an increase in funding or technological advancements. This upward trend continued in 2023, with 23 studies recording the highest activity level. Notably, the count decreased from 12 in 2017 to six in 2018. The subsequent years showed continued high activity with 11, 17, 21, and 16 studies from 2019 to 2022, respectively. So far, there has been one study in 2024.

3.2.3. Category of NbS

The studies covered various environmental initiatives emphasising restoration efforts, with 59 % of projects aimed at enhancing ecosystems' ecological integrity and functioning by returning ecosystems or habitats to their original state before disturbance or degradation. The high restoration prevalence indicates a significant response to environmental degradation and could coincide with the UN declaring a decade of restoration [93]. It suggests a reactive approach where efforts are concentrated on repairing damage already occurring, highlighting the need for intensive recovery measures in significantly impacted ASALs. Protection efforts, accounting for 31 % of the initiatives, focus on preserving current environmental conditions to prevent further degradation of essential ecosystems. This involves setting up protected areas, implementing sustainable management practices, and enacting regulations to conserve biodiversity and avoid overexploitation. The emphasis on protection demonstrates an awareness of the need to maintain ecological balance and prevent future environmental issues, aiming to sustain biodiversity and secure natural resources essential for life support. A smaller proportion, 8 %, involved projects that integrate both protection and restoration, designed to ensure ecosystems are restored to their former state and shielded against future threats. This dual approach maximises the resilience of ecosystems against ongoing and future challenges, reflecting a comprehensive strategy that heals past damages and guards against future vulnerabilities. Extension efforts are mentioned minimally at 1 %, likely referring to creating or expanding ecosystems beyond initial targets or areas, enhancing the scope or applying successful strategies in new contexts. Additionally, 1 % of the studies focused on a combination of restoration with extension, suggesting that these areas are ripe for development, where extending the reach of proven strategies could significantly amplify environmental benefits and indicate the potential for scaling successful practices to broader applications essential for large-scale environmental improvements (Fig. 4).

This distribution offers insights into the priorities and strategies within the ASALs in Africa, highlighting a strategic orientation towards dealing with environmental issues through reactive and proactive measures. The emphasis on restoration-related projects indicates a reactive approach to biodiversity conservation and water resource management, focusing on repairing past damage. Simultaneously, the focus on protection suggests proactive measures are valued, aiming to prevent degradation before it occurs. Integrating protection and restoration in some projects indicates a holistic strategy addressing prevention, which is essential for sustainable environmental management. The rare mention of extension alongside other categories suggests potential areas for further development, possibly indicating that creating new ecosystems is an area for future focus.

3.2.4. Focus of study

Of the 143 studies, 44 (31 %) concentrated on biophysical aspects of the environment (Fig. 4). These studies primarily delved into physical or biological conditions and processes related to natural ecosystems, examining water resources, land use, ecological impacts, etc. The focus on biophysical aspects indicates a scientific approach to understanding and managing the physical components of ecosystems and associated biodiversity. Meanwhile, 56 studies (39 %) prioritised socioeconomic issues, indicating a substantial emphasis on the interplay between economic activity and social processes within environmental management. These studies explored themes such as economic growth, public health, community stability, and the socioeconomic impacts of environmental policies and practices, reflecting a strong inclination towards integrating social and economic considerations into ecological strategies. Furthermore, 43 studies (30 %) addressed both biophysical and socioeconomic

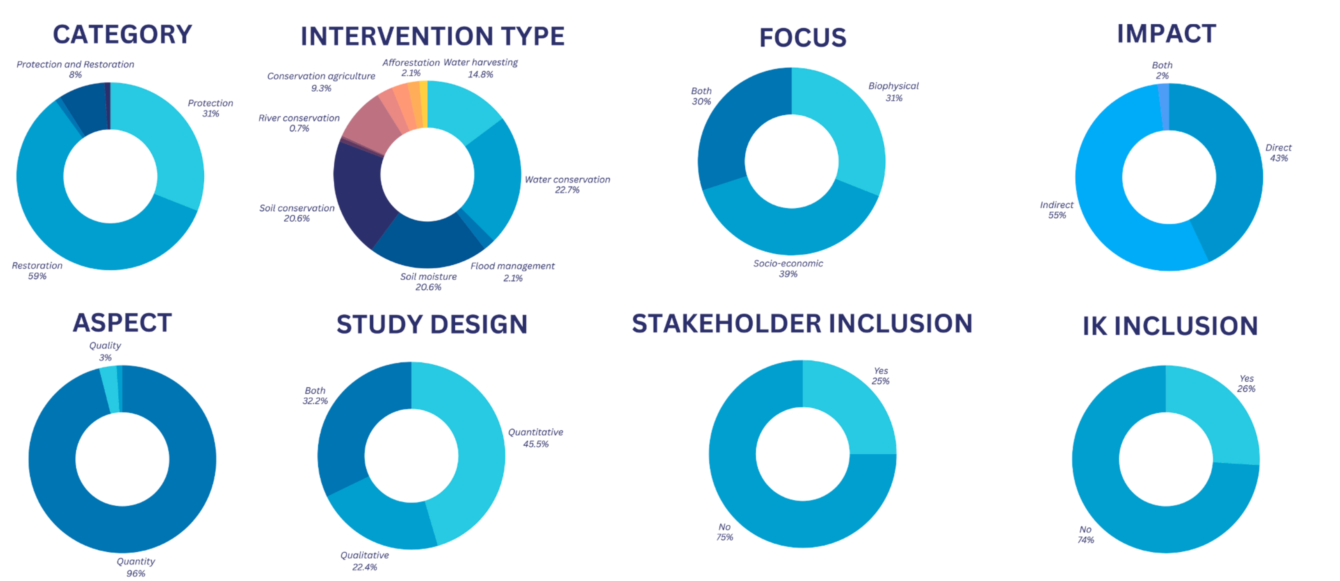

Fig. 4. Graphs showing the results of the category of NbS, type of intervention implemented, the focus of the intervention, impact of the intervention of water resources, aspect of water resources addressed, design of the study, level of stakeholder and Indigenous knowledge inclusion

dimensions, embodying a comprehensive environmental and resource management approach. This integrative focus highlights the complex interdependencies between the physical environment and the social or economic structures that influence human life. This thematic distribution within the studies illustrates the diverse orientations in environmental research and the nearly equal division between scientific (biophysical) and humanistic (socioeconomic) components. This is the crux of NbS, as integrating biophysical and socio-economic considerations is essential for its success. It is important to note that this section discusses the focus of the studies on the impacts of the interventions and not on the overall goals of the interventions.

3.2.5. Impact on water resources

The effects of water resource management were categorised into direct and indirect impacts. Of the studies analysed, 43 % had direct impacts, which are the immediate and observable consequences of water resource management on the biophysical and socioeconomic environment (Fig. 4). These direct impacts, detailed in 62 studies, include changes in water quality, hydrological alterations, and immediate effects on local communities, flora, and fauna. Such studies punctuate the significance of addressing and mitigating immediate threats to water resources, highlighting the need for responsive strategies to quickly counteract or minimise adverse effects on water systems, thereby protecting ecosystems, human well-being, and water quality. On the other hand, 55 % of the studies explored indirect impacts, which encompass a broader spectrum of effects extending beyond immediate environmental alterations. These impacts, discussed in 78 studies, include long-term ecological changes, socio-economic repercussions such as impacts on community livelihoods, public health, and economic stability, as well as broader policy implications. Indirect impacts, which may not have been the primary focus of the intervention, often result from complex ecological and socio-economic pathways, such as changes in water availability downstream due to upstream interventions or long-term alterations to the water cycle from land use changes. Interventions such as soil conservation and soil moisture are good examples of indirect impacts, where protecting or restoring soil impacts water quality and quantity. A few studies (2 %) involved interventions addressing direct and indirect impacts. The substantial attention to direct and indirect impacts demonstrates a comprehensive approach, recognising environmental and human activities' immediate and long-term consequences. This balance is vital for developing effective water management policies that are reactive to immediate problems and proactive in preventing future issues. The slight preference for studies on indirect impacts suggests a nuanced understanding within the academic and practical fields of water resource management, acknowledging that the effects extend far beyond the immediate environmental changes. This reflects a holistic approach, considering the extended repercussions that can influence various societal and ecological components. It is essential for researchers, policymakers, and practitioners as they develop strategies and interventions to manage water resources sustainably and responsibly.

3.2.6. Aspects of water addressed

The studies emphasised water quantity much more than quality, with 137 entries (96 %) accounting for this (Fig. 4). This overwhelming focus highlights the critical importance of water supply issues in African ASALs, with most studies concentrating on water availability, access, and volume. The extensive concern with the quantity of water encompasses studies on water availability, water distribution, water use efficiency, and other quantitative aspects, underlining that the primary concern in most studies or interventions is how much water is available or utilised. Conversely, only four studies, representing 3 % of the total, concentrate exclusively on water quality. These studies focus on water's chemical, physical, and biological characteristics, assessing pollutants and the overall health of water systems crucial for ecosystem vitality and human health. The relatively low percentage of studies on water quality indicates that while it is an important aspect, it may not be the central focus as frequently as water quantity within the study area.

Furthermore, a minimal number of 2 studies (1 %) address both quantity and quality. This rare but holistic approach to water management considers the amount of water available and its suitability for various uses, recognising the interconnectedness of these aspects in sustainable water management. These interdisciplinary studies are essential for comprehensive water management strategies. The analysis reveals a potential gap in integrating water quality issues within the broader research agenda, which could be crucial for developing comprehensive water resource management strategies. The dominance of water quantity issues suggests that concerns about water scarcity, allocation, and usage are paramount in the fields or regions represented in the studies. Global issues of water stress, the need for efficient water management in agriculture, industry, and urban settings, or the impacts of climate change on water availability could be the drivers of this focus. In contrast, the lesser emphasis on water quality might highlight a need for increased focus in this area, especially considering the growing challenges of pollution and the need for clean water to sustain human health and ecosystems. The studies that address quantity and quality reflect a holistic approach, which is essential for ensuring sustainable water management that meets supply and safety standards.

3.2.7. Study design

In the studies analysed, nearly half of the studies, accounting for 45 %, are quantitative methodologies, utilising numerical data and statistical methods to explore various variables (Fig. 4). This significant emphasis on quantitative methods points to a strong preference for data-driven insights within the research community, particularly relevant in fields such as environmental sciences, where precise measurements and data analysis are pivotal. Approximately one-third of the studies, or 32 %, employ a mixed-methods approach, integrating qualitative and quantitative techniques. This comprehensive strategy allows for a deeper and broader understanding of the research topics by combining numerical analysis with contextual insights from qualitative methods. Moreover, over 23 % of the studies are qualitative, focusing on non-numerical data to delve into concepts, opinions, or experiences. This is vital for understanding complex issues such as human behaviours, social processes, and contextual factors. The distribution of these methodological approaches offers valuable insights into the preferences and requirements within the research community. The prevalence of quantitative research highlights the importance of empirical evidence and measurable outcomes. In contrast, the significant use of mixed methods reflects the value of integrating diverse data types to enrich the analysis and conclusions, providing a holistic view of the research questions. A considerable proportion of qualitative studies emphasises their critical role in areas where numerical data alone might not fully capture the nuances, such as in studies focusing on community perceptions, policy impacts, or cultural factors.

3.2.8. Stakeholder involvement

A quarter of the studies (25 %) report that the NbS interventions were co-designed with stakeholders, involving collaborative planning and development with input from local communities, governments, and other relevant parties (Fig. 4). This collaborative approach enhances the solutions' relevance, acceptance, and effectiveness. However, over 74 % of the entries indicate that the NbS were either not co-designed with stakeholders or the stakeholder involvement was not reported. This suggests various implementation strategies, from top-down approaches to scenarios where stakeholder input was not deemed necessary or feasible. Despite the recognised benefits of such collaboration, the relatively low percentage of NbS projects co-designed with stakeholders highlights several critical considerations. Engagement challenges such as logistical issues, community resistance, or lack of resources might impede effective stakeholder involvement. This is crucial for ensuring that projects are well-adapted to local contexts and have the support needed for long-term success. Projects not co-designed with stakeholders may face challenges in acceptance and sustainability, as stakeholder involvement often plays a critical role in project success.

This situation presents a significant opportunity to enhance stakeholder engagement in NbS projects. By improving collaborative approaches, the outcomes and acceptance of these projects could be significantly improved, especially in sensitive or complex environmental and social contexts. Recognising the gap in co-design can motivate

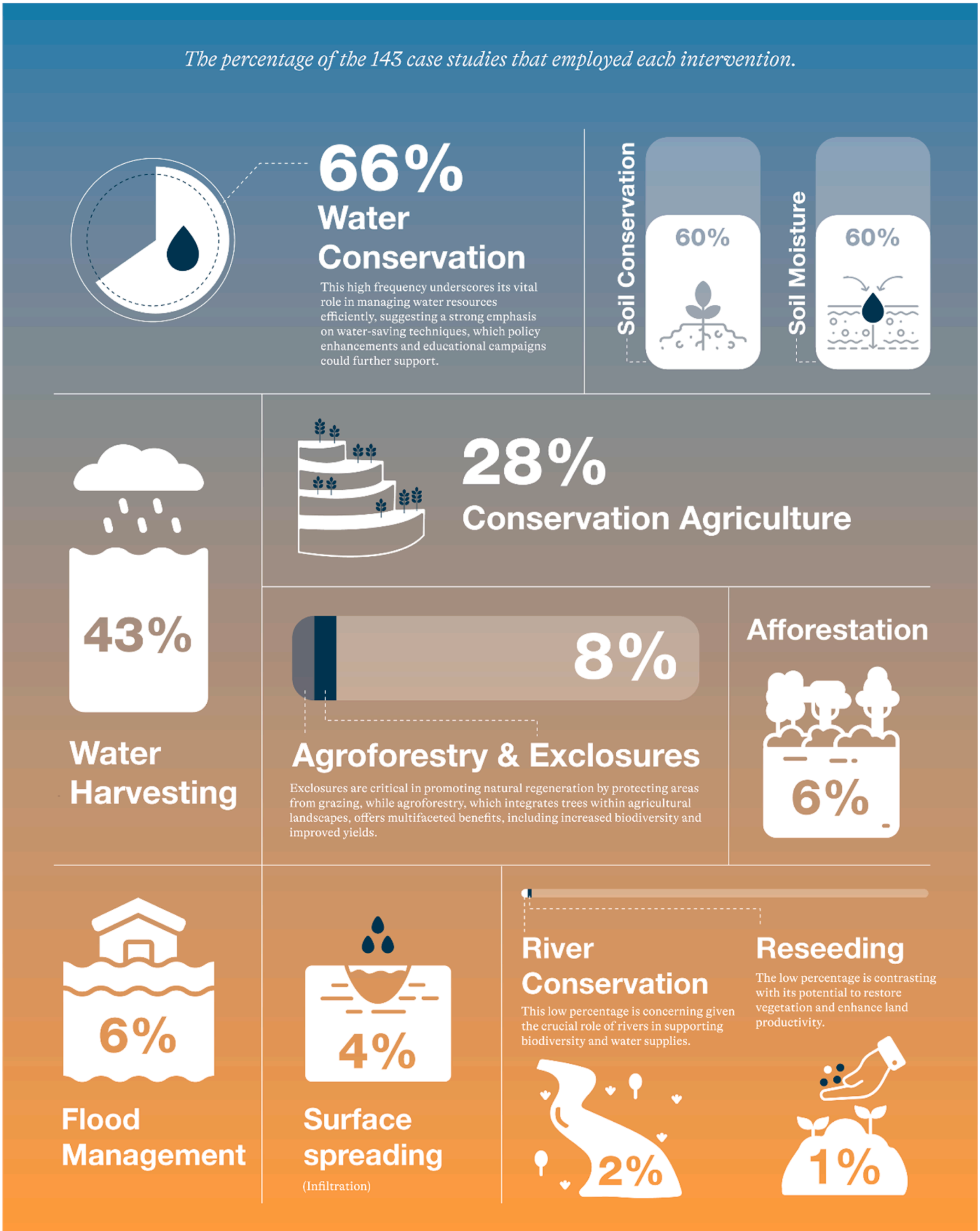

Fig. 5. A graphical representation of the percentage of the studies that employed each intervention (infographic created by Daria Vuistiner)

researchers, project managers, and policymakers to seek more robust engagement strategies to ensure that NbS are effective and supported by those they impact. This analysis underscores the importance of stakeholder involvement in environmental and sustainability projects. It serves as a call to action for increasing participation in the planning and development phases of NbS, ensuring that these initiatives effectively achieve their goals and are supported by the communities they serve.

3.2.9. *Incorporation of indigenous knowledge*

Approximately 26 % of the articles reviewed in this study indicated incorporating indigenous knowledge in the NbS interventions, acknowledging the value of traditional ecological knowledge and practices in enriching understanding and solutions, especially within environmental and resource management contexts (Fig. 4). Conversely, most studies (around 74 %) did not include indigenous knowledge (or report on its inclusion), which may reflect a range of issues from its perceived relevance in specific contexts to barriers in accessing or integrating such knowledge effectively. Incorporating indigenous knowledge in some studies demonstrates a valuable approach to leveraging local, culturally grounded insights into natural resource management, sustainability, and conservation practices. However, the relatively low percentage of studies integrating Indigenous knowledge highlights potential barriers, such as lack of awareness, insufficient engagement with Indigenous communities, or methodological challenges in merging traditional knowledge with scientific research. The findings suggest significant opportunities for enhancing solutions through increased integration of indigenous knowledge, which could lead to more holistic and culturally appropriate approaches that are critical in projects related to environmental conservation and community-based management. These results could inform policymakers and research institutions about the need to create more inclusive frameworks that facilitate the integration of indigenous perspectives and knowledge systems into mainstream research and project design. This analysis underlines the importance of incorporating diverse knowledge systems in research and development projects aimed at ecological and social sustainability. It suggests a crucial direction for future research and policymaking to ensure that environmental and community management projects are informed by a broad range of insights and practices, enhancing their effectiveness and relevance.

3.2.10. *Type of interventions*

A total of 12 NbS interventions were identified in the 143 studies (Fig. 5). Most of the projects deployed more than one intervention. Water conservation, pivotal for sustainable water management, was the most prevalent intervention in 66 % of the studies [94–102]. This high frequency indicates its vital role in managing water resources efficiently, suggesting a strong emphasis on water-saving techniques, which policy enhancements and educational campaigns could further support. Soil moisture and soil conservation were the second most used interventions, each reported in 60 % of studies [103–118]. This points to the critical importance of these practices in maintaining agricultural productivity, ecosystem health, and water resource management. Water harvesting, such as zai pits [119–121], borrow pits [122,123], and rainwater harvesting at the household level [124,125], among others, has emerged as a significant practice, with 43 % of studies focusing on it, highlighting a heightened awareness of water scarcity issues and emphasising the critical need to capture and store rainwater for agricultural and domestic purposes. Conservation agriculture was reported in 28 % of the studies, reflecting a commitment to sustainable farming practices like no-till agriculture and crop rotation that bolster soil health and reduce erosion, linked to higher water retention rates, supporting groundwater recharge [126–134]. Both exclosures and agroforestry were implemented in 8 % of studies each. Exclosures are critical in promoting natural regeneration by protecting areas from grazing [135–142], while agroforestry [99,143–148], which integrates trees within agricultural landscapes, offers multifaceted benefits, including increased biodiversity and improved yields. Afforestation was pursued in 6 % of studies [145,147,149,150], emphasising efforts to establish new forest areas vital for carbon sequestration and habitat restoration. Flood management was also reported in only 6 % of the studies [134, 151–156], highlighting the acute need to manage flood risks in ASALs with strategies like flood barriers and improved drainage systems to mitigate economic losses and protect lives. Surface spreading and infiltration, documented in 4 % of the studies [157,158], suggest a potential undervaluation or implementation challenges of this technique, particularly in urban settings where impermeable surfaces hinder natural water absorption. This indicates a need for increased awareness and adaptation of methods suited to different environmental contexts. River conservation was markedly less reported at only 2 % [159–161], indicating possible regional variations in priorities or integration into broader strategies that were not explicitly identified. This low percentage is concerning given the crucial role of rivers in supporting biodiversity and water supplies. Finally, reseeding degraded lands to restore grazing lands [105,162] appeared minimally practised, cited in only 1 % of the studies, contrasting with its potential to restore vegetation and enhance land productivity, especially in areas impacted by disturbances or degradation.

3.2.11. *Effectiveness criteria*

A slight majority, approximately 52 % (Fig. 6), of the studies meet all four defined effectiveness criteria, indicating that over half are considered effective across dimensions like socio-economic impacts, environmental resource use, conservation efforts, and infrastructure flexibility. This reflects a strong alignment with comprehensive effectiveness standards. Conversely, nearly 48 % of the studies fail to meet all four criteria, suggesting gaps in how effectively these projects achieve broad effectiveness goals, possibly due to limitations in scope, methodology, or focus areas that do not cover all criteria comprehensively.

The detailed analysis of "Effectiveness criteria" is as follows:

- Socio-economic aspects: Most studies, with an 85 % mean agreement, affirmed positive socio-economic impacts, such as growth and public health, with a low standard deviation of 0.355, indicating strong consensus, showing widespread recognition of socio-economic benefits.
- Use of natural and environmental resources: This criterion showed the highest agreement rate, at 90 %, with a low standard deviation of 0.298, suggesting consistent responses that effectively acknowledge using natural resources in most interventions.
- Enhancement and conservation of natural resources: About 89 % of the studies showed a positive relation with this criterion, reflecting a strong consensus on resource conservation and enhancement. Most

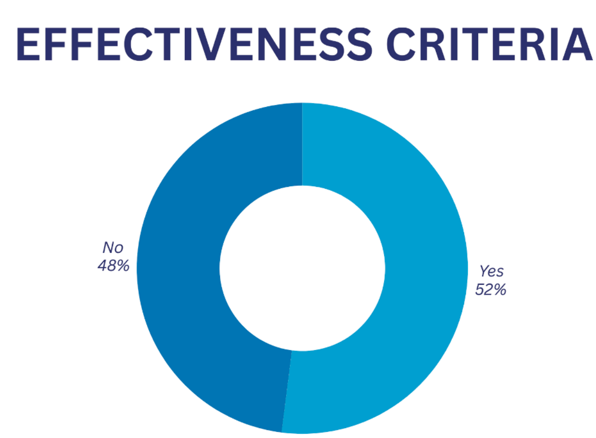

Fig. 6. Graphical representation of the results of studies that met the effectiveness criteria.

studies recognised the benefits of such efforts despite a slightly higher standard deviation of 0.316 compared to other criteria.

- Flexibility and sustainability of infrastructure: The mean agreement for this criterion is 71 %, the lowest among the four. This indicates more variability in responses, with a standard deviation of 0.457. This suggests that a majority still recognise the flexibility and sustainability of infrastructure despite diverse assessments.

This comprehensive analysis highlights the strengths and illuminates areas where consensus is strong and opinions diverge significantly, guiding future studies and interventions towards addressing all effectiveness criteria comprehensively. For researchers and practitioners, this information is crucial for designing and implementing projects that address these criteria effectively. Policymakers can use these insights to inform policy decisions and funding allocations, emphasising support for approaches that demonstrate comprehensive effectiveness. Strategic planners in organisations can leverage this analysis to review project portfolios, identify trends in effectiveness, and adjust strategies accordingly. This benchmark assesses studies' quality and impact to maximise the efficacy in tackling critical socio-economic and environmental challenges.

3.3. Statistical analysis

3.3.1. Tests of association

Table 2 provides the results of the association tests between the categorical variables. The focus of the interventions was associated with the stakeholders' engagement in co-designing the NbS interventions ($p = 0.0002$), incorporation of indigenous knowledge ($p = 0.0420$) and the study type/methodology employed ($p = 0.0062$). This implies that stakeholders' engagement and incorporation of indigenous knowledge would impact what the interventions focused on. It also implies that the focus of the intervention influences the methodology used to assess it (e.g., quantitative methods are likely to be used to evaluate interventions focusing on biophysical aspects of ecosystems). The impact on water resources was only associated with the effectiveness of the study ($p = 0.0001$). Co-designing with the stakeholders was associated with the incorporation of indigenous knowledge ($p = 0.0001$), the effectiveness of the intervention ($p = 0.0079$) and the study type ($p = 0.0475$), suggesting that involvement of stakeholders in the planning and implementation of NbS interventions will have a net positive effect on the probability of success of the project.

3.3.2. Strength of the association

The Cramer's V test was used to measure the strength of association between variables that showed association from the Chi-square/Fisher's exact test of independence. Table 3 provides the results of the test. Co-designing the NbS with stakeholders and incorporation of the indigenous solutions showed the highest level of Cramer's V of 0.3563, followed by impact on the water resource and effectiveness of the study at 0.3472 and focus of the intervention and stakeholders' co-designing at 0.3411. However, all the Cramer's V values were closer to 0 than to 1, suggesting that the associations between the variables were not very strong.

3.3.3. Factors associated with the effectiveness of the study

Table 4 presents the results of the factors associated with the study's effectiveness of the interventions both for the univariate (unadjusted) and the multivariable (adjusted) analyses. Studies that focused on the direct impact on water resources had 74 % less odds of meeting the effectiveness criteria than studies that focused on the indirect impact on water resources. Additionally, studies co-designed with the stakeholders had 229 % odds of meeting the effectiveness criteria compared to those not co-designed with the stakeholders. For the adjusted analysis, the odds of meeting the effectiveness criteria slightly changed to 77 % less for studies that focused on the direct impact on water resources than studies that focused on the indirect impact on water resources. Regarding co-designing with the stakeholders, the studies that included co-design with the stakeholders had 284 % odds of meeting the effectiveness criteria compared to those not co-designing with the stakeholders while holding other factors constant, further making a case for the need to co-design projects with relevant stakeholders.

3.3.4. Effect of Co-designing with stakeholders on incorporation of indigenous knowledge

Table 5 presents the results of the effect of co-designing nature-based solutions with stakeholders on the incorporation of indigenous knowledge. Co-designing nature-based solutions with stakeholders increases the odds of incorporating indigenous knowledge by 453 % more than

Table 3
Results of the Cramer's V test of association

Variable 1	*Variable 2*	*Cramer's V*
Focus	*Stakeholders*	*0.3411*
	Indigenous	*0.2106*
	Study type	*0.2242*
Impact	*Effectiveness*	*0.3472*
Stakeholders	*Indigenous*	*0.3563*
	Effectiveness	*0.2383*
	Study type	*0.2064*

Table 2
P-values of Chi-square and Fisher's tests of independence. Significant correlations ($p < 0.05$) are highlighted.

	Focus	Impact	Aspect	Stakeholders	Indigenous	Effectiveness	Study type
Focus		0.3019	0.0962	0.0002	0.0420	0.4266	0.0062
Impact			0.6026	0.2552	0.0865	0.0001	0.4361
Aspect				1.0000	1.0000	0.3668	0.1063
Stakeholders					0.0001	0.0079	0.0475
Indigenous						0.0977	0.6878
Effectiveness							0.4677
Study type							

Table 4
Logistic regression results of the factors associated with the study's effectiveness in addressing freshwater resource management.

Variable	Unadjusted		Adjusted	
	OR (95 % CI)	p-value	aOR (95 % CI)	p-value
Impact				
Indirect (ref)	1		1	
Direct	0.259 (0.126-0.519)	0.0002	0.226 (0.105-0.469)	0.0001
Stakeholder				
No (ref)	1		1	
Yes	3.294 (1.460-8.031)	0.0057	3.836 (1.585-10.098)	0.0041

Note: 3 observations that focused on both direct and indirect impacts on water resources were dropped in the univariate model of impact and the adjusted model.

Table 5
Logistic regression results on the effect of co-designing with stakeholders on incorporating indigenous knowledge.

Variable	OR (95 % CI)	p-value
Stakeholder		
No (ref)	1	
Yes	5.526 (2.438-12.859)	0.0001

those not co-designed with stakeholders.

Even though the focus showed an association with stakeholders, indigenous people, and study type, we would not further quantify the association across the different categories/levels through modelling, given that it has a third category focusing on biophysical and socio-economic interventions. Interpretation from such would not be useful programmatically.

4. Conclusions

The systematic review highlights the important role of Nature-based Solutions (NbS) in mitigating water scarcity and bolstering ecosystem resilience in Africa's ASALs. These interventions, including water conservation, soil moisture management, water harvesting, and agroforestry, demonstrate significant potential in enhancing water availability, addressing biodiversity loss, and fostering sustainable livelihoods, in line with SDGs 6 and 15 and GBF. However, the success of these solutions is closely linked to their design and implementation strategies. A key finding from the review is the critical importance of stakeholder engagement in the co-design of NbS projects. Interventions that integrated local knowledge and involved communities throughout the planning and execution phases were more likely to achieve effectiveness criteria and sustain long-term benefits. Furthermore, while most studies have concentrated on water quantity, there is a notable gap in addressing water quality, pointing to the need for a more comprehensive approach to water resource management. Geographically, the research has been predominantly focused on eastern, southern, and western Africa, leaving significant gaps in northern and central regions. This uneven distribution indicates the need for broader research efforts to understand the diverse challenges and opportunities across the continent.

To enhance the effectiveness and sustainability of NbS, future projects should prioritise the involvement of local communities and stakeholders from the planning stages to implementation. This approach ensures that interventions are culturally appropriate, widely accepted, and effectively meet local needs. Moreover, there is a pressing need to incorporate water quality considerations into NbS projects. Future research and interventions should adopt a holistic approach addressing water quantity and quality to ensure comprehensive water security. Efforts should also be made to conduct more research in underrepresented regions, particularly in northern and central Africa. The results should be mainstreamed in cases where research is being carried out. This expanded focus will help develop context-specific NbS to address unique regional challenges. Additionally, integrating indigenous knowledge into NbS can significantly enhance the relevance and effectiveness of interventions. These measures would address the challenges that led to 48 % of the studies being ineffective in addressing water-related challenges before scaling up NbS interventions. Policies and projects should facilitate merging traditional ecological knowledge with scientific approaches. Finally, promoting interdisciplinary collaboration is crucial for the success of NbS. Effective solutions require the integration of ecological, socio-economic, and technological perspectives. Encouraging interdisciplinary research and partnerships can lead to innovative and sustainable solutions. Such collaborations would include international cooperation as many water basins in ASALs transcend national borders. The collaborations would also encourage data sharing among organisations, enhancing monitoring and, ultimately, the effectiveness of the interventions. While including grey literature in future reviews would capture the data from NbS interventions carried out by NGOs but not available in scientific publications, implementing organisations should enhance their monitoring programmes and endeavour to publish their findings in publications with a broader reach. By addressing these recommendations, stakeholders can significantly improve the effectiveness and sustainability of NbS, contributing to better water resource management and climate resilience in Africa's ASALs.

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NbS impacts and implications

The study highlights that NbS offer significant environmental, economic, and social benefits. Environmentally, NbS support biodiversity conservation and ecosystem restoration through reforestation and habitat restoration. Economically, they provide cost-effective alternatives to conventional infrastructure by enhancing ecosystem services. Socially, NbS improve human well-being, foster community resilience, and enhance sustainable land management practices.

CRediT authorship contribution statement

Cornelius Okello: Writing – original draft, Validation, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Yvonne Wambui Githiora:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Simangele Sithole:** Writing – review & editing, Visualization, Formal analysis, Data curation, Conceptualization. **Margaret Awuor Owuor:** Writing – review & editing, Supervision, Methodology, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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References

[1] J-F Bastin, N Berrahmouni, A Grainger, D Maniatis, D Mollicone, R Moore, et al., The extent of forest in dryland biomes 356 (2017). https://www.science.org/doi/10.1126/science.aam6527.

[2] NN Omoyo, J Wakhungu, S Oteng'i, Effects of climate variability on maize yield in the arid and semi arid lands of lower eastern Kenya, Agric. Food Secur. 4 (2015), https://doi.org/10.1186/s40066-015-0028-2.

[3] DA Amwata, DM Nyariki, Climate variability, land-use, pastoral and agropastoral livelihoods in Arid and Semi-Arid Areas of Kenya, World J. Innov. Res. 10 (2021), https://doi.org/10.31871/wjir.10.5.38.

[4] E Umukiza, R Ntole, SR Chikavumbwa, E Bwambale, D Sibale, Z Jeremaih, et al., Rainwater harvesting in arid and semi-arid lands of Africa: challenges and opportunities, Acta Scientiarum Polonorum, Formatio Circumiectus 22 (2023) 41–52, https://doi.org/10.15576/ASP.FC/2023.22.2.03.

[5] Wambua BN. Analysis of the current and potential future climate hazards and their impacts on livelihoods and adaptation strategies in Arid and Semiarid Lands. 2019.

[6] CL Free, GS Baxter, CR Dickman, LKP. Leung, Resource pulses in desert river habitats: productivity-biodiversity hotspots, or mirages? PLoS. One 8 (2013) https://doi.org/10.1371/journal.pone.0072690.

[7] G Koech, GO Makokha, CN. Mundia, Climate change vulnerability assessment using a GIS modelling approach in ASAL ecosystem: a case study of Upper Ewaso Nyiro basin, Kenya. Model Earth Syst. Environ. 6 (2020) 479–498, https://doi.org/10.1007/s40808-019-00695-8.

[8] EC Koskei, JJ Kitetu, CW. Recha, Analysis of spatial variability in rainfall trends in Baringo County, Kenya, Afr. J. Environ. Sci. Tech. 12 (2018) 296–304, https://doi.org/10.5897/AJEST2016.2214.

[9] JR Goheen, TM Palmer, GK Charles, KM Helgen, SN Kinyua, JE Maclean, et al., Piecewise disassembly of a large-herbivore community across a rainfall gradient: the UHURU Experiment, PLoS. One 8 (2013), https://doi.org/10.1371/journal.pone.0055192.

[10] J Davis, A Pavlova, R Thompson, P. Sunnucks, Evolutionary refugia and ecological refuges: Key concepts for conserving Australian arid zone freshwater biodiversity under climate change, Glob. Chang. Biol. 19 (2013) 1970–1984, https://doi.org/10.1111/gcb.12203.

[11] E. López-López, Editorial: Freshwater Ecosystems in Arid and Semiarid Zones Facing Multiple Stressors: Human Disturbances, Climate Change, and Dryland River Conservation, Front. Environ. Sci. 9 (2021), https://doi.org/10.3389/fenvs.2021.814225.

[12] Wale HA, Dejenie T. Dryland Ecosystems: Their Features, Constraints, Potentials and Managements. vol. 2. 2013.

[13] R. Aroca, Plant responses to drought stress: From morphological to molecular features, Springer-Verlag, Berlin Heidelberg, 2013, https://doi.org/10.1007/978-3-642-32653-0.

[14] KU Ekwealor, CB Echereme, TN Ofobeze, GC. Ukpaka, Adaptive strategies of desert plants in coping with the harsh conditions of desert environments: a review, Int. J. Plant Soil. Sci. (2020) 1–8, https://doi.org/10.9734/ijpss/2019/v31i530224.

[15] Hasanuzzaman M, Tanveer M. Salt and drought stress tolerance in plants: signaling networks and adaptive mechanisms. 2020.

[16] T. Alemneh, Adaptation strategies of farm animals to water shortage in desert areas, Am. J. Biomed. Sci. Res. 2 (2019) 245–250, https://doi.org/10.34297/ajbsr.2019.02.000617.

[17] AT Conkey, C Purchase, R Richer, N. Yamaguchi, Terrestrial biodiversity in arid environments: one global component of climate crisis resilience, Gulf Studies 9 (2023) 229–256, https://doi.org/10.1007/978-981-19-7398-7_13, volSpringer.

[18] V Sejian, R Bhatta, JB Gaughan, FR Dunshea, N. Lacetera, Review: adaptation of animals to heat stress, Animal. 12 (2018) S431–S444, https://doi.org/10.1017/S1751731118001945.

[19] R Woodroffe, D Rabaiotti, DK Ngatia, TRC Smallwood, S Strebel, HMK O'Neill, Dispersal behaviour of African wild dogs in Kenya, Afr. J. Ecol. 58 (2020) 46–57, https://doi.org/10.1111/aje.12689.

[20] R Woodroffe, R Groom, JW. McNutt, Hot dogs: High ambient temperatures impact reproductive success in a tropical carnivore, J. Animal Ecology 86 (2017) 1329–1338, https://doi.org/10.1111/1365-2656.12719.

[21] Vorste R Vander, R Sarremejane, T Datry, Intermittent Rivers and Ephemeral Streams: A Unique Biome With Important Contributions to Biodiversity and Ecosystem Services, in: Encyclopedia of the World's Biomes: Volumes 1-5, 1–5, 2020, https://doi.org/10.1016/B978-0-12-409548-9.12054-8 volElsevierp. V4-419-V4-429.

[22] S Sabater, X Timoner, G Bornette, M De Wilde, JC Stromberg, JC. Stella, The Biota of Intermittent Rivers and Ephemeral Streams: Algae and Vascular Plants. Intermittent Rivers and Ephemeral Streams: Ecology and Management, Elsevier Inc. (2017) 189–216, https://doi.org/10.1016/B978-0-12-803835-2.00016-4.

[23] R Sarremejane, ML Messager, T. Datry, Drought in intermittent river and ephemeral stream networks, in: Ecohydrology, 15, John Wiley and Sons Ltd, 2022, https://doi.org/10.1002/eco.2390.

[24] F Sheldon, SE Bunn, JM Hughes, AH Arthington, SR Balcombe, CS. Fellows, Ecological roles and threats to aquatic refugia in arid landscapes: Dryland river waterholes, Mar. Freshw. Res. 61 (2010) 885–895, https://doi.org/10.1071/MF09239.

[25] WWF, Living Planet Report 2022 – Building a nature-positive society, WWF, Gland, 2022.

[26] IPCC. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press 2013:1535. https://www.ipcc.ch/report/ar5/wg1/ (accessed June 18, 2020).

[27] CS Mbuli, LN Fonjong, AJ. Fletcher, Climate change and small farmers' vulnerability to food insecurity in Cameroon, Sustainability. 13 (2021) 1523, https://doi.org/10.3390/SU13031523, 2021, Vol 13, Page 1523.

[28] T Erkossa, TO Williams, F. Laekemariam, Integrated soil, water and agronomic management effects on crop productivity and selected soil properties in Western Ethiopia, Int. Soil Water Conserv. Res. 6 (2018) 305–316, https://doi.org/10.1016/j.iswcr.2018.06.001.

[29] PA Williams, O Crespo, M Abu, NP. Simpson, A systematic review of how vulnerability of smallholder agricultural systems to changing climate is assessed in Africa, Environ. Res. Lett. 13 (2018) 103004, https://doi.org/10.1088/1748-9326/AAE026.

[30] T. Gebretsadik, Causes for Biodiversity Loss in Ethiopia: A Review from Conservation Perspective, 6, Online, 2016.

[31] A. Hussein, Factors of Biodiversity Loss and Conservation difficulties and opportunities in Ethiopia: systematic review, Biodivers. J. 13 (2022) 145–154, https://doi.org/10.31396/biodiv.jour.2022.13.1.145.154.

[32] Rathoure AK, Patel UR. Climate Conditions and Biodiversity Decline: Impact Assessment. https://ServicesIgi-GlobalCom/Resolvedoi/ResolveAspx?Doi=104018/978-1-7998-1226-5Ch005 2020:79–94. https://doi.org/10.4018/978-1-7998-1226-5.CH005.

[33] P Bridgewater, M Régnier, RC. García, Implementing SDG 15: Can large-scale public programs help deliver biodiversity conservation, restoration and management, while assisting human development? Nat. Resour. Forum. 39 (2015) 214–223, https://doi.org/10.1111/1477-8947.12084.

[34] S. Hoffmann, Challenges and opportunities of area-based conservation in reaching biodiversity and sustainability goals, Biodivers. Conserv. 31 (2022) 325–352, https://doi.org/10.1007/s10531-021-02340-2.

[35] P Katila, CJP Colfer, W de Jong, G Galloway, P Pacheco, G. Winkel, Sustainable development goals: Their impacts on forests and people, Cambridge University Press, 2019, https://doi.org/10.1017/9781108765015.

[36] AG. Omisore, Attaining Sustainable Development Goals in sub-Saharan Africa; The need to address environmental challenges, Environ. Dev. 25 (2018) 138–145, https://doi.org/10.1016/J.ENVDEV.2017.09.002.

[37] V Galvez, R Rojas, G Bennison, C Prats, E. Claro, Collaborate or perish: water resources management under contentious water use in a semiarid basin, Int. J. River Basin Manage. 18 (2020) 421–437, https://doi.org/10.1080/15715124.2019.1634083.

[38] K Unfried, K Kis-Katos, T. Poser, Water scarcity and social conflict, J. Environ. Econ. Manage 113 (2022) 102633, https://doi.org/10.1016/J.JEEM.2022.102633.

[39] N Mancosu, RL Snyder, G Kyriakakis, D. Spano, Water Scarcity and Future Challenges for Food Production, Water. (Basel) 7 (2015) 975–992, https://doi.org/10.3390/W7030975. Vol 7, Pages 975-992 2015.

[40] A AghaKouchak, A Mirchi, K Madani, G Di Baldassarre, A Nazemi, A Alborzi, et al., Anthropogenic Drought: Definition, Challenges, and Opportunities, Rev. Geophys. 59 (2021), https://doi.org/10.1029/2019RG000683.

[41] B Ashraf, A Aghakouchak, A Alizadeh, M Mousavi Baygi, HR Moftakhari, A Mirchi, et al., Quantifying Anthropogenic Stress on Groundwater Resources, Sci. Rep. 7 (2017), https://doi.org/10.1038/s41598-017-12877-4.

[42] JO Ogenga, EM Mugalavai, NO. Nyandiko, Impact of Rainfall Variability on Food production under Rainfed Agriculture in Homa Bay County, Kenya, International J. Scientific and Research Publications (IJSRP) 8 (2018), https://doi.org/10.29322/ijsrp.8.8.2018.p80110.

[43] A Dinar, A Tieu, H. Huynh, Water scarcity impacts on global food production, Glob. Food Sec. 23 (2019) 212–226, https://doi.org/10.1016/J.GFS.2019.07.007.

[44] M Hejazi, SR Santos Da Silva, F Miralles-Wilhelm, S Kim, P Kyle, Y Liu, et al., Impacts of water scarcity on agricultural production and electricity generation in the Middle East and North Africa, Front. Environ. Sci. 11 (2023), https://doi.org/10.3389/fenvs.2023.1082930.

[45] JK. Mishra, Status of coastal biodiversity in the face of climate change with respect to islands, in: IOP Conf Ser Earth Environ Sci, 420, Institute of Physics Publishing, 2020, https://doi.org/10.1088/1755-1315/420/1/012020 vol.
[46] IR. Orimoloye, Agricultural Drought and Its Potential Impacts: Enabling Decision-Support for Food Security in Vulnerable Regions, Front. Sustain. Food Syst. 6 (2022), https://doi.org/10.3389/fsufs.2022.838824.
[47] S. Suresh, Intersectoral competition for water between users and uses in Tamil Nadu-India, Front. Earth. Sci. (Lausanne) 9 (2021), https://doi.org/10.3389/feart.2021.663198.
[48] P Babuji, S Thirumalaisamy, K Duraisamy, G. Periyasamy, Human Health Risks due to Exposure to Water Pollution: A Review, Water (Switzerland) 15 (2023), https://doi.org/10.3390/w15142532.
[49] Craswell E Bijay-Singh, Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem, SN. Appl. Sci. 3 (2021), https://doi.org/10.1007/s42452-021-04521-8.
[50] P Li, D Karunanidhi, T Subramani, K. Srinivasamoorthy, Sources and Consequences of Groundwater Contamination, Arch. Environ. Contam. Toxicol. 80 (2021), https://doi.org/10.1007/s00244-020-00805-z.
[51] G Hutton, C. Chase, The knowledge base for achieving the sustainable development goal targets on water supply, sanitation and hygiene, Int. J. Environ. Res. Public Health 13 (2016), https://doi.org/10.3390/ijerph13060536.
[52] S Bilalova, J Newig, LC Tremblay-Lévesque, J Roux, C Herron, S. Crane, Pathways to water sustainability? A global study assessing the benefits of integrated water resources management, J. Environ. Manage 343 (2023) 118179, https://doi.org/10.1016/J.JENVMAN.2023.118179.
[53] K Makanda, S Nzama, T. Kanyerere, Assessing the role of water resources protection practice for sustainable water resources management: a review, Water (Switzerland) 14 (2022), https://doi.org/10.3390/w14193153.
[54] F Mugagga, BB. Nabaasa, The centrality of water resources to the realization of Sustainable Development Goals (SDG). A review of potentials and constraints on the African continent, Int. Soil Water Conserv. Res. 4 (2016) 215–223, https://doi.org/10.1016/J.ISWCR.2016.05.004.
[55] E Cohen-Shacham, G Walters, C Janzen, S Maginnis (Eds.), Nature-based solutions to address global societal challenges, IUCN International Union for Conservation of Nature, 2016, https://doi.org/10.2305/iucn.ch.2016.13.en.
[56] R Kaushal, D Mandal, P Panwar, Kumar P Rajkumar, JMS Tomar, et al., Soil and water conservation benefits of agroforestry, Forest Resour. Resilience Conflicts (2021) 259–275, https://doi.org/10.1016/B978-0-12-822931-6.00020-4.
[57] Marapara T. Eco-hydrology interactions between trees, soil and water in terrestrial and wetland areas: The effect of tree planting on water flow dynamics in Wairarapa Wetlands, New Zealand 2016. https://doi.org/10.26686/WGTN.17014109.V1.
[58] M. Abdelhak, Soil improvement in arid and semiarid regions for sustainable development, Nat. Resour. Conserv. Adv. Sustain. (2022) 73–90, https://doi.org/10.1016/B978-0-12-822976-7.00026-0.
[59] P Adhikari, H Araya, G Aruna, A Balamatti, S Banerjee, P Baskaran, et al., System of crop intensification for more productive, resource-conserving, climate-resilient, and sustainable agriculture: experience with diverse crops in varying agroecologies, Int. J. Agric. Sustain. 16 (2018) 1–28, https://doi.org/10.1080/14735903.2017.1402504.
[60] S McCulloch-Jones, P Novellie, DJ Roux, B. Currie, Exploring the alignment between the bottom-up and top-down objectives of a landscape-scale conservation initiative, Environ. Conserv. 48 (2021) 255–263, https://doi.org/10.1017/S0376892921000321.
[61] Panpette DG (ed), Jhala YK (ed). Soil fertility management for sustainable development. 2019.
[62] A. Saturday, Restoration of degraded agricultural land: a review, J. Environ. Health Sci. 4 (2018) 44–51, https://doi.org/10.15436/2378-6841.18.1928.
[63] LA Srivastav, R Dhyani, M Ranjan, S Madhav, M. Sillanpää, Climate-resilient strategies for sustainable management of water resources and agriculture, Environ. Sci. Pollut. Res. 28 (2020) 41576–41595, https://doi.org/10.1007/s11356-021-14332-4/Published.
[64] C King-Okumu, B Jillo, J Kinyanjui, I. Jarso, Devolving water governance in the Kenyan Arid Lands: from top-down drought and flood emergency response to locally driven water resource development planning, Int. J. Water. Resour. Dev. 34 (2018) 675–697, https://doi.org/10.1080/07900627.2017.1357539.
[65] CN Luwesi, JA Obando, CA. Shisanya, The impact of a warming micro-climate on muooni farmers of Kenya, Agriculture (Switzerland) 7 (2017), https://doi.org/10.3390/agriculture7030020.
[66] MW Beck, AH Claassen, PJ. Hundt, Environmental and livelihood impacts of dams: Common lessons across development gradients that challenge sustainability, Int. J. River Basin Manage. 10 (2012) 73–92, https://doi.org/10.1080/15715124.2012.656133.
[67] CB Gaye, C. Tindimugaya, Review: Challenges and opportunities for sustainable groundwater management in Africa, Hydrogeol. J. 27 (2019) 1099–1110, https://doi.org/10.1007/s10040-018-1892-1.
[68] Minoia P, Brusarosco A. Water infrastructures facing sustainable development challenges: integrated evaluation of impacts of dams on regional development in Morocco NRM-natural resources management water infrastructures facing sustainable development challenges: integrated evaluation of impacts of dams on regional development in Morocco. 2006.
[69] J. Cassin, Nature-based solutions for source water protection in North America, Nat. Based Sol. Water Secur. Action Agenda 21st Century (2021) 179–214, https://doi.org/10.1016/B978-0-12-819871-1.00005-1.
[70] J Cassin, BF. Ochoa-Tocachi, Learning from indigenous and local knowledge: The deep history of nature-based solutions, Nat. Based Sol. Water Secur. Action Agenda 21st Century (2021) 283–335, https://doi.org/10.1016/B978-0-12-819871-1.00012-9.
[71] Dupar M, Henriette E, Hubbard E. Nature-based green infrastructure: A review of African experience and potential. 2023.
[72] WWF. Living Planet Report 2020 : Bending the Curve of Biodiversity Loss. 2020.
[73] H. Briassoulis, Combating land degradation and desertification: The land-use planning quandary, Land. (Basel) 8 (2019), https://doi.org/10.3390/land8020027.
[74] Byron-Cox R. From Desertification to Land Degradation Neutrality: The UNCCD and the Development of Legal Instruments for Protection of Soils 2020:1–13. https://doi.org/10.1007/978-3-030-36004-7_1.
[75] P Chasek, M Akhtar-Schuster, BJ Orr, A Luise, H Rakoto Ratsimba, U Safriel, Land degradation neutrality: the science-policy interface from the UNCCD to national implementation, Environ. Sci. Policy. 92 (2019) 182–190, https://doi.org/10.1016/j.envsci.2018.11.017.
[76] A Maasri, SC Jähnig, MC Adamescu, R Adrian, C Baigun, DJ Baird, et al., A global agenda for advancing freshwater biodiversity research, Ecol. Lett. 25 (2022) 255–263, https://doi.org/10.1111/ele.13931.
[77] D Moher, A Liberati, J Tetzlaff, DG Altman, G Antes, D Atkins, et al., Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement, PLoS. Med. 6 (2009), https://doi.org/10.1371/JOURNAL.PMED.1000097.
[78] M Ouzzani, H Hammady, Z Fedorowicz, A. Elmagarmid, Rayyan-a web and mobile app for systematic reviews, Syst. Rev. 5 (2016) 1–10, https://doi.org/10.1186/S13643-016-0384-4/FIGURES/6.
[79] M Maiolo, D. Pantusa, Sustainable water management index, swam_index, Cogent. Eng. 6 (2019), https://doi.org/10.1080/23311916.2019.1603817.
[80] RNM Kareithi, C Lund, R. Kareithi, Review of NGO performance research published in academic journals between 1996 and 2008, Rev. Article S. Afr. J. Sci. 108 (2012), https://doi.org/10.4102/sajs.
[81] DO Olago, TA Downing, Y Githiora, C Borgemeister, J Kamau, G Kuiper, et al., Nature-based solutions in the savanna belt of Africa: Insights from a systematic review, Nature-Based Sol. 6 (2024) 100154, https://doi.org/10.1016/J.NBSJ.2024.100154.
[82] Njoka JT, Yanda P, Maganga F, Liwenga E, Kateka A, Henku A, et al. Kenya: Country situation assessment. Working paper. 2016.
[83] E Nkonya, A Minnick, E Ng'ang'a, J. Woelcke, Land and natural resources degradation in the arid and semi-arid lands in Kenya Land and natural resources degradation in the Arid and Semi-Arid Lands, Kenya Tech. Rep. Client World Bank (2018).
[84] C Fabricius, T. Pereira, Community biodiversity inventories as entry points for local ecosystem stewardship in a south African Communal Area, Soc. Nat. Resour. 28 (2015) 1030–1042, https://doi.org/10.1080/08941920.2015.1014591.
[85] Oksanen Tapani, Pajari Brita, Tuomasjukka Tomi, Forests in poverty reduction strategies : capturing the potential, European Forest Institute, Tuusula, Finland, 2003, 1-4 October, 2002.
[86] EJZ. Robinson, Resource-dependent livelihoods and the natural resource base, Annu Rev. Resour. Economics. 8 (2016) 281–301, https://doi.org/10.1146/ANNUREV-RESOURCE-100815-095521/CITE/REFWORKS.
[87] M Diop, N Chirinda, A Beniaich, M El Gharous, K. El Mejahed, Soil and water conservation in Africa: state of play and potential role in tackling soil degradation and building soil health in agricultural lands, Sustainability. 14 (2022) 13425, https://doi.org/10.3390/SU142013425, 2022, Vol 14, Page 13425.
[88] Eboi AA, Amunga H. African universities' performances in selected global ranking models for the period 2016-2021: Issues Suggest. Sol.. Https://ServicesIgi-GlobalCom/Resolvedoi/ResolveAspx?Doi=104018/978-1-6684-8266-7Ch008 2023:145–70. https://doi.org/10.4018/978-1-6684-8266-7.CH008.
[89] L Duchateau, P. Janssen, Two decades of statistical education collaboration in the global South: lessons learned from an Ethiopian project and the way forward, Stat. Med. 41 (2022) 845–846, https://doi.org/10.1002/SIM.9293.
[90] W Ali, A. Elbadawy, Research output of the top 10 African countries : An analytical study, COLLNET J. Scientometrics Inf. Manage. 15 (2021) 9–25, https://doi.org/10.1080/09737766.2021.1934181.
[91] W. Liu, The changing role of non-english papers in scholarly communication: Evidence from web of science's three journal citation indexes, Learned Publishing 30 (2017) 115–123, https://doi.org/10.1002/LEAP.1089.
[92] Bahji A, Acion L, Laslett AM, Adinoff B. Exclusion of the non-English-speaking world from the scientific literature: Recommendations for change for addiction journals and publishers. https://doiorg/101177/14550725221102227 2022;40:6–13. https://doi.org/10.1177/14550725221102227.
[93] UNEP & FAO. United Nations Decade on Ecosystem Restoration 2021-2030. Https://WwwDecadeonrestorationOrg/n.d.
[94] K Muthee, L Duguma, J Nzyoka, P. Minang, Ecosystem-based adaptation practices as a nature-based solution to promote water-energy-food nexus balance, Sustainability. 13 (2021), https://doi.org/10.3390/su13031142.
[95] A Cruickshank, VI. Grover, These are our water pipes—sand dams, women and donkeys: dealing with water scarcity in Kenya's Arid and Semi-Arid Lands. Climate change management, Springer (2012) 701–726, https://doi.org/10.1007/978-3-642-22266-5_42.
[96] M Everard, R Loayza Muro, L Bunclark, R Taboada, Comparative analysis of hybridized solutions to water resources management in Burkina Faso, India and Peru, Int. J. Water. Resour. Dev. 37 (2021) 94–117, https://doi.org/10.1080/07900627.2020.1712192.
[97] VM Silayo, I. Pikirayi, Community-based approaches in the construction and management of water infrastructures among the Chagga, Kilimanjaro, Tanzania, Land. (Basel) 12 (2023), https://doi.org/10.3390/land12030570.

[98] JM Lyatuu, TA Tuni, CJ. Kilawe, Factors influencing community's adoption of domestic water conservation measures in Moshi Rural District, Tanzania. Sustain. Water Resour. Manag. 9 (2023), https://doi.org/10.1007/s40899-023-00970-8.
[99] JW Recha, BM Mati, M Nyasimi, PK Kimeli, JM Kinyangi, M. Radeny, Changing rainfall patterns and farmers' adaptation through soil water management practices in semi-arid eastern Kenya, Arid Land Res. Manage. 30 (2016) 229–238, https://doi.org/10.1080/15324982.2015.1091398.
[100] AR Oduor, MM. Mabanga, Improving the efficiency of runoff pond system for supplementary irrigation in arid and semi-arid areas of Kenya, Rainwater-Smart Agriculture in Arid and Semi-Arid Areas: Fostering the Use of Rainwater for Food Security, Poverty Alleviation, Landscape Restoration and Climate Resilience (2017) 199–213, https://doi.org/10.1007/978-3-319-66239-8_11.
[101] Z Kelemewerk Mekuria, A Kassegn Amede, E Endris Mekonnen, Adoption of rainwater harvesting and its impact on smallholder farmer livelihoods in Kutaber district, South Wollo Zone, Ethiopia, Cogent. Food Agric. 6 (2020), https://doi.org/10.1080/23311932.2020.1834910.
[102] H Shiferaw, A Gebremedhin, N Solomon, G Taye, A. Zenebe, Comparative study on spatial variability of topsoil moisture content and carbon stocks as influenced by land use and soil and water conservation structures in the semi-arid Ethiopian highlands, Phys. Geogr. 41 (2020) 389–406, https://doi.org/10.1080/02723646.2019.1666563.
[103] K Kellner, RT Mangani, TJK Sebitloane, JG Chirima, N Meyer, HC Coetzee, et al., Restoration after bush control in selected rangeland areas of semi-arid savannas in South Africa, Bothalia 51 (2021), https://doi.org/10.38201/btha.abc.v51.i1.7.
[104] S Umer, A Aticho, E. Kiss, Effects of integrated use of grass strip and soil bund on soil properties, Southern Ethiopia, J. Degrad. Mining Lands Manage. 6 (2019) 1569–1578, https://doi.org/10.15243/jdmlm.2019.062.1569.
[105] KZ Mganga, NKR Musimba, MM Nyangito, DM Nyariki, AW Mwang'ombe, Improving hydrological responses of degraded soils in semi arid kenya, J. Environ. Sci. Technol. 3 (2010) 217–225, https://doi.org/10.3923/jest.2010.217.225.
[106] P Gicheru, C Gachene, J Mbuvi, E. Mare, Effects of soil management practices and tillage systems on surface soil water conservation and crust formation on a sandy loam in semi-arid Kenya, Soil. Tillage Res. 75 (2004) 173–184, https://doi.org/10.1016/S0167-1987(03)00161-2.
[107] DW Kimiti, C Riginos, J. Belnap, Low-cost grass restoration using erosion barriers in a degraded African rangeland, Restor. Ecol. 25 (2017) 376–384, https://doi.org/10.1111/rec.12426.
[108] BP Mbilinyi, SD Tumbo, HF Mahoo, EM Senkondo, N. Hatibu, Indigenous knowledge as decision support tool in rainwater harvesting, Phys. Chem. Earth 30 (2005) 792–798, https://doi.org/10.1016/j.pce.2005.08.022.
[109] GT Moroda, D Tolossa, N. Semie, Perception and adaptation strategies of rural people against the adverse effects of climate variability: a case study of Boset District, East Shewa, Ethiopia. Environ. Dev. 27 (2018) 2–13, https://doi.org/10.1016/j.envdev.2018.07.005.
[110] ET. Liwenga, Adaptive livelihood strategies for coping with water scarcity in the drylands of central Tanzania, Phys. Chem. Earth 33 (2008) 775–779, https://doi.org/10.1016/j.pce.2008.06.031.
[111] NM Pauline, C Vogel, S Grab, ET. Liwenga, Smallholder farmers in the Great Ruaha River sub-Basin of Tanzania: coping or adapting to rainfall variability? Clim. Dev. 9 (2017) 217–230, https://doi.org/10.1080/17565529.2016.1184607.
[112] RK. Asravor, On-farm adaptation strategies to climate change: the case of smallholder farmers in the Northern Development Authority Zone of Ghana, Environ. Dev. Sustain. 24 (2022) 5080–5093, https://doi.org/10.1007/s10668-021-01650-3.
[113] E Bojago, MW Delango, D. Milkias, Effects of soil and water conservation practices and landscape position on soil physicochemical properties in Anuwa watershed, Southern Ethiopia, J. Agric. Food Res. 14 (2023), https://doi.org/10.1016/j.jafr.2023.100705.
[114] M Masha, E Bojago, M. Belayneh, Assessing the impacts of soil and water conservation practices on soil physicochemical properties in contrasting slope landscapes of Southern Ethiopia, J. Agric. Food Res. 14 (2023), https://doi.org/10.1016/j.jafr.2023.100876.
[115] M Masha, E. Bojago, Evaluating soil erosion and determinants of farmers' adoption of soil and water conservation measures in the Offa district, southern Ethiopia, J. Agric. Food Res. 14 (2023), https://doi.org/10.1016/j.jafr.2023.100866.
[116] A Degfe, A Tilahun, Y Bekele, B Dume, OH. Diriba, Adoption of soil and water conservation technologies and its effects on soil properties: Evidences from Southwest Ethiopia, Heliyon. 9 (2023), https://doi.org/10.1016/j.heliyon.2023.e18332.
[117] K Getyengana, ET Kamba, MV. Mkwanazi, SZ Ndlela, M Mwale, M. Chimonyo, Factors influencing the integration of indigenous and conventional knowledge of water security for livestock, Trop. Anim. Health Prod. 55 (2023), https://doi.org/10.1007/s11250-023-03529-z.
[118] M Mersha, B Alamirew, L. Ayele, Factors determining farmers' decision and level of participation in terracing as a response to land degradation in Dejen Woreda, North-West Ethiopia, Cogent. Soc. Sci. 8 (2022), https://doi.org/10.1080/23311886.2022.2126080.
[119] SW Kimaru-Muchai, FK Ngetich, MW Mucheru-Muna, M. Baaru, Zai pits for heightened sorghum production in drier parts of Upper Eastern Kenya, Heliyon. 7 (2021), https://doi.org/10.1016/j.heliyon.2021.e08005.
[120] MW Njenga, JN Mugwe, H Mogaka, G Nyabuga, M Kiboi, F Ngetich, et al., Communication factors influencing adoption of soil and water conservation technologies in the dry zones Of Tharaka-Nithi County, Kenya, Heliyon. 7 (2021), https://doi.org/10.1016/j.heliyon.2021.e08236.
[121] EM Bagula, JGM Majaliwa, TA Basamba, JGM Mondo, B Vanlauwe, G Gabiri, et al., Water use efficiency of maize (Zea mays L.) crop under selected soil and water conservation practices along the slope gradient in Ruzizi Watershed, Eastern D.R. Congo. Land (Basel) 11 (2022), https://doi.org/10.3390/land11101833.
[122] JM Kiragu, W Chiuri, V. Ngure, Surface runoff harvesting in promotion of horticultural potentials in Kenyan ASALs, Acta Hortic. 1348 (2022) 179–183, https://doi.org/10.17660/ACTAHORTIC.2022.1348.24.
[123] I Nyagumbo, G Nyamadzawo, C. Madembo, Effects of three in-field water harvesting technologies on soil water content and maize yields in a semi-arid region of Zimbabwe, Agric. Water. Manage 216 (2019) 206–213, https://doi.org/10.1016/j.agwat.2019.02.023.
[124] TA Gebru, GK Brhane, YG. Gebremedhin, Contributions of water harvesting technologies intervention in arid and semi-arid regions of Ethiopia, in ensuring households' food security, Tigray in focus, J. Arid. Environ. 185 (2021), https://doi.org/10.1016/j.jaridenv.2020.104373.
[125] JS Pachpute, SD Tumbo, H Sally, ML. Mul, Sustainability of rainwater harvesting systems in rural catchment of Sub-Saharan Africa, Water Resources Manage. 23 (2009) 2815–2839, https://doi.org/10.1007/s11269-009-9411-8.
[126] SM Mureithi, A Verdoodt, E. Van Ranst, Effects and Implications of Enclosures for Rehabilitating Degraded Semi-arid Rangelands: Critical Lessons from Lake Baringo Basin, Kenya. Land Degradation and Desertification: Assessment, Mitigation and Remediation, Springer, Netherlands, 2010, pp. 111–129, https://doi.org/10.1007/978-90-481-8657-0_9.
[127] DA Tofu, K. Wolka, Evaluating adaptation efforts of food-aid-reliant smallholder farmers in the drought-prone area, Environ. Sustain. Indicat. 19 (2023), https://doi.org/10.1016/j.indic.2023.100276.
[128] S Gashure, D. Wana, Smallholder farmers' perceptions, coping and adaptation strategies to climate variability in the UNESCO designated cultural landscapes of Konso, Ethiopia, Local. Environ. 28 (2023) 1243–1262, https://doi.org/10.1080/13549839.2023.2202379.
[129] DJMB File, G. Nhamo, Farmers' choice for indigenous practices and implications for climate-smart agriculture in northern Ghana, Heliyon. 9 (2023), https://doi.org/10.1016/j.heliyon.2023.e22162.
[130] Z Ndebele, M. Zenda, Climate change impact and adaptation of agro-pastoral farmers in Awerial County, Lakes State of South Sudan, South Afr. J. Agric. Extens. 51 (2023) 135–160, https://doi.org/10.17159/2413-3221/2023/v51n3a14086.
[131] ON Oduor, M Mucheru-Muna, NJ Mugwe, I Sijali, G Nyabuga, ND. Mugendi, Soil water use efficiency under integrated soil management practices in the drylands of Kenya, Heliyon. 9 (2023), https://doi.org/10.1016/j.heliyon.2023.e16145.
[132] A Micheni, P Gicheru, O. Kitonyo, Conservation Agriculture for climate smart agriculture in smallholder farming systems in Kenya, Conserv. Agric. Africa Clim. Smart Agric. Dev. (2022) 431–442, https://doi.org/10.1079/9781789245745.0027.
[133] E Ali, Farm households' adoption of climate-smart practices in subsistence agriculture: evidence from Northern Togo, Environ. Manage 67 (2021) 949–962, https://doi.org/10.1007/s00267-021-01436-3.
[134] AO Onoja, AZ Abraha, A Girma, AI. Achike, Climate-smart agricultural practices (CSA) adoption by crop farmers in semi-arid regions of West and East Africa: evidence from Nigeria and Ethiopia, Clim. Change Manage. (2019) 89–113, https://doi.org/10.1007/978-3-319-75004-0_6.
[135] TC Kumasi, P Antwi-Agyei, K. Obiri-Danso, Small-holder farmers' climate change adaptation practices in the Upper East Region of Ghana, Environ. Dev. Sustain. 21 (2019) 745–762, https://doi.org/10.1007/s10668-017-0062-2.
[136] A Asfaw, B Simane, A Bantider, A. Hassen, Determinants in the adoption of climate change adaptation strategies: evidence from rainfed-dependent smallholder farmers in north-central Ethiopia (Woleka sub-basin), Environ. Dev. Sustain. 21 (2019) 2535–2565, https://doi.org/10.1007/s10668-018-0150-y.
[137] AA Adem, TM Wassie, T Gashaw, SA. Tilahun, Evaluation of exclosures in restoring degraded landscapes in the semi-arid highlands of northwestern Ethiopia, Catena (Amst) 237 (2024), https://doi.org/10.1016/j.catena.2024.107826.
[138] HG Araya, OV Wasonga, S Mureithi, E. Birhane, Natural regeneration offers an effective way for large-scale restoration of degraded lands in Tigray, Ethiopia. Land Degrad. Dev. 34 (2023) 4346–4357, https://doi.org/10.1002/ldr.4781.
[139] K Wolka, B Biazin, F Getachew, F Girma, G. Desta, Towards sustainable watershed-based landscape restoration in degraded drylands: Perceived benefits and innovative pathways learnt from project-based interventions in Ethiopia, J. Environ. Manage 335 (2023), https://doi.org/10.1016/j.jenvman.2023.117499.
[140] E Mugari, H Masundire, M. Bolaane, Adapting to climate change in semi-arid rural areas: A case of the limpopo basin part of Botswana, Sustainability (Switzerland) 12 (2020) 1–34, https://doi.org/10.3390/su12208292.
[141] L Myeni, ME. Moeletsi, Factors determining the adoption of strategies used by smallholder farmers to cope with climate variability in the eastern free state, South Africa, Agriculture (Switzerland) 10 (2020) 1–16, https://doi.org/10.3390/agriculture10090410.
[142] K Jeddi, M. Chaieb, Changes in soil properties and vegetation following livestock grazing exclusion in degraded arid environments of South Tunisia, Flora Morphol. Distrib. Function. Ecol. Plants 205 (2010) 184–189, https://doi.org/10.1016/j.flora.2009.03.002.
[143] Z Yohannes, M Teshome, M. Belay, Adaptive capacity of mountain community to climate change: case study in the Semien Mountains of Ethiopia, Environ. Dev. Sustain. 22 (2020) 3051–3077, https://doi.org/10.1007/s10668-019-00334-3.

[144] P Antwi-Agyei, K. Amanor, Typologies and drivers of the adoption of climate smart agricultural practices by smallholder farmers in rural Ghana, Curr. Res. Environ. Sustain. 5 (2023), https://doi.org/10.1016/j.crsust.2023.100223.
[145] C Ofoegbu, PW Chirwa, J Francis, FD. Babalola, Assessing forest-based rural communities' adaptive capacity and coping strategies for climate variability and change: The case of Vhembe district in south Africa, Environ. Dev. 18 (2016) 36–51, https://doi.org/10.1016/j.envdev.2016.03.001.
[146] RA Cyamweshi, S Kuyah, A Mukuralinda, J Ngango, SR Mbaraka, JD Manirere, et al., Farming with trees for soil fertility, moisture retention and crop productivity improvement: perceptions from farmers in Rwanda, Small-Scale Forest. 22 (2023) 649–667, https://doi.org/10.1007/s11842-023-09547-x.
[147] A Eshete, S Teshome, A Edaso, G Yilma, G. Furo, Selection of soil and water conservation technologies and native tree species for rehabilitation of degraded arid lands in Southeast Ethiopia, Int. J. Forest. Res. 2023 (2023), https://doi.org/10.1155/2023/7357131.
[148] H. Sawadogo, Using soil and water conservation techniques to rehabilitate degraded lands in Northwestern Burkina Faso, Int. J. Agric. Sustain. 9 (2011) 120–128, https://doi.org/10.3763/ijas.2010.0552.
[149] A Takele, HB Lakew, G. Kabite, Does the recent afforestation program in Ethiopia influenced vegetation cover and hydrology? A case study in the upper awash basin, Ethiopia, Heliyon. 8 (2022), https://doi.org/10.1016/j.heliyon.2022.e09589.
[150] Kasusya P. Combating desertification in northern Kenya (Samburu) through community action: a community case experience. 1998.
[151] CC Nnaji, NC. Mama, Preliminary Assessment of Rainwater Harvesting Potential in Nigeria: Focus on Flood Mitigation and Domestic Water Supply, Water Resour. Manage. 28 (2014) 1907–1920, https://doi.org/10.1007/s11269-014-0579-1.
[152] JB Isunju, CG Orach, J. Kemp, Community-level adaptation to minimize vulnerability and exploit opportunities in Kampala's wetlands, Environ. Urban. 28 (2016) 475–494, https://doi.org/10.1177/0956247816647342.
[153] TG Andualem, YG Hagos, AH. Teka, Rainwater harvesting potential assessment for non-potable use in urban areas, Sustain. Water. Resour. Manage 6 (2020), https://doi.org/10.1007/s40899-020-00464-x.
[154] T Amede, E Van Den Akker, W Berdel, C Keller, G Tilahun, A Dejen, et al., Facilitating livelihoods diversification through flood-based land restoration in pastoral systems of Afar, Ethiopia, Renew. Agric. Food Syst. 37 (2022) S43–S54, https://doi.org/10.1017/S1742170520000058.
[155] M Hadaro, T Ayele, S Parshotam Datt, R Teshome, Soil properties as affected by soil conservation practices and soil depths in Uwite Watershed, Hadero Tunto District, Southern Ethiopia. Appl Environ Soil Sci. 2021 (2021), https://doi.org/10.1155/2021/5542326.
[156] T Sinore, D. Doboch, Effects of soil and water conservation at different landscape positions on soil properties and farmers' perception in Hobicheka Sub-Watershed, Southern Ethiopia, Appl. Environ. Soil. Sci. 2021 (2021), https://doi.org/10.1155/2021/9295650.
[157] K Wolka, T Uma, DA. Tofu, The role of integrated watershed management in climate change adaptation for small-scale farmers in Southwest Ethiopia, Environ. Sustain. Indicat. 19 (2023), https://doi.org/10.1016/j.indic.2023.100260.
[158] H Dagne, E Assefa, E. Teferi, Sustainable Use of Soil and Water Conservation Technologies and Its Determinants: The Case of the Handosha Watershed, Omo-Gibe River Basin, Ethiopia, Earth (Switzerland) 4 (2023) 315–330, https://doi.org/10.3390/earth4020017.
[159] JJ Kashaigili, K Rajabu, P. Masolwa, Freshwater management and climate change adaptation: Experiences from the Great Ruaha River catchment in Tanzania. Lessons for climate change adaptation from better management of rivers, Taylor and Francis, 2015, pp. 220–228, https://doi.org/10.3763/cdev.2009.0025.
[160] S Pollard, D du Toit, H. Biggs, River management under transformation: The emergence of strategic adaptive management of river systems in the kruger national park, Koedoe 53 (2011), https://doi.org/10.4102/koedoe.v53i2.1011.
[161] CK Songok, P Kimeu, J Kamunge, R Ngumbi, L Chammah, C Adiema, et al., Lessons learned in the replication and scaling-up of rainwater harvesting technologies in arid and semi-arid areas: A case study of Kilifi County, Kenya, Rainwater-Smart Agric. Arid Semi-Arid Areas Foster. Use of Rainwater Food Secur. Povert. Alleviat. Landscape Restor. Clim. Resilience (2017) 379–392, https://doi.org/10.1007/978-3-319-66239-8_20.
[162] T Erkossa, D Geleti, TO Williams, F Laekemariam, A. Haileslassie, Restoration of grazing land to increase biomass production and improve soil properties in the Blue Nile basin: effects of infiltration trenches and Chloris Gayana reseeding, Renew. Agric. Food Syst. 37 (2022) S64–S72, https://doi.org/10.1017/S1742170519000425.