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Advancing trait-based biomonitoring approach for freshwater ecosystems assessment in Africa: current status, challenges, and future directions

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Freshwater ecosystems across Africa are increasingly threatened by anthropogenic pressures, including land-use changes, pollution, hydrological alterations, and climate variability. While traditional taxonomic approaches for biomonitoring these ecosystems remain valuable, they often fall short in detecting ecological processes and stressor-specific responses. In contrast, trait-based approaches (TBAs) provide a function-oriented perspective on ecosystem integrity by linking organismal traits to environmental gradients. This review synthesizes the current state of TBAs in African freshwater ecosystems assessments, highlighting their limited but growing application across the continent. We identify key challenges hindering wider implementation, such as the scarcity of trait databases tailored to African taxa, inconsistent taxonomic resolution, limited institutional capacity, and gaps in ecological traits knowledge. Despite these limitations, TBAs offer strong potential to improve diagnostic precision, enable ecological comparisons across regions, and support resilience assessment in data-limited contexts.

We suggest future avenues to advance standardized trait frameworks, regional trait banks, and coordinated monitoring schemes in line with global biodiversity objectives and sustainable freshwater ecosystems management in Africa.

KEYWORDS

freshwater ecosystems, Africa, trait-based approaches (TBAs), biomonitoring, functional traits, anthropogenic pressures, conservation

1 Introduction

Despite representing only about 1% of the Earth's surface area, rivers, lakes, streams, and wetlands harbor an estimated 7% of all known species, making them critical for maintaining global biodiversity (Baggio et al., 2021; Karimidastenaei et al., 2022; Cooke et al., 2024; Li et al., 2025). These ecosystems support a wide array of organisms—including aquatic plants, fishes, amphibians, and macroinvertebrates—that are specifically adapted to freshwater environments and cannot be found elsewhere (Cooke et al., 2024; Casatti et al., 2024). In addition to their ecological importance, freshwater ecosystems provide numerous ecosystem services. These include waste treatment, fisheries, potable water provision, and cultural and recreational services such as boating and swimming, which contribute to human wellbeing (Barbarossa et al., 2021; Lynch et al., 2023). However, freshwater ecosystems face mounting anthropogenic pressures. Pollution, water extraction, habitat modification, invasive species, waterway degradation, and nutrient enrichment threaten their ecological integrity. Urbanization, population growth, industrial activities, climate change, and socio-political conflicts further exacerbate these pressures (Stamenković et al., 2024). Comprehensive assessments involving over 200 scientists and 5,167 species have documented widespread biodiversity loss and disruption of ecological processes across Africa (Darwall et al., 2009; Sayer et al., 2018; Edegbene and Akamagwuna, 2022; Masese et al., 2021; Masese et al., 2023). This degradation not only affects biodiversity but also impairs essential ecosystem services, including water purification and nutrient cycling, which are vital for human wellbeing (IPBES, 2019; El Yaagoubi, 2024; El Kourchi et al., 2025).

These global pressures are especially well documented in Africa, where comprehensive assessments have revealed significant biodiversity loss and ecological disruption. African freshwater ecosystems—comprising lakes, wetlands, streams, and major transboundary river basins such as the Nile, Niger, Orange, Tana, and Zambezi—are essential ecological and socio-economic repositories that provide freshwater for agriculture, fisheries, and domestic consumption for millions of Africans (McClain, 2013; Gharnit et al., 2024; Dube et al., 2025). Unfortunately, Africa's freshwater ecosystems are increasingly threatened by eutrophication, habitat degradation, climate change, and land-use changes (e.g., deforestation and agricultural encroachment) that modify hydrology, accelerate sedimentation, and introduction of contaminants (Parmesan et al., 2023; Edegbene et al., 2024a; Edegbene A. O. et al., 2025; El Yaagoubi et al., 2025).

Over the years, the state of freshwater ecosystems ecological health and resilience have been adjudged by using the traditional monitoring methods that depend primarily on physicochemical criteria, which are widely regarded as inadequate. While these methods provide useful snapshots of short-term environmental conditions, they frequently fail to capture the cumulative and long-term consequences of anthropogenic pressures, and they can be prohibitively expensive (Odume et al., 2012; 2023; Edegbene et al., 2020a; Olatunji et al., 2023). As a result, there is growing agreement on the importance of including biological indicators, particularly TBAs, to obtain a more holistic and ecologically meaningful assessment of freshwater ecosystem health (Arimoro et al., 2015). TBAs, which focus on species' functional features and ecological preferences, are increasingly being used around the world to assess how aquatic communities respond to environmental perturbations. By moving beyond taxonomic composition and emphasizing organismal function. This integrated strategy increases early diagnosis of ecological degradation and promotes evidence-based, long-term management techniques (El Yaagoubi et al., 2024a; El Yaagoubi et al., 2024c).

Understanding the functional composition of macroinvertebrate communities on the African continent is critical for detecting environmental stress and informing intervention attempts to enable action. These discoveries are vital not only for ecological resilience, but also for protecting socio-economic development that relies on healthy freshwater ecosystems in the long term (Akamagwuna et al., 2024; Ferreira et al., 2012; Mohammed et al., 2024a). These methods offer critical insights into ecosystem functioning, biodiversity conservation, and resilience building. However, in Africa, the application of TBAs—particularly for assessing the cumulative impacts of multiple stressors such as urbanization and agriculture on aquatic macroinvertebrate communities remain limited and underdeveloped. Understanding how such stressors influence functional trait composition is essential for the development of robust biomonitoring tools tailored to Africa's diverse freshwater ecosystems.

This narrative literature review provides a comprehensive synthesis of the development and application of TBAs in African freshwater research. It highlights the spatial distribution of studies, with a strong emphasis on benthic macroinvertebrates and the range of aquatic habitats explored. Particular attention is given to lotic systems (rivers and streams), as these are especially sensitive to environmental change due to their variable hydrology, direct connectivity to catchment processes, and rapid responses to disturbances such as altered flow regimes, increased sediment loads, and nutrient enrichment (Vörösmarty et al., 2010; Dudgeon et al., 2006). Although lentic environments (e.g., lakes, ponds, wetlands) are also vulnerable, the greater dynamism of lotic systems makes them especially effective as early indicators in trait-based monitoring (Downing, 2010; Moss, 2017; Heino et al., 2021; Hill et al., 2021a; Workie et al., 2024).

We also explored the significant limitations to the TBAs research produced in Africa, which include limited taxonomic resolution, reliance on global (non-African) trait databases, and the ongoing lack of relevant taxonomic trait information from Africa, all of which limits the application of TBAs in Africa generally. Even so, there are indications from new studies (e.g., Stamenković et al., 2024; Coccia et al., 2021; Hill et al., 2021b) that combining lotic and lentic systems is important for appropriately quantifying ecological responses for assessing the interactions of environmental stressors, adding further significance to our lotic ecosystem approach, within the context of freshwater ecosystems overall. For example, Stamenković et al. (2024) found that trait measurements accurately assess ecological integrity in both lotic and lentic systems while Hill et al. (2021a) emphasized the need to include wetlands and standing waters in order to capture larger ecological responses to environmental stressors. These findings support our focus on lotic systems while placing our research within the larger context of freshwater ecosystem studies. This review specifically aims to: i) synthesize existing literature on the use of TBAs in African freshwater biomonitoring; ii) evaluate the progress made, as well as the benefits and limitations of TBAs application in the region; and iii) identify current knowledge gaps and propose future research directions to advance TBAs and strengthen the management of Africa's freshwater ecosystems.

2 Approach and scope of the literature review

While investigating the present state of TBAs in freshwater environments across Africa, we conducted a systematic literature review to provide a comprehensive and objective summary by consulting the following databases; Web of Science, Scopus, and Google Scholar, and they were selected for their full coverage of environmental and ecological sciences, ensuring access to connected research in both Africa and other continents of the world. We used the following keywords: Africa, macroinvertebrates, functional traits, biological traits, biomonitoring, and bioassessment, to identify relevant literature. Further, a combination of keywords was used to conduct the search and to identify relevant studies on TBAs and African freshwater ecosystems, and they include; trait-based approach, functional traits, biological monitoring, freshwater ecosystems, macroinvertebrates and Africa. Additionally, other keywords include; —rivers, lakes, wetlands, benthic invertebrates, and ecological assessment, and keywords identifying specific African regions (e.g., North Africa, West Africa, South Africa, Central Africa, East Africa).

To capture recent advancements in TBAs, the review focused on studies published within the last 30 years. Articles, theses, and book chapters that specifically addressed theme research, were included.

2.1 Inclusion and exclusion criteria

In the inclusion criteria, we explored studies that investigated and analyzed functional traits such as life cycle, body size, body shape, and feeding habits, or aquatic organisms' ecological preferences. Researches that discussed topic that concern how TBAs are used in assessing freshwater ecosystem health, such as rivers, streams, wetlands, or lakes and studies conducted in African countries or regions were also included.

The exclusion criteria comprised: i) studies concentrated only on taxonomic-based assessments without mentioning functional traits; ii) studies or researches conducted outside Africa or in non-freshwater ecosystems such as marine environments, but not directly relevant to freshwater TBAs; and iii) sources or studies lacking clear methodology. In order to minimize and reduce selection bias, we make sure that the review incorporated searches of works by African and non-African researchers. We checked up more relevant papers by analyzing the references from important research, minimizing reliance on the authors' own contributions. The data extracted comprised study location, ecosystem type, target taxa, functional traits analyzed and key findings. At first instance, 114 publications popped up during our search using the various keywords, but after scrutiny-proofreading of titles, abstracts, and full texts for pertinence, a total of 47 publications were chosen for characteristic analysis for the review of the advancement of TBAs studies in Africa.

In this review, we ensured transparency and reproducibility were systemically followed, providing a balanced representation of TBAs applications across Africa's diverse freshwater ecosystems.

3 Ecological assessments and the limitations of traditional taxonomic approaches in biomonitoring freshwater ecosystems in Africa: why TBAs is gradually replacing the traditional approach

Historically, taxonomy-based approaches dominated ecological studies of freshwater ecosystems, relying on species composition to assess biodiversity and pollution impacts (Ochieng et al., 2019; Pang et al., 2024). While valuable, these methods face challenges: dependence on scarce taxonomic expertise, sensitivity to spatial/temporal heterogeneity, and limited functional insight (Eriksen et al., 2025). To address these constraints, TBAs have emerged as cost-effective alternatives, focusing on biological and ecological features that link directly to ecosystem processes and resilience (Charvet et al., 2000).

Globally, benthic macroinvertebrates, long recognized as key bioindicators, have been central to the adoption of TBAs worldwide (Charvet et al., 2000; Fierro et al., 2017; Odume, 2020; Edegbene et al., 2021a). Trait diversity at the community level—measured through richness, redundancy, or evenness—provides meaningful indicators of ecosystem function (Coccia et al., 2021). In the Afrotropical region, benthic macroinvertebrates are widely applied in bioassessments (Errochdi et al., 2012; Edegbene et al., 2020b). Studies in Africa (e.g., Masese et al., 2014; Masese et al., 2023; Akamagwuna et al., 2022a; Akinpelu et al., 2024) have shown that traits are effective for detecting land-use impacts, pollution, and habitat stress. However, many assessments still concentrate on a limited set of traits. For instance, studies in East Africa often emphasize functional feeding groups, while those in southern and western Africa apply broader suites of traits (Odume, 2020; Edegbene et al., 2021a; Edegbene et al., 2021b). Progress in advancing trait-based approaches is further constrained by the absence of comprehensive trait databases and the limited technical capacity reported in countries such as Nigeria, Kenya, and Uganda (Sitati et al., 2021; Adedapo et al., 2023). Overall, integrating TBAs with taxonomy-based methods provides a more robust framework for freshwater bioassessment, facilitating cross-regional comparisons and improving ecological interpretation across diverse African contexts (Akamagwuna et al., 2019a; Edegbene et al., 2020a).

4 TBAs as an innovative method for understanding ecosystem processes and biodiversity

Globally, TBAs have emerged as an effective and useful addition to traditional taxonomy-based assessments of riverine water quality (Desrosiers et al., 2019). Based on the Habitat Template Concept (HTC) (Townsend and Hildrew, 1994), TBAs predict that organisms will survive in a spatial area of habitat where the trait matches the spatial condition, allowing for adaptation and persistence (Desrosiers et al., 2019). Traits that inform on the reproductive turnover produces species resilience to an environmental disturbance in riverine ecosystems (Dolédec and Statzner, 2008; Feio and Dolédec 2012; Feio et al., 2021) and variability (Statzner et al., 2001; Culp et al., 2020). A rapid reproductive turnover provide populations several opportunities to quickly recover after an environmental disturbance occurs (e.g., pollutions or a habitat degradation). The ability to rebound quickly is facilitated by increasing reproduction output and breeding turnover (Townsend et al., 1983). As previously noted, TBAs are less sensitive to factors such as seasonal variability, sampling effort (Charvet et al., 2000; Tomanova et al., 2006), taxonomic resolution (Dolédec et al., 2000; Gayraud et al., 2003), and large-scale spatial taxonomic differences, compared to traditional taxonomy-based methods (Statzner et al., 2001; Bonada et al., 2006).

Over the past one decade in Africa, the study of functional feeding groups (FFGs) became a key aspect of TBAs since FFGs are true indicators of ecological integrity (Masese et al., 2014; Addo-Bediako, 2021a; Bediako, 2021b; El Yaagoubi et al., 2023; Nahli et al., 2023; Dalu et al., 2025; Edegbene O. A. et al., 2025). A number of studies have increasingly explored how the traits and ecological preferences of macroinvertebrates respond to urban pollution gradients, including evidence from the Niger Delta ecoregion of Nigeria (e.g., Edegbene and Akamagwuna, 2022). It is important to observe that Edegbene et al. (2021b) made an important distinction between traits and ecological preferences, where traits are physiological, morphological, and behavioural characteristics of organisms, ecological preferences represent the results of the interactions of organisms with the environment. The evaluation of traits is important for assessing and quantifying the ecological integrity of riverine ecosystems, and helps to provide understanding, for example, of overall ecosystem health (Edegbene et al., 2020a; Edegbene et al., 2020b; Edegbene et al., 2022). In Northern Africa (e.g., Morocco), many studies conducted in the Rif region documented the functional responses of key taxonomic groups - EPT (Ephemeroptera, Plecoptera, and Trichoptera), OCH (Odonata, Coleoptera, and Heteroptera) (El Yaagoubi et al., 2023; El Yaagoubi et al., 2024a; El Yaagoubi et al., 2024b). The FFGs categorize macroinvertebrates based on traits relevant to food acquisition, providing an accessible means to assess environmental conditions and ecosystem processes (Merritt et al., 2017). Their composition and diversity offer valuable insights into ecosystem functioning, with the relative abundance of each group informing key ecological properties, such as the autotrophy–heterotrophy ratio and energy flow in river food webs (Merritt et al., 2002).

5 Challenges and gaps in functional ecology studies in African aquatic ecosystems

Globally, Europe has led the development and application of trait-based biomonitoring (e.g., Dolédec et al., 1999; 2000; Charvet et al., 2000; Gayraud et al., 2003), with the approach also gaining traction in regions such as Australia (Chessman and Royal, 2004), New Zealand (Dolédec et al., 2006), North America (Merritt et al., 2002), and Latin America (Sotomayor et al., 2022). However, in Africa, the implementation of TBAs remains sporadic and uneven across regions. Significant contributions have emerged from South Africa and Nigeria, where pioneering research has advanced the field (e.g., Akamagwuna et al., 2021; Edegbene et al., 2020a; Edegbene et al., 2020b; Edegbene et al., 2021a; Edegbene et al., 2021b; Edegbene et al., 2023a; Edegbene et al., 2023b). This is reflected in the spatial distribution of scientific publications (Figure 1). Nigeria leads with 14 publications, followed by South Africa with 11—both standing out as regional leaders, likely due to stronger research infrastructure, dedicated expertise, and consistent international collaboration. Morocco has a more modest output with six publications, while Kenya (three), Egypt (two), and Algeria (one) contribute at lower levels (Figure 1). These imbalances underscore disparities in national research capacity and highlight the need for more inclusive and geographically representative TBAs studies across the continent.

In West Africa, Nigeria is the most productive country as measured in the trait-based aquatic ecology literature, with multiple studies in both the southern and northern regions, pioneered by Prof. Augustine Ovie Edegbene (e.g., Edegbene et al., 2020a; Edegbene et al., 2020b; Edegbene et al., 2021a; Edegbene et al., 2021b; Edegbene et al., 2023b; Edegbene and Akamagwuna, 2022; Akinpelu et al., 2024). Conversely, countries like Ghana and Benin Republic have limited or no data on TBAs, with available research focused largely on taxonomic composition (e.g., Oppong et al., 2021; Hounyèmè et al., 2023). In Southern Africa, most of the studies on TBAs are skewed towards South Africa (e.g., Addo-Bediako, 2021a; Addo-Bediako, 2021b; Addo-Bediako, 2022; Akamagwuna et al., 2019a; Addo-Bediako, 2019b; Addo-Bediako, 2022a; Addo-Bediako, 2022b; Addo-Bediako, 2023; Addo-Bediako, 2024; Matomela et al., 2021; Ntloko et al., 2021; Odume, 2020; Odume et al., 2023). In Northern Africa, researchers have examined TBAs in Algeria (Benzina et al., 2021), Egypt (Bendary et al., 2022; Bendary et al., 2023), and Morocco (El Yaagoubi et al., 2023; El Yaagoubi et al., 2024a; El Yaagoubi et al., 2024b; El Yaagoubi et al., 2025). In East Africa, Kenya has incorporated TBAs to study the ecology of freshwater species (Masese et al., 2014; Masese et al., 2023; Benjamin et al., 2023). There is relatively little evidence for trait-based biomonitoring or even existence of TBAs in freshwater environments of Uganda, Tanzania and Ethiopia (Olotu et al., 2024; Fentaw et al., 2024).

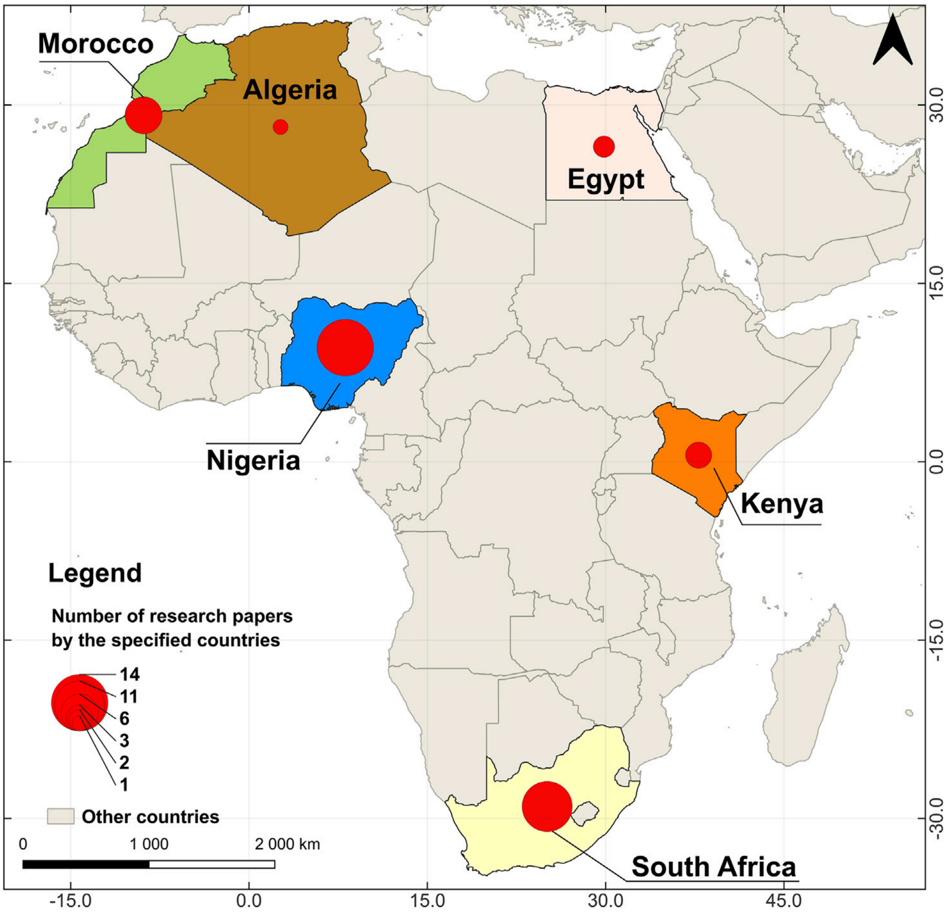

FIGURE 1
Geographic Distribution of Trait-Based ecological publications in selected African countries. Many other regions, such as Central, Eastern, and Southern Africa, still face significant constraints in TBAs development and exploration. Those challenges encompass the absence of integrative trait databases (open-access), the lack of technical capacity, the lack of funding and harmonized biomonitoring frameworks. In Ethiopia, Kenya, Uganda, and Rwanda, freshwater ecosystems assessments still rely mainly on traditional taxonomic approaches. While valuable, these methods often fail to capture ecological processes and responses that TBAs can reveal. This limits the capacity to track important ecological responses to stressors such as pollution, climate variability and land-use change. In order to address these gaps throughout Africa there is a need to co-develop regionally adapted TBAs that employ strong trait data alongside local ecological knowledge. For instance, by establishing TBAs in selected countries in North Africa (e.g., Morocco), West Africa (e.g., Nigeria), Southern Africa (e.g., South Africa), Eastern Africa (e.g., Kenya) and Central Africa (e.g., Cameroon), a more Afro-centred databases on TBAs developments that is functionally-based focused will form biomonitoring frameworks that can scale across the continent, thereby improving the examination of freshwater ecosystems in the wake of accelerating anthropogenic pressures.

6 Functional traits classes/attributes analyzed in African freshwater ecosystems and their applications

Functional traits have been used globally to assess the ecological health conditions of freshwater ecosystems (Kuzmanovic et al., 2017; Hill et al., 2021b). The significance of traits and TBAs have lies in their wide geographical usability-as organisms' traits does not vary from one geographical region to another, unlike the taxonomic-based approaches (Edegbene et al., 2021b). Some of the traits that have been explored include; body sizes, body shapes, body armouring, mobility, mode of respiration, feeding habits, food preferences, reproductive stages, etc. These traits portray important mechanisms in detecting the responses of organisms (e.g., macroinvertebrates) to varied environmental conditions. For instance, it has widely been documented that organisms with small body size, respond positively to environmental degradation while those with large body size are sensitive to pollution (e.g., Desrosiers et al., 2019).

Lately, traits and TBAs are beginning to gain traction in Africa. Some of the commonly analyzed traits in Africa include maximal potential size, life cycle duration, number of reproductive cycles per year, aquatic stages, respiratory mechanisms, body armouring, mobility, body shape, feeding habits, food preferences, dispersal modes, and resistance forms (e.g., Akamagwuna et al., 2019a; Akamagwuna et al., 2019b; Edegbene et al., 2020a; Akamagwuna et al., 2020b; Akamagwuna et al., 2021a; Akamagwuna et al., 2021b; Odume, 2020; El Yaagoubi et al., 2025). For example, the trait maximal potential size includes attributes such as "very small", (≤5 mm), "small" (>5–10 mm), "medium" (>10–20 mm), "large" (>20–40 mm) and "very large" (>40–80 mm) have been widely explored in Africa.

Another trait widely explored in Africa is life cycle duration, and this trait has attributes such as univoltinism- 1 year, bivoltinism-

2 years, multivoltinism- > 2 years, semivoltinism-longer than 1 year (Akamagwuna et al., 2019a; 2019b; Odume, 2020; Akamagwuna, 2021; Akamagwuna et al., 2021; Edegbene et al., 2020b; Edegbene et al., 2021a; Edegbene et al., 2021b; Edegbene et al., 2021c; Edegbene et al., 2021d; Edegbene et al., 2021e). The number of reproductive cycles per year and aquatic stages (e.g., egg, larva, nymph and pupa) have also been incorporated into trait-based assessments in Africa (e.g., Akamagwuna et al., 2021; Odume, 2020).

Despite the attention that traits and TBAs have received in Africa, there are regional imbalance in the application of traits and TBAs in assessing ecological health of freshwater ecosystems in Africa. For instance, in Western Africa (e.g., Nigeria) and Southern Africa (e.g., South Africa), most of the outlined functional trait attributes have been explored (e.g., Akinpelu et al., 2024; Edegbene et al., 2023b; Akamagwuna et al., 2022a) unlike in some other regions where selected traits have been explored. For instance, in Kenya and Morocco, studies on TBAs have mostly be centered on functional feeding groups (e.g., Masese et al., 2014; El Yaagoubi et al., 2023). This regional imbalance in the exploration of traits has hindered the advancement of the TBAs in Africa. This call for urgent intervention to build the research-based of the use of functional traits to assess the ecological health of freshwater ecosystems in the continents. A summary of selected trait-based studies and their corresponding references in Africa is provided in Supplementary Table S1.

7 Methodological approaches in trait-based analyses in African aquatic ecosystems

The TBAs in aquatic ecology rely on two key methodological dimensions: (i) how functional traits are coded and assigned to taxa, and (ii) the statistical tools used to analyze relationships between traits, species composition, and environmental gradients.

7.1 Trait coding and affinity scores

In ecological studies of benthic macroinvertebrates traits, researchers allocated codes to functional traits before analysis. Two systems are commonly applied: binary coding and fuzzy coding. Binary coding (e.g., 0 and 1) is simple and convenient but tends to over-simplify trait expression, failing to capture variability or uncertainty within taxa. Fuzzy coding, by contrast, represents the degree of association between a taxon and a trait (e.g., 0, 1, 2, 3 or 0, 1, 3, 5), providing a more nuanced reflection of ecological reality (Chevenet et al., 1994). Introduced within the fuzzy set theory framework of Zadeh (1965), this system allows traits to be expressed as affinity scores that capture partial associations and enable complex modeling of trait–environment relationships. Fuzzy coding has become increasingly favored in African TBAs studies because of its ability to improve predictive power and identify functionally important traits. Examples include applications by Odume (2020), Edegbene et al. (2020b), Edegbene et al. (2021a), Edegbene et al. (2021b), and El Yaagoubi et al. (2025). However, binary coding has also been employed, for instance by Edegbene and Akamagwuna (2022), particularly in contexts where data availability or simplicity is prioritized.

7.2 Statistical tools for trait–environment analysis

Once traits are coded, statistical tools are employed to link them with environmental gradients and ecosystem processes. Among these, RLQ analysis is one of the most widely used approaches. RLQ is a multivariate method that simultaneously examines species traits (L), environmental variables (R), and species abundance or presence across sites (Q) (Dolédec et al., 1996). RLQ enables researchers to identify which traits correspond most strongly to environmental gradients and to reveal patterns in trait distributions that inform ecosystem dynamics. In African freshwater ecosystems, RLQ has been applied to explore ecosystem health, land-use impacts, and pollution stressors (Edegbene et al., 2020a; Edegbene et al., 2020b; Edegbene et al., 2021a; Edegbene et al., 2023b; Edegbene et al., 2024b; El Yaagoubi et al., 2024a; Edegbene et al., 2024b). Complementary methods, such as fourth-corner and combined fourth-corner tests, are also widely used. These approaches directly test the relationships between species traits and environmental variables, making it possible to identify sensitive or tolerant traits and guide conservation and management interventions (Akamagwuna et al., 2019b; Edegbene et al., 2020a; Edegbene et al., 2021b; Edegbene et al., 2022; Edegbene et al., 2023b). Factorial maps, though less frequently applied in African contexts, provide an additional tool for visualizing associations among traits, community composition, and environmental drivers, helping to pinpoint biodiversity hotspots or shifts in community structure (Edegbene et al., 2023b; El Yaagoubi et al., 2024c).

Together, these methodological tools—trait coding systems and statistical frameworks—form the backbone of TBAs in African aquatic ecology. By combining nuanced trait representation with robust analytical methods, researchers are better able to characterize organism–environment interactions and predict ecological responses to stressors.

8 Gaps and general challenges in trait databases for African species

Despite the growing prevalence of TBAs in ecosystem monitoring and conservation across regions such as Europe, North America, and Australia—where both *a priori* and *a posteriori* methods are commonly applied (Dolédec and Chessel 1994; Townsend and Hildrew 1994)—many areas like Africa still lack the necessary tools to fully implement TBAs (Edegbene et al., 2021a; Edegbene et al., 2021b; El Yaagoubi et al., 2025). The *a priori* approach relies on predefined trait categories and assumptions drawn from literature or expert knowledge (Statzner et al., 2008; Martini et al., 2021). This method is particularly useful when there is a well-established theoretical framework linking ecosystem functions to specific traits that correspond to particular environmental conditions (Usseglio-Polatera et al., 2000; Pallottini et al., 2017; Schmera et al., 2022). For example, category for trait considerations may be based on respiration types (gill versus cutaneous respiration) in benthic macroinvertebrates or body size of fish species, to predict responses of aquatic ecosystems to changes in water quality or flow conditions. Another example in the *a priori* consideration of traits is the use of functional feeding groups in macroinvertebrates (e.g., shredders, scrapers, or filter feeders) to assess nutrient cycles and organic matter processing in freshwater systems. The *a posteriori* approach that extracts trait-environment relationships from empirical data is more adaptable to a local ecological context than traditional *a priori* approaches. The *a posteriori* approach offers the ability to identify traits that are context-specific which may be relevant to specific ecosystems (Edegbene et al., 2021b; Edegbene et al., 2021c). Within Africa, we still have an issue relying on expected standardized *a priori* trait capability frameworks. Standardized *a priori* trait capability frameworks often oversimplify Africa's immense range of ecological variation/heterogeneity across immense differences in climates, land uses, and biogeographic zones (Edegbene and Akamagwuna, 2022; El Yaagoubi et al., 2025). *A posteriori* approaches that are more firmly based on field and laboratory observations are more likely suited to provide context-specific dimensions of trait–environment relationships relevant to African freshwater systems, but regrettably, it is yet to be fully explored in the region.

9 Challenges of field applications of trait-based approaches (TBAs) in Africa

The application of TBAs in Africa faces several challenges, largely due to the continent's diverse ecosystems and climatic conditions. This ecological complexity complicates the standardization and consistent implementation of TBAs across multiple regions. Below, we outline the main challenges identified in the literature:

a. Habitat Diversity: Africa hosts a wide range of aquatic ecosystems, from ephemeral rivers and wetlands to large lakes and estuaries (Fouchy et al., 2019; Mohammed et al., 2024b). These habitats display considerable variability in abiotic and biotic characteristics, including water temperature, salinity, total dissolved solids, and nutrient concentrations (Statzner et al., 2001; Scotti et al., 2022). Consequently, there is no universal TBAs framework, and different habitat types often require specific calibration of traits for accurate ecological assessment.
b. Climate Variability: The continent's diverse climate introduces additional complexity. Temporal fluctuations in rainfall, seasonal droughts, and extreme events such as floods can strongly affect hydrological regimes, water quality, and nutrient availability, directly influencing aquatic communities (Brown et al., 2013). Standard TBAs frameworks, which often assume relatively stable conditions, may not fully capture these dynamic seasonal and spatial patterns.
c. Limited Access to Resources: Conducting field studies in remote or underdeveloped regions presents logistical and practical challenges. Limited funding, insufficient scientific equipment, and inadequate infrastructure can restrict the collection of comprehensive ecological data (Masese et al., 2014). Such constraints hinder large-scale TBAs applications and limit researchers' ability to apply modern methods effectively.
d. Taxonomic Resolution: In many African contexts, species-level taxonomic expertise is limited, resulting in most TBAs being conducted at the family level (Agboola and Bekun, 2019; Edegbene et al., 2020b; Edegbene et al., 2021a; Edegbene et al., 2021b; Edegbene et al., 2021c; El Yaagoubi et al., 2024a; El Yaagoubi et al., 2024b). While family-level analyses provide general insights, they miss species-specific interactions and adaptations, reducing the precision of ecological assessments and limiting targeted conservation efforts. Important functional trait differences often occur at the species level, and overlooking these diminishes the effectiveness of TBAs in capturing key ecological dynamics (Mueller et al., 2013; Sotomayor et al., 2022; El Yaagoubi et al., 2025).
e. Functional Expertise: Beyond taxonomic knowledge, there is a shortage of researchers skilled in linking functional traits to ecosystem processes, particularly for Afrotropical fauna. The ecological roles of many African species, especially endemics, remain poorly understood due to limited trait information. This knowledge gap further constrains the application of TBAs in highly biodiverse regions.
f. Comparative Deficiency: In contrast to regions such as Europe, North America, and Australia—where close collaboration among taxonomists, ecologists, and modelers has enabled high-resolution, species-level TBAs and robust trait databases—most African studies rarely reach beyond the genus level. The scarcity of species-level assessments limits Africa's capacity to fully understand and manage its aquatic ecosystems, highlighting a need for enhanced collaboration and database development.

10 Future directions, conclusions and recommendations

Building on the major challenges outlined in the previous section, this framework aims to enhance biodiversity assessment and ecosystem management in Africa by promoting the use of TBAs across research, policy, and practice. Key strategies include:

- Capacity Building: To address the shortage of taxonomic expertise, local capacity should be enhanced through hands-on field training in biodiversity hotspots, development of digital learning modules, and provision of AI-based identification tools. These initiatives aim to establish a self-sustaining network of African taxonomists while supporting early-career researchers and promoting policy advocacy.
- Trait Database Development: A comprehensive, open-access trait database for key and invasive species is critical. Data can be aggregated from academic research, NGOs, and citizen science initiatives and shared via portals such as Afro-Traits. Complementary technologies—mobile applications, machine

learning approaches to museum collections, and low-cost environmental sensors—can further facilitate data collection and accessibility.

- Expanded Geographic Coverage: TBAs should be extended to under-represented ecosystems, including arid-zone streams, coastal lagoons, and groundwater systems. Approaches such as remote sensing, long-term ecological monitoring, and collaboration with large-scale initiatives (e.g., the African Great Green Wall) can enhance spatial representation and ecological relevance.
- Interdisciplinary Collaboration and Policy Integration: Strengthening partnerships between researchers, policymakers, conservation practitioners, and water managers is essential to co-produce actionable knowledge. TBAs should be integrated into national and regional monitoring frameworks and aligned with existing water quality standards and biodiversity strategies.
- Sustainable Funding: Dedicated support from national governments and international donors is crucial for implementing, scaling, and maintaining trait-based biomonitoring programs.

Author contributions

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Conflict of interest

Author UNK is employed by Saskatchewan Government Insurance.

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

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