

## RESEARCH ARTICLE OPEN ACCESS

# Assessing the Conservation Status, Drivers of Threat and Available Occurrence Records of Sub-Saharan African Freshwater Molluscs: Gaps and Patterns

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## ABSTRACT

Freshwater molluscs are key bioindicators of ecosystem health, yet their conservation status and data coverage in sub-Saharan Africa remain poorly understood. Mollusca is the third most evaluated phylum on the IUCN Red List in Africa, with 1394 species assessed (656 freshwater), of which 39.6% are Least Concern and 12% Critically Endangered. Notably, 22.4% are Data Deficient, signalling major knowledge gaps. This study assessed the availability of freshwater mollusc occurrence records and molecular data across mainland sub-Saharan Africa. Occurrence records were compiled from the Global Biodiversity Information Facility (GBIF), filtered geographically, taxonomically standardised and linked to IUCN Red List categories. In parallel, cytochrome oxidase I (COI) barcode coverage was evaluated using the Barcode of Life Data System (BOLD). We identified 36,927 occurrence records, with South Africa (6683) and Tanzania (4299) contributing the most data. Sampling effort was strongly clustered in central and southern Africa, revealing pronounced spatial biases. The Democratic Republic of Congo supported the highest number of threatened species, including 10 Critically Endangered and 19 Endangered taxa. Despite this concentration of diversity and threat, only 94 sub-Saharan freshwater mollusc species possessed COI barcodes, exposing a severe shortfall in molecular reference data. By integrating GBIF occurrences, IUCN assessments and BOLD barcodes, this work jointly evaluates conservation status, data completeness and genetic information for freshwater molluscs in sub-Saharan Africa. Analyses of geographic, taxonomic and threat-related patterns exposed critical gaps in occurrence records, inconsistencies in threat documentation and widespread deficiencies in molecular resources. Pollution, habitat modification, invasive species and overharvesting were the most frequently reported threats. Collectively, these findings identify priority regions and taxa for reassessment, enhanced monitoring and strategic expansion of genetic reference libraries, providing a targeted framework to strengthen freshwater mollusc conservation in the region.

## 1 | Introduction

Sub-Saharan Africa hosts a rich and diverse array of freshwater habitats that support a wide variety of mollusc species, many of which play essential roles in maintaining ecological balance (Darwall et al. 2011; Seddon et al. 2011; Atkinson et al. 2023).

Within Mollusca, the classes Gastropoda and Bivalvia comprise approximately 96% of all known species (Gomes-dos Santos et al. 2020). Freshwater molluscs provide crucial ecosystem services, including improving water quality, enhancing nutrient cycling and supporting aquatic food webs (Oehlmann and Schulte-Oehlmann 2003; Atkinson et al. 2023), and serve as

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bioindicators of environmental change due to their sensitivity to shifts in water quality and habitat condition (Ziganira and Downs 2025). Biodiversity knowledge across the region is, however, highly uneven, with research effort historically concentrated in areas such as South Africa, the catchments of Lake Victoria, Lake Tanganyika and Lake Malawi, the Niger River delta and the Congo Basin, reflecting both the exceptional molluscan diversity of these systems and the elevated research activity associated with schistosomiasis vector monitoring in these regions (Herbert 1998; Steinmann et al. 2006; Seddon et al. 2011; Schultheiß et al. 2011). Despite a recent increase in research output on African freshwater snails (Ziganira and Downs 2025), significant knowledge gaps persist regarding species distributions, conservation status and population trends across much of sub-Saharan Africa (Ziganira et al. 2026), further reflected in the considerably less attention molluscs receive in conservation assessments compared to more charismatic taxa such as mammals, birds and reptiles (Cardoso et al. 2011; Böhm et al. 2021; Bourlat et al. 2023). Similarly to other taxonomic groups, mollusc research has historically had a strong European and North American bias (Aldridge et al. 2023). Globally, more than 7000 species of freshwater molluscs have been identified, with around one-third estimated to be threatened with extinction, a concern compounded by evidence that freshwater biodiversity is declining more rapidly than terrestrial biodiversity and that extinction risk is likely equally high or higher in under-studied regions and taxa (Dudgeon et al. 2006; Böhm et al. 2021, 2022). Within the Afrotropical region, significant declines in Mollusca populations have been reported, particularly within the order Unionida, attributed to a combination of confirmed species extinctions and ongoing taxonomic revisions (Graf and Cummings 2021). Freshwater molluscs are increasingly vulnerable to a range of anthropogenic threats, including habitat destruction, pollution and the introduction of non-native species (Darwall et al. 2011, 2018; Prestes et al. 2024), while invasive species such as *Tarebia granifera* and *Melanoides tuberculata* remain poorly studied in Africa despite representing a globally significant driver of biodiversity loss (Gurevitch and Padilla 2004; Dueñas et al. 2021; Ziganira and Downs 2025).

The IUCN Red List serves as a critical tool for global biodiversity conservation by offering an objective framework for assessing the risk of extinction, categorising species, and guiding policy and legislation (Borgelt et al. 2022; Bourlat et al. 2023). It is widely recognised as the most authoritative system for species conservation (Maes et al. 2015). As of 2024, the phylum Mollusca ranks third in terms of the number of species evaluated on the IUCN Red List of Threatened Species, with 1394 species assessed in Africa, 656 of which inhabit freshwater systems (IUCN 2024). However, it suffers from uneven taxonomic coverage. The conservation status of these freshwater species is summarised in Table 1. Although birds, mammals and amphibians have been comprehensively assessed, reptiles and fish remain under-represented, with vertebrates covering only about 68 of the described species (Bachman et al. 2019). In contrast, invertebrates, plants and fungi are significantly under-assessed, with fewer than three known species evaluated (Bachman et al. 2019). Globally, approximately one in six assessed species are considered DD (Bland et al. 2015). Although DD species lack sufficient data for full assessment, studies suggest that they may be at equal or even greater risk of extinction than species

**TABLE 1** | Conservation status of freshwater molluscs in Africa (IUCN 2024) including number of species and percentage.

| Conservation status        | Number of species | Percentage (%) |
|----------------------------|-------------------|----------------|
| Critically Endangered (CR) | 79                | 12.0           |
| Endangered (EN)            | 75                | 11.4           |
| Vulnerable (VU)            | 38                | 5.8            |
| Near Threatened (NT)       | 36                | 5.5            |
| Data Deficient (DD)        | 147               | 22.4           |
| Least Concern (LC)         | 260               | 39.6           |
| Extinct (EX)               | 21                | 3.2            |
| Total freshwater species   | 656               | 100            |

classified formally as threatened (Bland et al. 2015; Roberts et al. 2016). While the high proportion of LC species may appear reassuring, the substantial number of DD species highlights a major limitation in assessing the conservation status of invertebrates (Bourlat et al. 2023).

Bourlat et al. (2023) noted that species are often classified as DD due to unresolved taxonomy, limited knowledge of their geographic range, lack of occurrence data and insufficient information on population trends. These knowledge gaps correspond to well-established biodiversity shortfalls: the Wallacean shortfall, which reflects limited data on species distributions, and the Prestonian shortfall, which concerns the lack of information on species abundance and population dynamics (Lopes-Lima et al. 2021). In sub-Saharan Africa, Seddon et al. (2011) found that the primary reasons for species being classified as DD are taxonomic uncertainty and poor knowledge of species distributions, a concern echoed in subsequent regional IUCN assessments for both Western and Central Africa (Darwall et al. 2011; IUCN 2024). Globally, close to one-third of freshwater mollusc species are estimated to be threatened with extinction, with pollution and modification of natural systems reported as the most frequently documented threats (Böhm et al. 2021). Conservation efforts have traditionally favoured more charismatic taxa, leading to a significant under-representation of invertebrates, despite their vital ecological functions (Cardoso et al. 2011; Böhm et al. 2021; Bourlat et al. 2023). Correcting this imbalance is particularly critical in biodiversity-rich regions like sub-Saharan Africa, where freshwater molluscs are integral to the health and sustainability of aquatic ecosystems. Similarly to other taxonomic groups, mollusc research has historically had a strong Europe and North America bias (Aldridge et al. 2023).

Recent advances in molecular techniques offer promising solutions to address these limitations. DNA barcoding, particularly using the cytochrome oxidase I (COI) mitochondrial gene, has proven effective in species identification and resolving taxonomic ambiguities, enabling more accurate species inventories (Andrew et al. 2013; Kress et al. 2015; Sousa 2024). DNA barcodes serve as standardised genetic identifiers for species worldwide. However, their application in mollusc

research remains limited compared to other groups, including invertebrates like arthropods (Gomes-dos Santos et al. 2020; Sousa 2024). Furthermore, molecular approaches are not without their own limitations; in Africa specifically, the application of DNA barcoding to freshwater snails has been hindered by incomplete reference databases, uneven geographic sampling across water basins and the historical concentration of molecular studies in disease vector taxa rather than broader taxonomic groups (Ziganira and Downs 2025). These gaps in sequence coverage risk miss assignment of taxa and may further compound existing taxonomic uncertainties rather than resolve them (Gomes-dos Santos et al. 2020; Ziganira and Downs 2025). Additionally, environmental DNA (eDNA) techniques have emerged as powerful tools for non-invasive biodiversity monitoring by detecting species through genetic traces in water samples (Thomsen et al. 2012; Clusa et al. 2017; Sousa 2024).

Despite the ecological and conservation significance of freshwater molluscs in sub-Saharan Africa, occurrence records remain spatially fragmented and geographically biased, largely concentrated in a limited number of well-studied countries, leaving vast areas severely undersampled (Ziganira and Downs 2025; Ziganira et al. 2026). The majority of assessed species remain Data Deficient, reflecting persistent Wallacean and Prestonian shortfalls that undermine the reliability of IUCN Red List assessments for the region (Lopes-Lima et al. 2021; Bourlat et al. 2023). Compounding this, genetic barcode data for sub-Saharan African freshwater molluscs remain sparse and unevenly distributed, limiting the utility of molecular tools for resolving taxonomic uncertainties and improving species inventories (Gomes-dos Santos et al. 2020; Ziganira and Downs 2025). Without a systematic evaluation of the extent and distribution of these data gaps, targeted conservation efforts for native freshwater molluscs in sub-Saharan Africa cannot be effectively prioritised.

To address these gaps, a comprehensive gap analysis was conducted to evaluate the availability of occurrence records and genetic barcode data (COI) for freshwater mollusc species in sub-Saharan Africa, along with their current status on the IUCN Red List. The study assessed the completeness of species occurrence data at the country level, analysed the availability of genetic barcoding data and identified the main challenges in red-listing freshwater molluscs throughout the region.

## 2 | Methods

### 2.1 | Occurrence Records

Using GBIF (2024), occurrence data for Mollusca from the African continent were downloaded with records restricted to a basis of record identified as preserved specimens, thereby excluding fossil records at the point of download, with no restriction on date ranges. The initial dataset contained 408,990 occurrences for the entire African continent as of May 20, 2024. These data were compiled in MS Excel, after which duplicate records were identified and removed based on matching combinations of species name, country and coordinate data where available. All species names were

subsequently cross-referenced against MolluscaBase (2024) to ensure taxonomic standardisation, with accepted names used consistently throughout the dataset to account for synonymies. Records were then classified by country, after which all records not originating from mainland sub-Saharan Africa were removed. Records with missing or zero coordinate values were removed, and records flagged by GBIF as having known geospatial issues were excluded from spatially explicit analyses. The remaining records were classified by taxonomic level (order, class, family, genus and species) and assigned as freshwater or brackish molluscs based on the taxonomic resolution required to determine habitat type (Table 2). Records with insufficient taxonomic resolution, or those identified only to high-level taxonomy, were assigned to an incomplete category (Figure 1 and Table 2). Two additional classes were created to accommodate records that could not be confidently assigned to freshwater habitats: an inconclusive marine class for taxa known to occur in both marine and freshwater environments, and an inconclusive terrestrial class for taxa occurring in both terrestrial and freshwater environments. These categories were applied to records resolved at the genus or species level, but whose habitat associations could not be definitively determined due to overlapping ecological distributions (Figure 1 and Table 2). Several mollusc taxa occupy transitional environments, such as estuaries, seepage zones and wetland margins, where habitat boundaries between freshwater, brackish and marine systems are ecologically diffuse (Attrill and Rundle 2002; Graf and Cummings 2007; Strong et al. 2008). Consequently, their habitat classification varies between sources, necessitating treatment as an inconclusive category to avoid misassigning habitat associations.

The total number of records was determined for each of the four classification groups in the 43 countries within sub-Saharan Africa. To assess temporal trends in data availability, freshwater mollusc records were classified into four time periods, before 1900, 1900–1950, 1950–2000 and after 2000, at the country level (Table 3, Figure 2). This periodisation reflects recognised shifts in collection effort and data availability across the history of natural history and follows comparable temporal binning approaches applied to freshwater mollusc occurrence data (Ziganira et al. 2026). This allowed for the evaluation of the historical sampling effort and possible temporal biases. A record was considered ‘complete’ if it met the following criteria: (1) an accepted scientific name verified in MolluscaBase (2024), (2) habitat information confirming freshwater occurrence, and (3) absence of taxonomic uncertainty such as unresolved synonymy or ambiguous placement at higher levels. This classification was applied at the country level to evaluate historical trends in data availability and potential sampling biases.

### 2.2 | Red List Data

#### 2.2.1 | Red Listed Species per Country

Upon completion of the analysis of the occurrence records for sub-Saharan Africa, all inconclusive or incomplete records were removed to generate a list of freshwater and brackish molluscs for each country, which contained only accepted species

**TABLE 2** | Occurrence records for freshwater and brackish molluscs in sub-Saharan countries, including total records, freshwater/brackish records, incomplete records and inconclusive records (terrestrial and marine).

| Country                      | Total records | Freshwater records | Incomplete records | Inconclusive records |     | Inconclusive year |
|------------------------------|---------------|--------------------|--------------------|----------------------|-----|-------------------|
|                              |               |                    |                    | (T)                  | (M) |                   |
| Angola                       | 702           | 467                | 177                | 0                    | 58  | 1865–2016         |
| Benin                        | 29            | 23                 | 0                  | 0                    | 6   | 1972–1984         |
| Botswana                     | 124           | 120                | 2                  | 0                    | 2   | 1880–2015         |
| Burkina Faso                 | 156           | 155                | 0                  | 0                    | 1   | 1900–2015         |
| Burundi                      | 19            | 18                 | 0                  | 0                    | 1   | 1955–1999         |
| Cameroon                     | 575           | 512                | 18                 | 0                    | 45  | 1891–2016         |
| Central African Republic     | 60            | 54                 | 0                  | 0                    | 6   | 1904–2013         |
| Chad                         | 494           | 494                | 0                  | 0                    | 0   | 1903–2019         |
| Congo                        | 294           | 228                | 41                 | 0                    | 25  | 1904–2006         |
| Côte d'Ivoire                | 309           | 295                | 2                  | 0                    | 12  | 1919–2017         |
| Djibouti                     | 44            | 3                  | 22                 | 1                    | 18  | 1926–2012         |
| Democratic Republic of Congo | 3934          | 3778               | 73                 | 0                    | 83  | 1875–2017         |
| Equatorial Guinea            | 157           | 73                 | 54                 | 0                    | 30  | 1919–2012         |
| Eritrea                      | 89            | 20                 | 57                 | 1                    | 11  | 1870–1973         |
| Ethiopia                     | 381           | 375                | 2                  | 1                    | 3   | 1870–2015         |
| Gabon                        | 166           | 132                | 18                 | 0                    | 16  | 1880–2013         |
| Gambia                       | 102           | 38                 | 18                 | 0                    | 46  | 1953–2013         |
| Ghana                        | 931           | 818                | 28                 | 0                    | 85  | 1920–2020         |
| Guinea                       | 110           | 68                 | 19                 | 0                    | 23  | 1909–1960         |
| Guinea-Bissau                | 10            | 6                  | 2                  | 0                    | 2   | 1988–2000         |
| Kenya                        | 2244          | 1982               | 138                | 37                   | 87  | 1889–2019         |
| Lesotho                      | 25            | 24                 | 1                  | 0                    | 0   | 1904–1998         |
| Liberia                      | 439           | 355                | 37                 | 0                    | 47  | 1880–2012         |
| Malawi                       | 957           | 920                | 36                 | 0                    | 1   | 1899–2012         |
| Mali                         | 70            | 70                 | 0                  | 0                    | 0   | 1927–2015         |
| Mauritania                   | 324           | 17                 | 254                | 0                    | 53  | 1909–2004         |
| Mozambique                   | 1067          | 302                | 477                | 4                    | 284 | 1864–2019         |
| Namibia                      | 195           | 142                | 46                 | 0                    | 7   | 1908–2017         |
| Niger                        | 3213          | 3213               | 0                  | 0                    | 0   | 1971–2017         |
| Nigeria                      | 536           | 437                | 78                 | 0                    | 21  | 1911–2021         |
| Rwanda                       | 64            | 62                 | 2                  | 0                    | 0   | 1902–1954         |
| South Africa                 | 6683          | 4383               | 1548               | 97                   | 655 | 1859–2022         |
| Senegal                      | 4231          | 3896               | 177                | 0                    | 158 | 1845–2018         |
| Sierra Leone                 | 227           | 160                | 23                 | 2                    | 42  | 1924–2006         |
| Somalia                      | 197           | 106                | 53                 | 4                    | 34  | 1895–1996         |

(Continues)

TABLE 2 | (Continued)

| Country              | Total records | Freshwater records | Incomplete records | Inconclusive records |       | Inconclusive year |
|----------------------|---------------|--------------------|--------------------|----------------------|-------|-------------------|
|                      |               |                    |                    | (T)                  | (M)   |                   |
| South Sudan          | 52            | 51                 | 1                  | 0                    | 0     | 1889–1950         |
| Sudan                | 515           | 436                | 55                 | 0                    | 24    | 1857–1956         |
| Eswatini (Swaziland) | 19            | 19                 | 0                  | 0                    | 0     | 1956–2001         |
| Tanzania             | 4299          | 3633               | 464                | 8                    | 194   | 1864–2019         |
| Togo                 | 93            | 83                 | 2                  | 0                    | 8     | 1969–1984         |
| Uganda               | 1591          | 1558               | 33                 | 0                    | 0     | 1909–2019         |
| Zambia               | 747           | 737                | 9                  | 0                    | 1     | 1900–2022         |
| Zimbabwe             | 453           | 421                | 25                 | 1                    | 6     | 1859–2019         |
| Total                | 36,927        | 30,684             | 3992               | 156                  | 2095  | —                 |
| Percentage           | —             | 83.09%             | 10.81%             | 0.42%                | 5.67% | —                 |

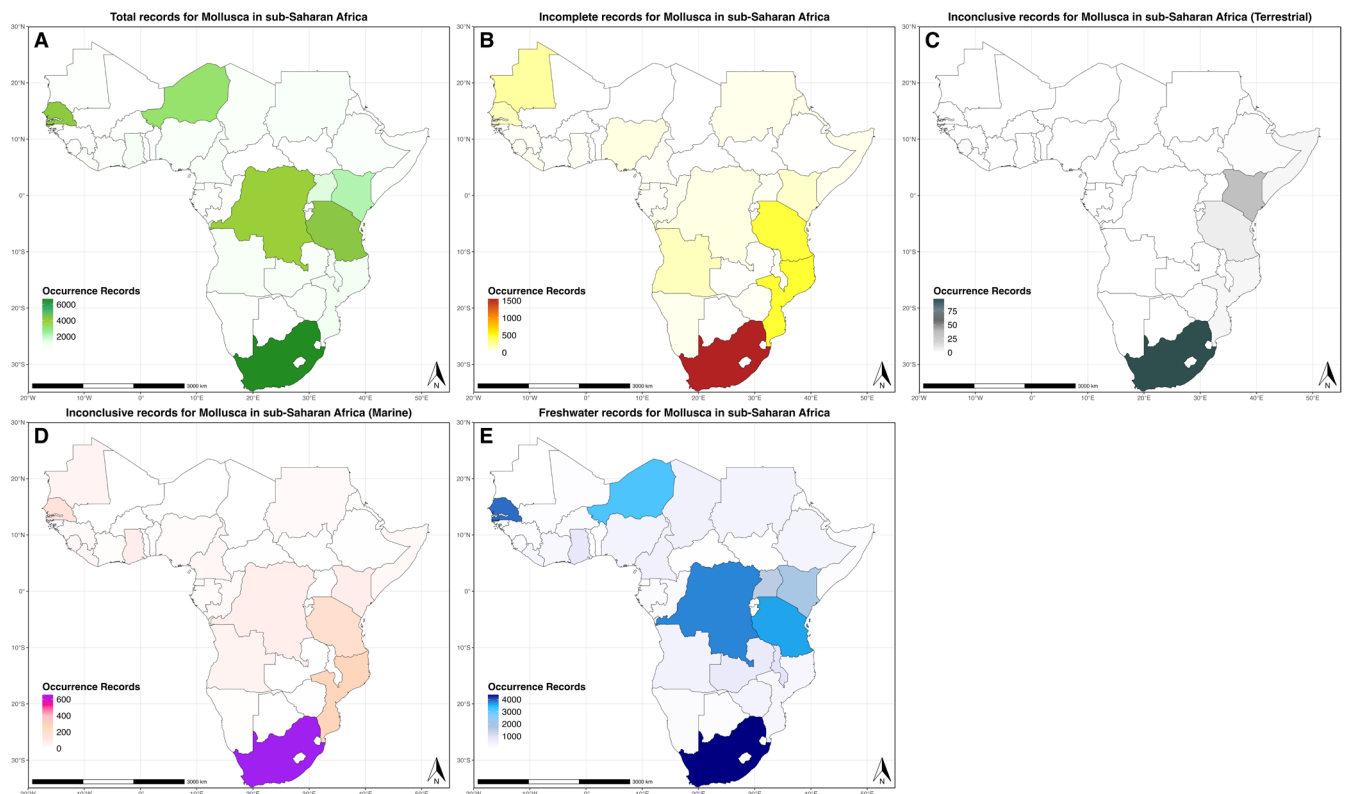


FIGURE 1 | Total occurrence records for sub-Saharan molluscs available on GBIF. The maps in the plot display the: (A) total occurrences records, (B) incomplete occurrences records, (C) inconclusive occurrences records (terrestrial), (D) inconclusive occurrences records (marine) and (E) freshwater occurrence records.

names. The status of the Red List for all African molluscs was retrieved from IUCN (2024) and matched to each species. For each country, the total number of species in each IUCN Red List category was calculated as of September 2024. These categories include Extinct (EX), Extinct in the wild (EW), Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Near Threatened (NT), DD and LC. A species is categorised as not

evaluated (NE) if it is absent from the IUCN (2024) website (Table 4 and Figure 3). For comparison with the Global and African percentages for each category of the red list, the advanced search function of the IUCN (2024) website was used to obtain the percentages for each of these categories of the red list for freshwater molluscs (Figure 4). To investigate the relationship between the number of species and the number

**TABLE 3** | Distribution of freshwater molluscs occurrence records from 1900–1950, 1950–2000, pre-1900 and post-2000.

| Country                      | 1900–1950 | 1950–2000 | Post-2000 | Pre-1900 |
|------------------------------|-----------|-----------|-----------|----------|
| Angola                       | 24        | 21        | 161       | 1        |
| Benin                        | 0         | 4         | 0         | 0        |
| Botswana                     | 14        | 21        | 18        | 2        |
| Burkina Faso                 | 0         | 10        | 0         | 0        |
| Burundi                      | 2         | 69        | 15        | 0        |
| Cameroon                     | 26        | 95        | 38        | 3        |
| Central African Republic     | 5         | 0         | 3         | 0        |
| Chad                         | 6         | 29        | 395       | 0        |
| Congo                        | 37        | 27        | 55        | 0        |
| Côte d'Ivoire                | 2         | 26        | 97        | 0        |
| Democratic Republic of Congo | 349       | 570       | 95        | 25       |
| Djibouti                     | 0         | 0         | 0         | 0        |
| Equatorial Guinea            | 13        | 2         | 1         | 0        |
| Eritrea                      | 1         | 0         | 2         | 0        |
| Eswatini                     | 0         | 10        | 6         | 0        |
| Ethiopia                     | 27        | 103       | 2         | 1        |
| Gabon                        | 3         | 16        | 11        | 1        |
| Gambia                       | 0         | 7         | 0         | 0        |
| Ghana                        | 7         | 659       | 3         | 0        |
| Guinea                       | 2         | 2         | 0         | 0        |
| Guinea-Bissau                | 0         | 0         | 0         | 0        |
| Kenya                        | 72        | 439       | 915       | 1        |
| Lesotho                      | 0         | 4         | 0         | 0        |
| Liberia                      | 25        | 19        | 3         | 3        |
| Malawi                       | 13        | 237       | 229       | 1        |
| Mali                         | 4         | 14        | 2         | 0        |
| Mauritania                   | 0         | 11        | 0         | 0        |
| Mozambique                   | 10        | 58        | 69        | 4        |
| Namibia                      | 4         | 63        | 9         | 0        |
| Niger                        | 0         | 16        | 3175      | 0        |
| Nigeria                      | 8         | 44        | 199       | 0        |
| Rwanda                       | 7         | 4         | 0         | 0        |
| Senegal                      | 7         | 10        | 3561      | 8        |
| Sierra Leone                 | 7         | 58        | 1         | 0        |

(Continues)

**TABLE 3** | (Continued)

| Country      | 1900–1950 | 1950–2000 | Post-2000 | Pre-1900 |
|--------------|-----------|-----------|-----------|----------|
| Somalia      | 0         | 26        | 0         | 0        |
| South Africa | 249       | 2024      | 570       | 28       |
| South Sudan  | 5         | 3         | 2         | 0        |
| Sudan        | 107       | 54        | 0         | 0        |
| Tanzania     | 113       | 299       | 2045      | 3        |
| Togo         | 0         | 65        | 0         | 0        |
| Uganda       | 117       | 183       | 201       | 0        |
| Zambia       | 91        | 152       | 189       | 0        |
| Zimbabwe     | 20        | 82        | 93        | 2        |

of occurrence records in different categories of IUCN, scatter plots were generated for each category IUCN (2024). For each category, a correlation analysis was conducted to assess the strength and significance of the relationship between these two variables. The coefficient of determination ( $R^2$ ) and the  $p$ -value were calculated to quantify the linear association. Scatter plots were produced using the ggplot2 package in R (Wickham 2016), with a regression line included to illustrate the direction and strength of the linear trend. The  $p$ -values smaller than 0.0001 were reported as  $<0.001$  to enhance readability. Each plot was colour-coded according to the official IUCN colour scheme to ensure consistency and clarity in visual representation (Figure 5).

### 2.2.2 | Threat Summary

Threats to freshwater mollusc species in sub-Saharan Africa were obtained using the IUCN (2024) website and its Threat Classification Scheme version 3.2 (IUCN 2024). The full list of threat categories is shown in Table A1. For each category of threat, the number of affected species was recorded (Figures 6 and 7). A single species can face multiple threats, as these categories are not mutually exclusive. As a result, the totals for each threat category exceed the total number of species assessed.

### 2.3 | Cytochrome Oxidase I

The availability of COI barcodes for the list of accepted freshwater mollusc species in sub-Saharan Africa was evaluated using the Barcode of Life Database (BOLD) version 4 (Ratnasingham and Hebert 2007). The Barcode Index Numbers (BINS) database was queried using the relevant genus names; the results were then downloaded in August 2024 to evaluate barcode availability. To be considered valid, the barcode must originate from sub-Saharan Africa. The barcodes were then classified as 'available' if there was a barcode that originated from sub-Saharan Africa or as 'unavailable' if there was not a barcode available. For records in which the location was not specified or disclosed, they were classified as 'inconclusive' (Figure 8). Where relevant, the NCBI GENBANK

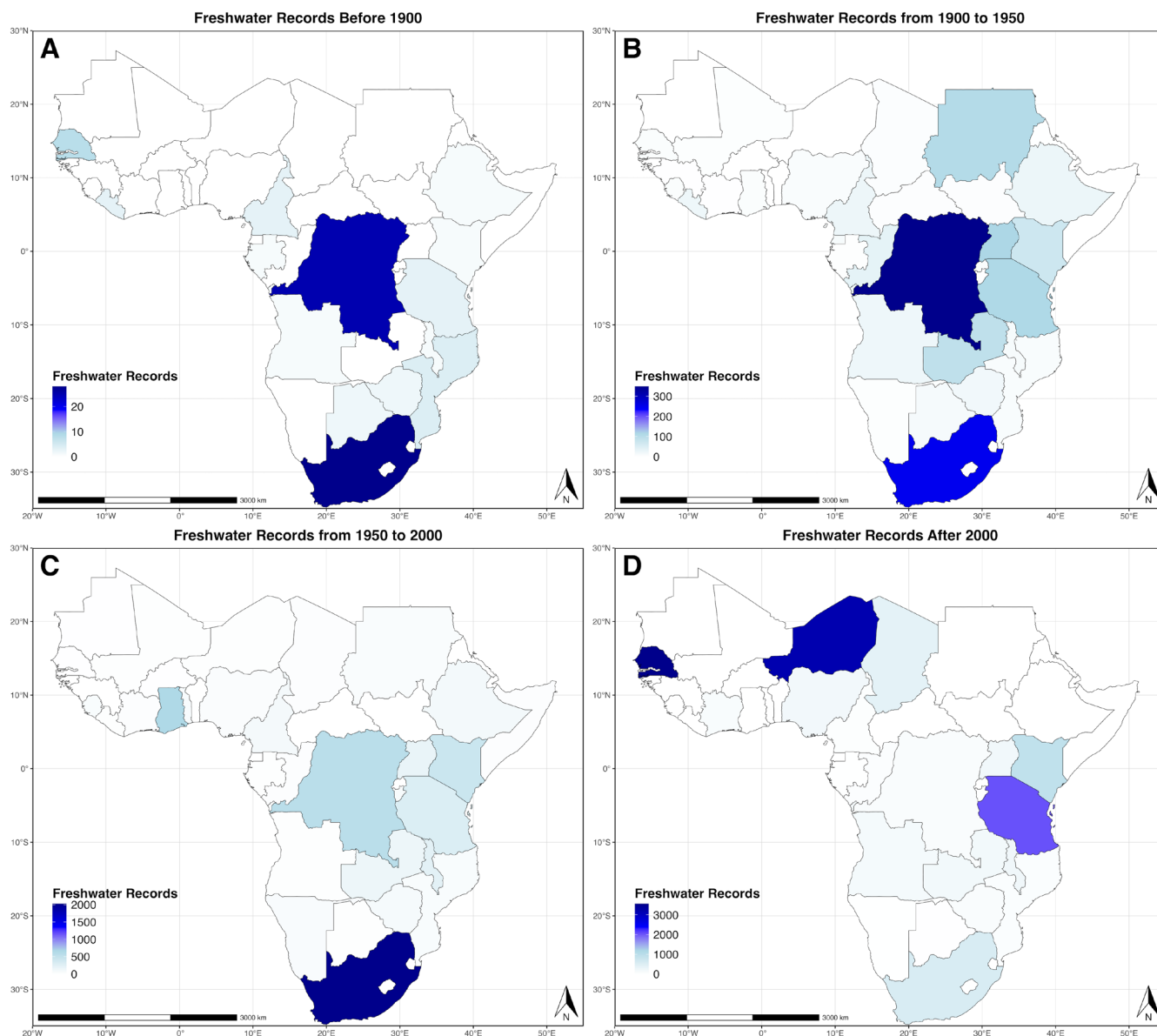


**FIGURE 2** | Distribution of freshwater mollusc occurrence records throughout the years based on data available on GBIF. The maps in the plots display the: (A) occurrence records pre-1900, (B) occurrence records 1900–1950, (C) occurrence records 1950–2000 and (D) occurrence records post-2000.

database (Benson et al. 2009) was also consulted for available COI sequences.

### 3 | Results

#### 3.1 | Occurrence Records

The 43 different sub-Saharan African countries have noticeable differences in the availability of occurrence records. Overall, sub-Saharan Africa had 36,927 records available for all 43 different countries on GBIF with 620 species present. The species records differ between the different countries, with South Africa ( $n = 6683$ ), Tanzania ( $n = 4299$ ), Senegal ( $n = 4231$ ) and the Democratic Republic of Congo ( $n = 3934$ ) having upwards of 3000 records available (Table 2). In contrast,

countries like Burundi ( $n = 19$ ), Eswatini (Swaziland) ( $n = 19$ ) and Guinea-Bissau ( $n = 10$ ) have fewer than 20 records available (Table 2 and Figure 1).

Of the 36,927 records available, 83% of the records are complete freshwater/brackish records. Countries such as Chad (100%), Niger (100%), Rwanda (97%) and Senegal (92%) have the highest percentage of complete records, while Mozambique (28%), Eritrea (24.5%), Djibouti (6.8%) and Mauritania (5.2%) have the lowest (Table 2). Most records are concentrated in the central African region followed by southern Africa (Figure 1). The most records are found in South Africa ( $n = 4383$ ), Senegal ( $n = 3896$ ), Democratic Republic of Congo ( $n = 3778$ ), Tanzania ( $n = 3633$ ) and Niger ( $n = 3213$ ). The lowest number of complete freshwater records is found in Eritrea ( $n = 20$ ), Eswatini (Swaziland) ( $n = 19$ ), Burundi ( $n = 18$ ), Mauritania

**TABLE 4** | Global Red List status table for freshwater molluscs in sub-Saharan countries, categorising species by IUCN (2024) status.

| Country                      | NE | DD | LC  | NT | VU | EN | CR | EX |
|------------------------------|----|----|-----|----|----|----|----|----|
| Angola                       | 10 | 5  | 44  | 2  | 0  | 1  | 0  | 0  |
| Benin                        | 0  | 0  | 5   | 0  | 0  | 1  | 0  | 0  |
| Botswana                     | 0  | 0  | 16  | 0  | 1  | 0  | 0  | 0  |
| Burkina Faso                 | 1  | 0  | 5   | 0  | 0  | 0  | 0  | 0  |
| Burundi                      | 1  | 6  | 34  | 1  | 1  | 1  | 1  | 0  |
| Cameroon                     | 3  | 2  | 40  | 4  | 0  | 5  | 5  | 0  |
| Central African Republic     | 4  | 0  | 23  | 0  | 1  | 0  | 1  | 0  |
| Chad                         | 2  | 3  | 18  | 1  | 0  | 2  | 2  | 0  |
| Congo                        | 6  | 2  | 47  | 5  | 4  | 5  | 3  | 0  |
| Côte d'Ivoire                | 3  | 3  | 28  | 3  | 1  | 1  | 1  | 0  |
| Djibouti                     | 0  | 0  | 1   | 0  | 0  | 0  | 0  | 0  |
| Democratic Republic of Congo | 25 | 31 | 131 | 13 | 8  | 19 | 10 | 0  |
| Equatorial Guinea            | 0  | 0  | 9   | 2  | 0  | 1  | 0  | 0  |
| Eritrea                      | 0  | 0  | 5   | 0  | 0  | 0  | 0  | 0  |
| Ethiopia                     | 10 | 8  | 28  | 0  | 1  | 3  | 2  | 0  |
| Gabon                        | 2  | 2  | 21  | 1  | 0  | 1  | 0  | 0  |
| Gambia                       | 1  | 1  | 13  | 0  | 0  | 0  | 1  | 0  |
| Ghana                        | 3  | 1  | 32  | 2  | 0  | 1  | 4  | 0  |
| Guinea                       | 8  | 2  | 9   | 0  | 0  | 0  | 1  | 0  |
| Guinea-Bissau                | 0  | 0  | 2   | 1  | 0  | 0  | 0  | 0  |
| Kenya                        | 16 | 10 | 57  | 7  | 8  | 8  | 5  | 0  |
| Lesotho                      | 2  | 2  | 3   | 0  | 0  | 0  | 0  | 0  |
| Liberia                      | 2  | 3  | 20  | 2  | 1  | 0  | 2  | 0  |
| Malawi                       | 6  | 4  | 46  | 3  | 2  | 3  | 5  | 0  |
| Mali                         | 1  | 4  | 12  | 1  | 2  | 0  | 2  | 0  |
| Mauritania                   | 1  | 1  | 9   | 0  | 0  | 0  | 0  | 0  |
| Mozambique                   | 9  | 5  | 29  | 0  | 3  | 0  | 2  | 0  |
| Namibia                      | 1  | 2  | 31  | 1  | 0  | 0  | 1  | 0  |
| Niger                        | 0  | 0  | 16  | 0  | 0  | 0  | 1  | 0  |
| Nigeria                      | 5  | 4  | 42  | 3  | 0  | 1  | 0  | 0  |
| Rwanda                       | 3  | 0  | 12  | 1  | 1  | 0  | 1  | 0  |
| South Africa                 | 37 | 29 | 61  | 3  | 0  | 5  | 5  | 0  |
| Senegal                      | 6  | 2  | 41  | 1  | 2  | 1  | 2  | 0  |
| Sierra Leone                 | 1  | 1  | 19  | 2  | 1  | 2  | 2  | 0  |
| Somalia                      | 1  | 5  | 13  | 0  | 0  | 2  | 0  | 0  |
| South Sudan                  | 2  | 1  | 22  | 1  | 0  | 0  | 0  | 0  |
| Sudan                        | 2  | 6  | 39  | 2  | 0  | 0  | 3  | 0  |
| Eswatini (Swaziland)         | 0  | 0  | 6   | 0  | 0  | 0  | 0  | 0  |

(Continues)

TABLE 4 | (Continued)

| Country  | NE | DD | LC | NT | VU | EN | CR | EX |
|----------|----|----|----|----|----|----|----|----|
| Tanzania | 24 | 17 | 82 | 6  | 4  | 5  | 8  | 0  |
| Togo     | 1  | 1  | 20 | 2  | 0  | 0  | 1  | 0  |
| Uganda   | 15 | 13 | 63 | 5  | 3  | 4  | 9  | 0  |
| Zambia   | 5  | 8  | 65 | 2  | 3  | 3  | 3  | 0  |
| Zimbabwe | 16 | 5  | 41 | 1  | 0  | 0  | 0  | 0  |

Abbreviations: CR, Critically Endangered; DD, Data Deficient; EN, Endangered; EX, Extinct; LC, Least Concern; NE, Not Evaluated; NT, Near Threatened; VU, Vulnerable.

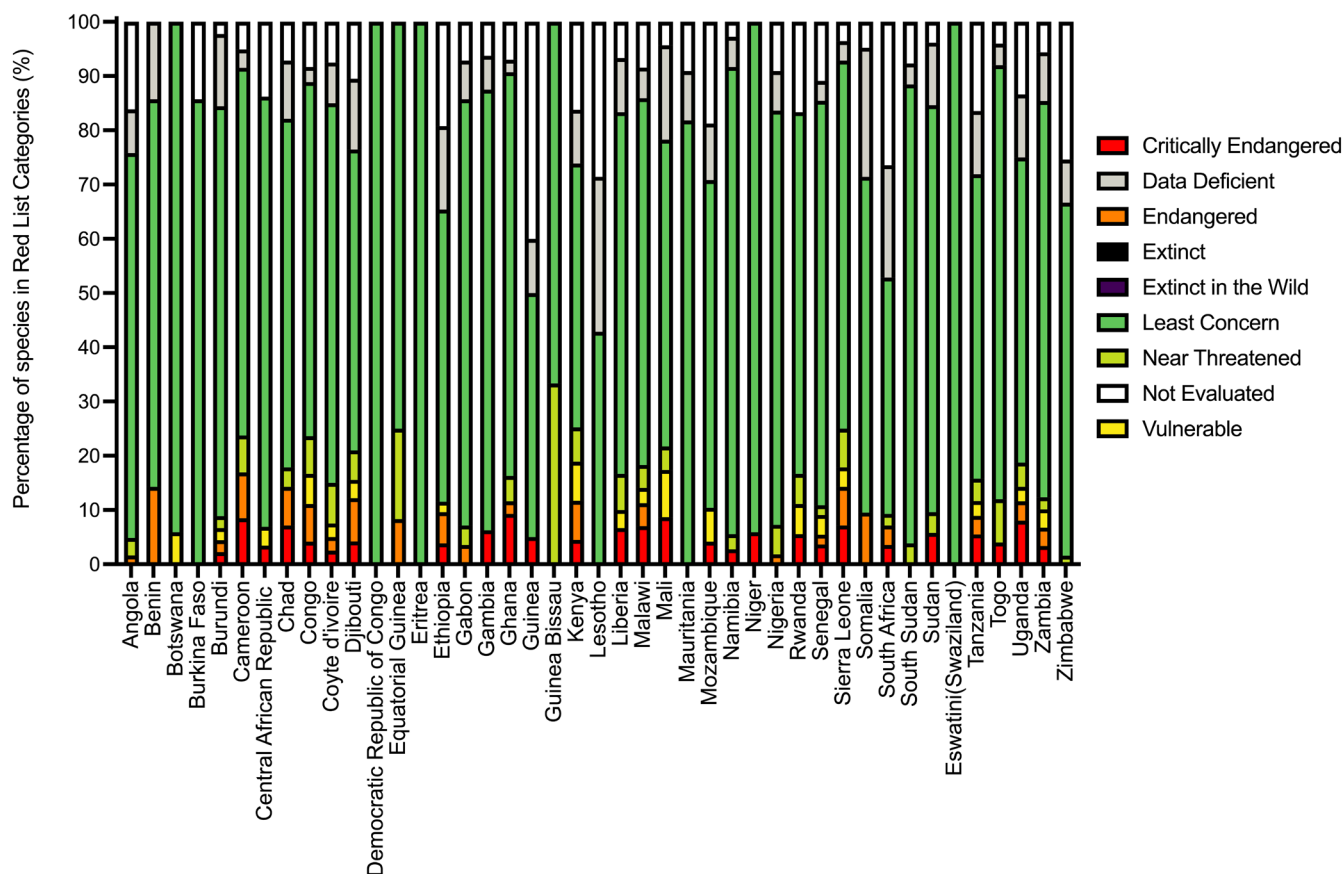


FIGURE 3 | Distribution of freshwater mollusc species across IUCN (2024) Red List categories in sub-Saharan African countries.

( $n = 17$ ), Guinea-Bissau ( $n = 6$ ) and Djibouti ( $n = 3$ ). The majority of records available for each country provided enough taxonomic resolution needed to categorise the records into the corresponding class, with the exception of South Africa ( $n = 1548$ ), Mozambique ( $n = 477$ ), Tanzania ( $n = 464$ ), Mauritania ( $n = 254$ ), Senegal ( $n = 177$ ), Angola ( $n = 177$ ) and Kenya ( $n = 138$ ) having more than 100 records (Table 2 and Figure 1). The total number of incomplete records represents only 10.8% of the total. Only 10 countries have inconclusive records, where species inhabit terrestrial and freshwater environments. South Africa ( $n = 97$ ) and Kenya ( $n = 37$ ) have more than 10 inconclusive records (Figure 1 and Table 2), but they constitute <1% of the total records. South Africa ( $n = 655$ ), Mozambique ( $n = 284$ ), Tanzania ( $n = 194$ ) and Senegal ( $n = 158$ ) are the only countries to have more than 100 records

that could not be classified due to the species that inhabit marine and freshwater environments (Table 2 and Figure 1). Only seven countries had no records of marine/freshwater species. In addition to the 36,927 records for sub-Saharan Africa, there were a further 901 records that lacked location data; therefore, these records could not be assigned to a specific country (Table 2).

Analysis of species occurrence data reveals significant temporal variability between sub-Saharan African countries. Senegal has the longest temporal span, with occurrence records covering 173 years (1845–2018). South Africa and Zimbabwe each exhibit records spanning 163 years (1859–2022). Mozambique has a range of 155 years (1864–2019), while the Democratic Republic of Congo has 142 years of documented occurrences (1875–2017).

In contrast, Guinea-Bissau and Benin each have the shortest data range of 12years (1988–2000 and 1972–1984, respectively) (Table 2). Togo has a slightly broader range of 15years

(1969–1984), and Burundi presents 44years (1955–1999). Djibouti has a temporal range of 86years (1926–2012) (Table 2). In the pre-1900 period, species occurrence records are sparse, with significant contributions from South Africa (28 records) and the Democratic Republic of Congo (25 records). The 1900–1950 period showed a noticeable increase in documentation, particularly from South Africa (249 records), the Democratic Republic of Congo (349 records) and Cameroon (26 records). The 1950–2000 period sees further surges, with South Africa reporting 2024 records, Ghana 659 records and Kenya 439 records. The most dramatic increase occurs in the post-2000 period, where Kenya had 915 records, Tanzania 2045 and Senegal with 3561 records (Figure 2 and Table 3).

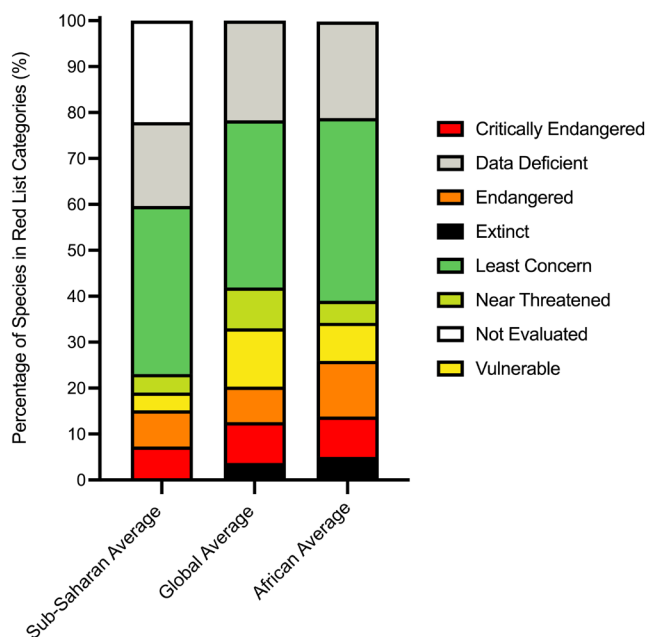


**FIGURE 4** | Summary of the percentage of species within each IUCN Red List category within the different geographical regions assessed/evaluated (IUCN 2024).

### 3.2 | Red List Data

#### 3.2.1 | Red List Status

Upon analysis of the Red List status of sub-Saharan freshwater molluscs on the Red List, the results reveal notable trends in the different categories. The Red List categories were grouped into three broader groups: (*Threatened* [CR, EN, VU]), (*Not Threatened* [NT, LC]) and (*Data Deficient* [DD]). An additional category (*Not Evaluated* [NE]), was also considered. In the *Threatened* category, the DRC has the highest representation of CR species with 10. Meanwhile, 15 countries do not have species considered CR. In the EN category, the DRC leads with 19 species. A total of 21 countries do not have species classified as EN (Table 4). In the VU category,

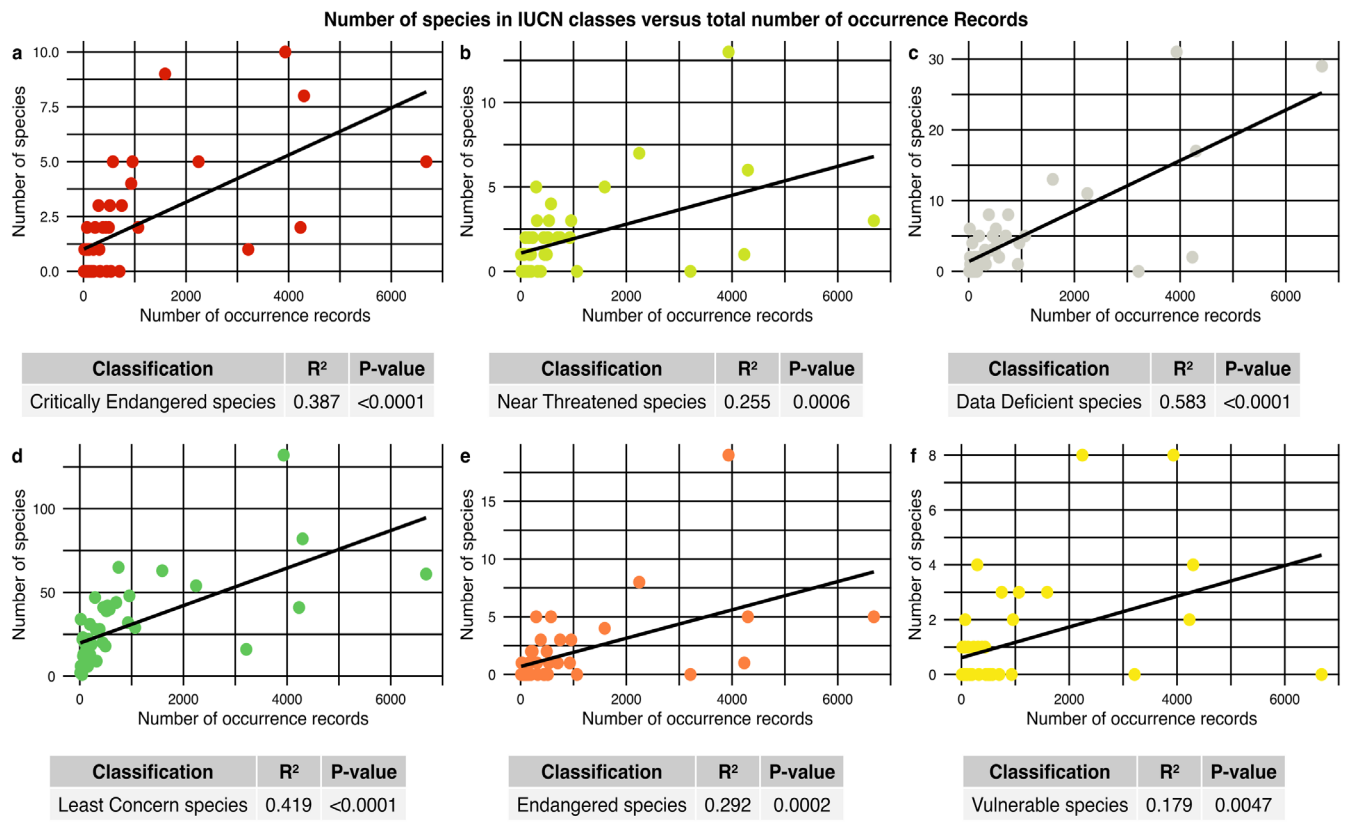


**FIGURE 5** | Number of species in IUCN (2024) classes versus total number of occurrence records. Scatter plots display the relationship for: (a) Critically Endangered, (b) Near Threatened, (c) Data Deficient, (d) Least Concern, (e) Endangered and (f) Vulnerable species. A trend line has been fitted to each scatter plot to provide visual aid.

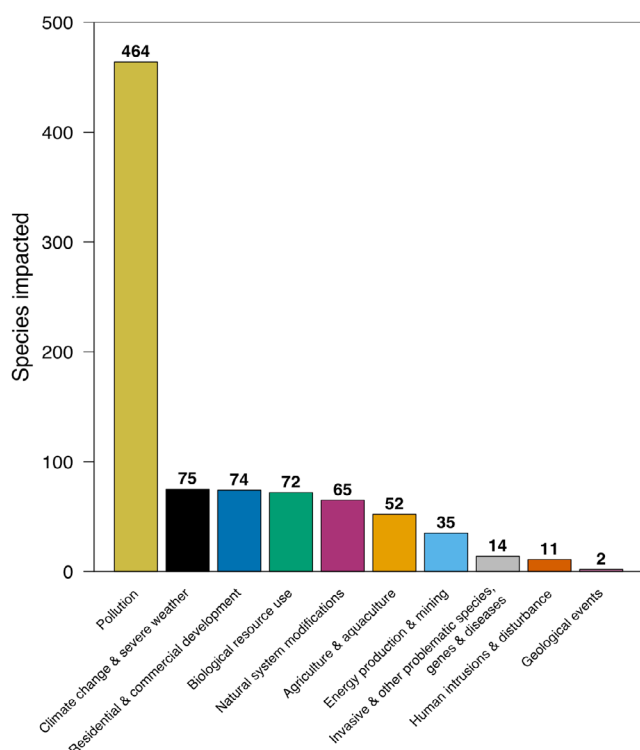


**FIGURE 6** | Main threats faced by freshwater mollusc in sub-Saharan Africa based on classification in Table A1.

the DRC and Kenya each have eight species, while 24 countries do not have species recorded in this category.

In the *Not Threatened* category, the DRC has 13 species listed; 14 countries do not have species in the NT category (Table 4). The LC category shows that the DRC again has the highest number of species (131). In contrast, Djibouti has only one species listed as LC (Table 4). The Data Deficient and Not Evaluated categories show that the DRC leads with 31 species, while eight countries do not have species classified under DD (Table 4). In the NE category, the highest species representation is seen in South Africa, with 37 species. Only 10 countries have no species listed as NE.

The distribution of species across the various Red List categories shows substantial variation between the 43 sub-Saharan African countries. For CR species, Ghana and Mali stand out, with 9% of their species classified as CR, followed closely by Cameroon and Uganda, each with 8% (Figure 3). Benin has the highest proportion of EN species at 16.6%, making it the only country with more than 10% in this category (Figure 3). In the VU category, the highest percentages are found in Mali (8.33%) and Mozambique (6.25%) (Figure 3). For NT species, Guinea-Bissau has the highest representation at 33.33%, followed by Equatorial Guinea (16.6%) and Sierra Leone (7.1%) (Figure 3). The LC category has the highest percentages in Djibouti, Eswatini (Swaziland) and Eritrea, each with 100%. On the contrary, South Africa (43.5%) and Lesotho (42.8%) have the lowest percentages of LC species (Figure 3). Lesotho also shows the highest percentage of DD species (28.57%), followed by Somalia (23.8%) and South Africa (20.7%) (Figure 3). Finally, the category of NE is more prominent in Lesotho (28.5%), South Africa (26.4%), Zimbabwe (25.3%) and Ethiopia (19.2%) (Figure 3).

The analysis of Red List categories for freshwater molluscs in sub-Saharan Africa, expressed as percentages, displays differences compared to global and African percentages. In the EX category, sub-Saharan Africa has no species (0%), while the global percentage is 3.7% and the African percentage is 5%. For CR species, sub-Saharan Africa has 7.26%, which is close to the global percentage of 8.9% and the African percentage of 8.8%. In the EN category, the sub-Saharan percentage is 7.90%, slightly above the global percentage of 7.7% but well below the African percentage of 12.1%. In the VU category, sub-Saharan Africa has a lower percentage (3.87%) compared to the global percentage of 12.7% and the African percentage of 8.3%.

For NT species, the sub-Saharan percentage is 4.03%, which is below the global percentage of 8.9% and the African percentage of 4.8%. In the LC category, the sub-Saharan percentage is 36.61%, aligning closely with the global percentage of 36.4% but slightly lower than the African percentage of 39.8%. For DD species, sub-Saharan Africa has a percentage of 18.23%, which is slightly below both the global percentage of 21.7% and the African percentage of 21%. Finally, in the NE category, sub-Saharan Africa has a substantial representation of 22.10%, while neither the global nor African percentages include any species in this category (Figure 4).

### 3.2.2 | Threats

Freshwater Mollusca in sub-Saharan Africa is affected by a wide range of threats, with pollution being the most frequently reported, affecting 472 species (Figure 6). Within this category, industrial and military effluents (9.1.2) accounted for the highest number of species (132), while excess energy (9.5) affected the fewest (one species) (Figure 7). Climate change and severe weather were related to 75 species, primarily through droughts (11.2) that affected 42 species, and the least through storms and flooding (11.4) that affected five species (Figures 6 and 7).

Residential and commercial development affected 74 species, most commonly from housing and urban areas (1.1) with 65 species, while commercial and industrial areas (1.2) affected only three species (Figures 6 and 7). Biological resource use accounted for threats to 71 species, led by logging and wood harvesting (5.3) with 27 species and lowest in unknown logging motivation (5.3.3) with only one species (Figure 7).

Modifications to the natural system contributed 63 threats, mainly from dams and water management/use (7.2), which affected 21 species, with large dams (7.2.1) and land reclamation (7.3.2) each affecting three species (Figures 6 and 7). Agriculture and aquaculture posed threats to 52 species, with agro-industry farming (2.1.4) leading (27 species), and marine/freshwater aquaculture (2.4) and other farming (2.1.5) affecting only one species each (Figures 6 and 7).

Energy production and mining were associated with 35 species, primarily driven by mining and quarrying (3.2) with 28 species, while oil and gas drilling (3.1) affected 7 (Figures 6 and 7). Invasive and other problematic species, genes and diseases affected 14 species, led by non-native invasive species (8.1) with 8, and introduced genetic material (8.3) with one species (Figures 6 and 7). Human intrusions and disturbance affected 11 species,

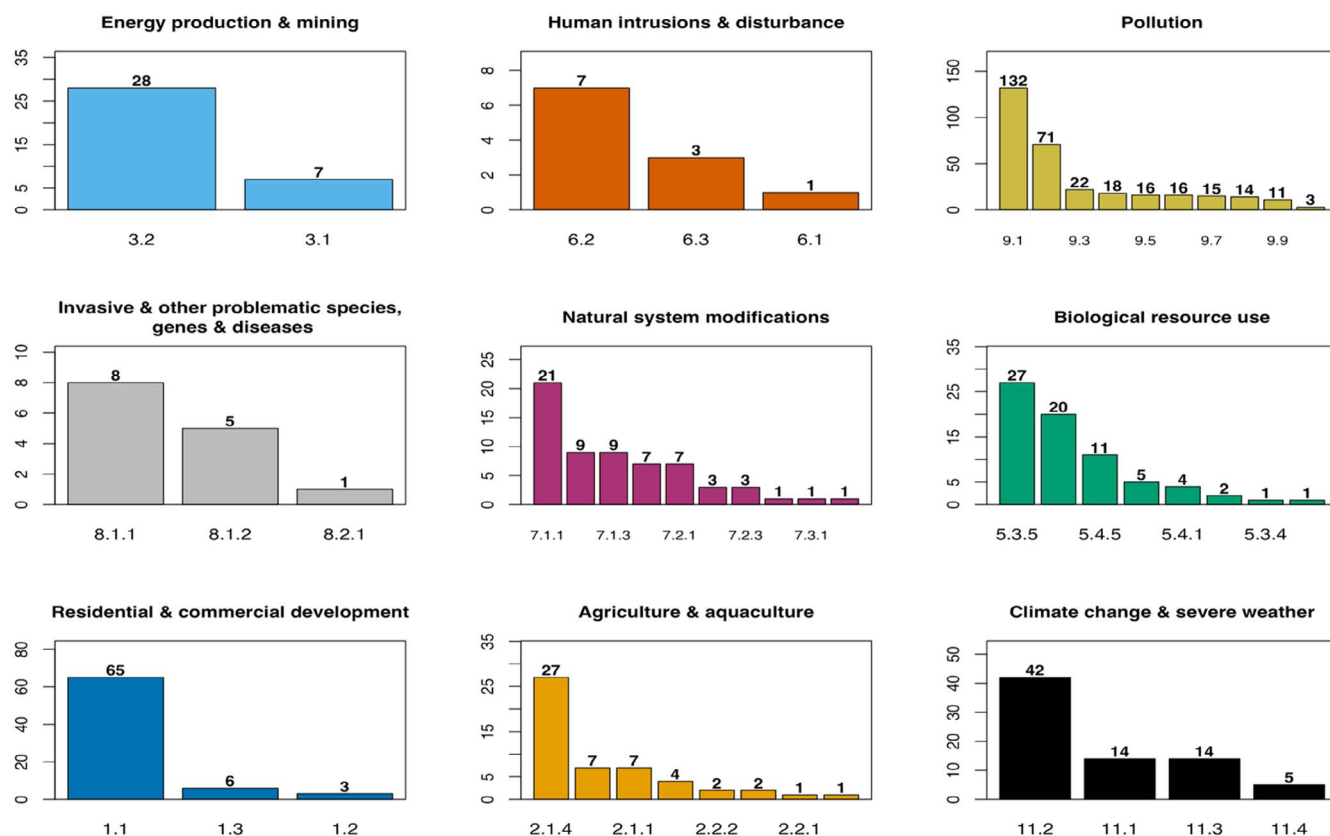


**FIGURE 7** | Breakdown of main threats faced by freshwater mollusc in sub-Saharan Africa based on classification in Table A1. With threat codes displayed on the x-axis and the threat count on the y-axis.

mostly due to recreational activities (6.1) with 7 species, and least due to war/civil unrest (6.2) with 1. Geological events were the least reported, affecting only two species under volcanic activity (10.1) (Figures 6 and 7). No species were reported to be affected by transport and service corridors, despite the known links between infrastructure and freshwater degradation.

### 3.3 | Correlation Between Red List and Occurrence Records

The number of species within each Red List category was positively correlated with the total number of occurrence records across all six categories (Figure 5). The strongest correlation was observed for Data Deficient species ( $R^2=0.583$ ,  $p<0.0001$ ), followed by Least Concern ( $R^2=0.419$ ,  $p<0.0001$ ) and Critically Endangered species ( $R^2=0.387$ ,  $p<0.0001$ ). Moderate correlations were recorded for Endangered ( $R^2=0.292$ ,  $p=0.0002$ ) and Near Threatened species ( $R^2=0.255$ ,  $p=0.0006$ ), while the weakest, though still significant, relationship was observed for Vulnerable species ( $R^2=0.179$ ,  $p=0.0047$ ). These results indicate that countries with higher occurrence record availability tend to have more species represented across all conservation categories.

### 3.4 | Cytochrome Oxidase I Barcodes

Of the 620 species identified by this gap analysis as occurring within sub-Saharan Africa, only 94 species have COI barcodes

available, 486 species lack barcodes entirely, and 40 species have barcodes that could not be confidently assigned to sub-Saharan Africa due to missing metadata, such as collection location or precise species identification (Figure 8A). Among the two main mollusc groups, Gastropoda and Bivalvia, availability of the sequences varied considerably (Figure 8B). Within Bivalvia, families such as Coelaturidae and Unionidae displayed a higher proportion of available COI sequences, although smaller families, such as Etheriidae and Mytilopsis, remained largely unrepresented (Figure 8C). In contrast, Gastropoda families such as Viviparidae and Planorbidae had the highest number of sequences, but many families, including Hydrobiidae and Ellobiidae, had no available COI barcodes (Figure 8D).

## 4 | Discussion

The distribution of occurrence records in sub-Saharan Africa highlights clear disparities in data availability between countries. South Africa, Tanzania, Senegal and the Democratic Republic of Congo contribute the highest number of occurrence records in this study, reflecting their exceptional molluscan diversity and the concentration of historical collecting efforts in major river catchments and lake systems (Dudgeon et al. 2006; Strayer and Dudgeon 2010). It should be noted, however, that South Africa's high record count reflects its relatively well-developed natural history collection infrastructure, long-term monitoring programmes and greater degree of museum digitisation rather than an indication of regional research leadership

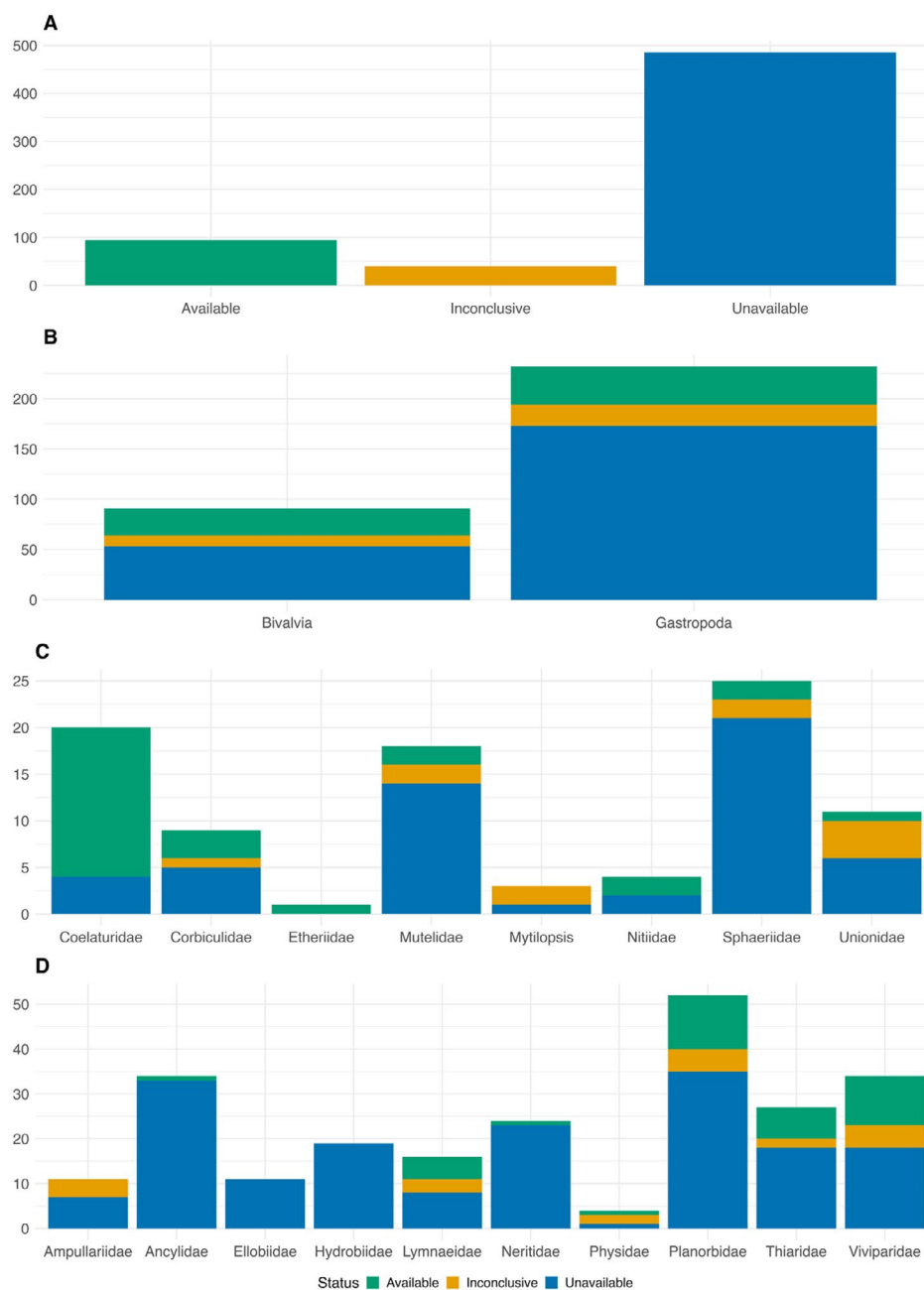


**FIGURE 8** | Number of freshwater mollusc species from the accepted species list in sub-Saharan Africa with available COI barcodes in BOLD version 4 (Ratnasingham and Hebert 2007) and the NCBI GenBank database (Benson et al. 2009): (A) overall availability of COI barcodes, (B) availability of COI barcodes for bivalves and gastropods, (C) breakdown of COI barcodes by bivalve families and (D) breakdown of COI barcodes by gastropod families. The number of COI sequences is indicated on the y-axis.

in freshwater Mollusca more broadly (Ziganira and Downs 2025; Ziganira et al. 2026), with other regions, particularly East Africa, having made substantial contributions to freshwater mollusc research especially in relation to the Rift Valley lakes (Seddon et al. 2011). For example, studies in South Africa have documented the distribution and habitat preferences of invasive species such as *Pseudosuccinea columella*, revealing their role as intermediate hosts in disease transmission (de Kock and Wolmarans 1992), while comparative studies between the relatively pristine Marico River and the impacted Crocodile River demonstrated how habitat transformation leads to decreased mollusc diversity and the establishment of invasive species such as *Physella acuta* (Kemp et al. 2016).

The concentration of records around South Africa, the East African Rift lakes, the Niger delta and the Congo Basin further reflects elevated research activity driven by schistosomiasis vector monitoring and the legacy of colonial collecting in accessible major river catchments (Herbert 1998; Steinmann et al. 2006; Seddon et al. 2011; Schultheiß et al. 2011). When viewed through an ecoregional lens, this concentration has direct implications for the present study, as Red List representation, threat documentation and COI barcode availability are all disproportionately skewed towards these well-studied systems, a pattern consistent with broader documentation of research and knowledge gaps in sub-Saharan African freshwater Mollusca (Ziganira and Downs 2025; Ziganira et al. 2026). This unevenness reinforces the need

for targeted survey efforts in undersampled regions, particularly given that river basin boundaries more accurately reflect the biogeographic units within which freshwater mollusc populations are structured and threatened than national borders alone (Darwall et al. 2011; Lopes-Lima et al. 2021).

In contrast, countries such as Burundi and Guinea-Bissau each have fewer than 20 records, indicating significant gaps in data collection. However, the drivers of these gaps are not straightforward, as record availability does not correspond consistently with political stability or economic development. The Democratic Republic of Congo, despite decades of civil unrest and conflict, contributes among the highest number of records in this study, likely reflecting its exceptional molluscan diversity and the historical concentration of collecting efforts in the Congo Basin during the colonial era (Strong et al. 2008; Costello et al. 2013). Conversely, politically stable countries such as eSwatini show comparatively few records, suggesting that geographic size, habitat extent, taxonomic diversity and the degree to which a country has been targeted by historical or contemporary survey programmes are more influential determinants of record availability than political stability alone (Daskin and Pringle 2018; Hodgetts et al. 2019). These patterns reflect well-documented geographic and institutional biases inherent in natural history collections, where sampling effort has historically been shaped by colonial collecting priorities, the accessibility of major river systems and the research interests of European institutions rather than by systematic continental coverage (Lopes-Lima et al. 2021; Meyer et al. 2016; Kemp 2015; Troudet et al. 2017). While geopolitical instability can restrict researcher access and divert attention from environmental concerns towards immediate humanitarian priorities, with post-conflict stigmas further preventing the resumption of conservation activities (Daskin and Pringle 2018; Hodgetts et al. 2019), broader structural factors more accurately explain the uneven availability of occurrence data across sub-Saharan Africa. These include disparities in long-term funding, limited taxonomic capacity, challenges associated with accessing remote freshwater systems, and the historical concentration of museum infrastructure and biodiversity research in the Global North (Lopes-Lima et al. 2021; Bourlat et al. 2023). This disparity is further illustrated by the finding that just 12 countries in northern Europe collectively hold more freshwater mollusc occurrence records than the entire sub-Saharan African continent (Bourlat et al. 2023).

Disparities in the temporal documentation of freshwater mollusc occurrences further highlight significant data limitations across the region. Countries with extensive temporal records, such as South Africa, benefit from long-term monitoring providing valuable information on population trends over time, while those with limited historical data face challenges in representing distribution changes, affecting both Red List assessments and conservation planning. The marked increase in species occurrence records from 1900 onwards, particularly post-2000, reflects growing recognition of biodiversity importance, improvements in ecological research and technological advances in digitisation. However, differences in historical documentation between countries underscore the need for improved data collection, particularly in nations with limited pre-2000 records, as evidenced by studies in South Africa's Kruger National Park

where comparisons between periods of drought and high rainfall demonstrated significant impacts on mollusc diversity (de Kock et al. 2002).

A subset of GBIF records fell into inconclusive habitat categories because many molluscan taxa inhabit ecotones or transitional environments where freshwater, brackish and sometimes marine habitats overlap. Ecological ambiguity of this type is well documented in taxa that occupy estuarine gradients, seepage wetlands or hydrologically variable systems (Attrill and Rundle 2002; Graf and Cummings 2007; Strong et al. 2008). Because habitat affiliation cannot be confidently inferred from higher-level taxonomy alone, including these records in freshwater analyses risks inflating species richness or misrepresenting true distributions.

#### 4.1 | Data Completeness of Sub-Saharan Freshwater Mollusc Records

The majority of sub-Saharan occurrence records (83.03%) are taxonomically complete and were regarded as usable for this gap analysis; this is essential as it allows for a better understanding of the freshwater biodiversity in the region. Countries such as Chad and Niger, with 100% freshwater records, provide more reliable data for freshwater conservation efforts. However, Mozambique and Eritrea, with only 28% and 24.5% freshwater records, respectively, show gaps that may limit accurate assessments of the distributions of freshwater species and environmental needs. These disparities in the completeness of the record highlight the challenges of compiling consistent data in diverse environments, where factors such as mixed habitats and uncertainty in species classification can affect the quality of the record. The disparities in occurrence records align with the Wallacean and Prestonian shortfall, as these refer to the shortfalls in taxonomy and distribution data (Lopes-Lima et al. 2021). These gaps in distribution data and population dynamics impair the ability to identify areas of biodiversity hotspots (Lopes-Lima et al. 2021). This is further supported by Lopes-Lima et al. (2021), who identified taxonomy as one of the key shortfalls in terms of molluscan biodiversity and conservation. Historical taxonomic errors are seen to go unnoticed in ecology, as it requires a well-trained taxonomist to rectify these mistakes (Bortolus 2008).

#### 4.2 | Red List Status and Conservation Priorities

The Red List analysis revealed significant variation in conservation status across sub-Saharan Africa, with the distribution of species across IUCN categories positively correlated with the availability of occurrence records (Figure 5). Countries with higher record counts tend to show a more comprehensive distribution across threat categories, while those with limited records display skewed distributions more attributable to data gaps than to actual species status, reflecting the well-documented influence of information access on conservation outcomes. This pattern is compounded by the fact that Red List assessments for African freshwater molluscs have not been updated since 2011, raising the concern that recent declines may be underestimated and that effective conservation strategies are being formulated on the basis of outdated information (Seddon et al. 2011).

The Critically Endangered, Endangered and Vulnerable species identified in this study are likely an underestimate, given that 18% of species were Data Deficient and 22% Not Evaluated, figures substantially higher than global and broader African averages (IUCN 2024). Bland et al. (2015) and Roberts et al. (2016) suggest that Data Deficient species may face extinction risks equal to or higher than those of assessed threatened species, implying that the true extent of threat is significantly underestimated. This concern is reinforced by evidence that freshwater biodiversity is declining at rates exceeding those of terrestrial systems (Böhm et al. 2021, 2022), and that molluscs have experienced disproportionately higher extinction rates than birds and mammals, contributing to an overlooked biodiversity crisis driven largely by human activities and the ongoing sixth mass extinction (Cowie et al. 2022).

The persistent mismatch between taxonomic knowledge, distributional data and Red List coverage in sub-Saharan Africa reflects broader global challenges in freshwater biodiversity monitoring, as relying on incomplete or outdated assessments undermines the ability of countries to report on extinction risk trends and formulate effective conservation responses (van Rees et al. 2025). The temporal distribution of occurrence records in this study, with minimal data available before 1900 and a pronounced concentration in the post-2000 period, further suggests that distributional knowledge for many species rests on historically sparse and geographically uneven sampling rather than systematic survey coverage, a concern reinforced by the 901 records lacking georeferenced data identified in this study. Taxonomic uncertainty, including synonymy, cryptic species and historical oversplitting of genera, further undermines the precision of Red List categories (Graf and Cummings 2007; Lopes-Lima et al. 2021), resulting in a growing mismatch between contemporary taxonomy as reflected in MolluscaBase (2024) and current IUCN listings, where more than 70 species remain unassessed. Addressing these taxonomic and distributional shortfalls is therefore essential for realistic conservation planning.

#### 4.2.1 | Main Drivers of Threats

Pollution was the most pervasive threat recorded in this study, a pattern consistent with global assessments identifying it as one of the two most reported threats to freshwater molluscs alongside natural system modification (Böhm et al. 2021), and with its designation as the dominant threat in the Afrotropical realm specifically. The sources driving this pattern reflect broader pressures associated with rapid industrialisation, urban expansion and insufficient waste management infrastructure across the region (Dudgeon et al. 2006; Vörösmarty et al. 2010). These threat patterns mirror broader continental and global assessments, with sub-Saharan ecosystems having already lost substantial proportions of their original biodiversity intactness (Clements et al. 2026), while freshwater systems are identified among the most heavily impacted environments worldwide due to cumulative human pressures (Keck et al. 2025).

Although climate change ranked second in this study, its full impact on extinction trajectories may not yet be fully captured in current IUCN assessments, where it is more frequently cited as a future rather than present risk (Boehm and Cronk 2021; IPCC 2014; Reid et al. 2019). Natural system modification, while

less frequently reported overall, was more strongly associated with Critically Endangered species than any other threat category, underscoring its disproportionate role in extinction risk relative to its recorded frequency (Boehm and Cronk 2021; Böhm et al. 2021). Freshwater molluscs are particularly sensitive to hydrological alteration given their dependence on specific flow conditions and, in many taxa, on fish hosts to complete their life cycles.

Residential development, biological resource use and agriculture collectively affected comparable numbers of species and rarely operate in isolation, typically intensifying co-occurring stressors such as pollution and water abstraction (Darwall et al. 2018; Boehm and Cronk 2021). Biological resource use, including logging and commercial exploitation, is often associated with less Endangered species globally, though its localised impact in sub-Saharan Africa may be underestimated (WWF 2020; Böhm et al. 2021), while agriculture frequently acts synergistically with pollution through pesticide run-off and increased sedimentation (Boehm and Cronk 2021). The absence of recorded threats from transport and service corridors is noteworthy given well-established links between infrastructure development and freshwater; this may reflect gaps in threat documentation rather than a genuine absence of impact. Invasive species and diseases, while currently among the least prevalent threats recorded, are increasingly recognised as disruptive to native ecosystems and competitive with endemic molluscs (Strayer and Dudgeon 2010; Böhm et al. 2021; Boehm and Cronk 2021).

It should be acknowledged that threat frequency derived from IUCN Red List datasets does not necessarily reflect true ecological prevalence. The patterns reported here are subject to the limitations of assessor-based documentation, including different reporting standards across regions, taxonomic and geographic biases in assessment effort and the tendency for well-studied threats such as pollution to be more consistently recorded than structurally complex or diffuse pressures such as hydrological alteration or climate change. These limitations are recognised as systemic constraints of IUCN threat classifications more broadly (Bland et al. 2015; Böhm et al. 2021) and imply that the relative ranking of threat categories in this study should be interpreted as a reflection of current documentation rather than a definitive account of the drivers of decline across sub-Saharan Africa. Standardised threat assessment protocols and more consistent application of IUCN criteria across assessors and regions would substantially improve the comparability and reliability of threat data for freshwater molluscs going forward.

#### 4.3 | Cytochrome Oxidase I Barcode: Gaps and Implications

Of the 620 mollusc species identified in Africa, only 94 have available COI barcodes. This is concerning since Bourlat et al. (2023) found that only 37% of freshwater species in Europe lack a barcode, and similarly large barcode gaps in African freshwater macroinvertebrates have been documented, with molluscs consistently among the least represented groups in available reference databases (Weigand et al. 2019; Kgatla et al. 2026). The absence of COI sequences for 486 African species represents a significant limitation, as these barcodes are essential

to confirm species identity and to understand phylogenetic relationships (Kress et al. 2015; Weigand et al. 2019). This gap is consistent with broader barcoding deficiencies documented across South African taxa, where molluscs remain among the least represented groups in available reference databases, and where poor metadata quality in GenBank records further compounds the reliability of existing sequences (Kgatla et al. 2026). Broader evaluations across taxa likewise show that incomplete barcode libraries reduce the reliability of molecular identification (Hollingsworth et al. 2009).

The uneven distribution of barcode availability across molluscan lineages further compounds this gap. Families such as Planorbidae, Physidae and Thiaridae are comparatively well represented in barcode databases, largely owing to their medical importance as intermediate hosts for parasitic infections. In contrast, Unionidae, Iridinidae and Hydrobiidae possess few or no COI sequences, limiting phylogenetic resolution and hindering accurate identification in eDNA surveys (Elbrecht et al. 2018). This pattern reflects a broader bias in African freshwater mollusc research towards disease vector taxa, which was also identified in the literature review conducted by Ziganira and Downs (2025). The low barcode coverage observed in this study is particularly concerning given the likelihood of cryptic diversity within the region. Weigand et al. (2019) suggested that widely distributed species could consist of genetically distinct complexes, a concern supported by our findings and by recent molecular phylogenetic analyses. For example, *Physella acuta*, which appears in our dataset as a single taxon, comprises multiple nominal taxa and several clades in a comparatively shallow topology (Albrecht et al. 2025). Similarly, molecular analysis has confirmed that *Physella waterloti* and *Physella mosambiquensis* are synonyms of *Stenophysa marmorata*, demonstrating how the absence of barcoding in our dataset may mask complex taxonomic relationships that morphological data alone cannot resolve (Albrecht et al. 2025). These findings suggest that the 620 species recorded in this study may underestimate true mollusc diversity in sub-Saharan Africa.

The choice of molecular marker also has implications for interpreting barcode gaps in this dataset. COI offers high taxonomic resolution and is effective for species identification, particularly for detecting cryptic diversity, but may suffer from primer bias (Elbrecht et al. 2016). In bivalves specifically, the 16S rRNA marker often outperforms COI in species-level identification (Lopes-Lima 2024), suggesting that the barcode gap for bivalve taxa in our dataset may be even more functionally limiting than the raw numbers indicate. The reliance on COI as the primary barcode marker in this study therefore reflects both the availability of existing data and a recognised methodological constraint.

These results highlight that expanding COI barcoding efforts in sub-Saharan Africa is an urgent priority. Strong morphological understanding, integrated with genetic data, is crucial for conservation efforts, as a DNA sequence alone is insufficient for practical on-the-ground conservation management (Elderkin et al. 2016). The development of robust reference libraries with verified links between morphology and genetics is therefore essential. Although eDNA is often regarded as a powerful tool for biodiversity monitoring, its effectiveness is only as strong as the fundamental taxonomic knowledge that underpins it (Elderkin et al. 2016). Addressing taxonomic shortfalls, improving

occurrence and Red List data, and expanding barcode coverage therefore emerge from this study as tightly linked and mutually dependent priorities for the conservation of sub-Saharan freshwater molluscs.

## 5 | Conclusion

This study provides the first comprehensive assessment of freshwater mollusc biodiversity in sub-Saharan Africa by integrating occurrence records, Red List data and COI barcode availability, revealing 36,927 occurrence records across 43 countries that are nonetheless unevenly distributed, temporally biased towards the post-2000 period, and characterised by substantial proportions of Data Deficient (18%) and Not Evaluated (22%) species. Occurrence absence in this context does not necessarily reflect true species absence; uneven survey effort, habitat accessibility constraints and the prevalence of cryptic taxa mean that poorly represented countries are likely undersampled rather than genuinely depauperate, a limitation that should be considered when interpreting distributional patterns across the region. These spatial biases are compounded by several interacting sources of systematic error, including museum digitisation bias, whereby institutions with greater resources have disproportionately contributed digitised records to global databases; collector bias, reflecting the historical tendency for sampling to concentrate along accessible river systems, roads and previously surveyed localities; accessibility bias, where remote or politically unstable regions remain chronically undersampled irrespective of their true biodiversity; and colonial legacy effects, through which the majority of historical African freshwater mollusc specimens were collected by European institutions and remain housed in European and North American museums with limited digital metadata, constraining their contribution to contemporary biodiversity assessments and Red List evaluations (Strong et al. 2008; Costello et al. 2013; Kemp 2015; Troudet et al. 2017). The positive correlation between occurrence records and Red List category representation reinforces that under-sampling directly propagates into conservation knowledge gaps, while threat analysis identified pollution, habitat modification and agriculture as the most widespread drivers of decline, highlighting the urgent need for targeted conservation interventions.

Molecular data are similarly limited, with only 94 of 620 assessed species possessing COI barcodes, a shortfall that impedes molecular identification, the detection of cryptic diversity and the effective application of eDNA-based biodiversity monitoring. Although GBIF provides the largest openly accessible source of digitised African mollusc occurrence records, it represents only a fraction of the material housed in museum collections worldwide, with significant holdings remaining undigitised, unpublished or restricted by institutional data policies (Ariño 2010; Page et al. 2015; Meyer et al. 2016; Troudet et al. 2017; Heberling et al. 2021). Addressing these shortfalls through expanded field surveys, updated Red List assessments, targeted molecular barcoding and open digitisation initiatives is essential to improve the completeness and precision of distribution datasets and to inform conservation priorities across the continent (Guralnick and Hill 2009; Soberón and Peterson 2004; IUCN Standards and Petitions Committee 2022; van Rees et al. 2025).

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

All data used in this study are derived from open source. Species occurrence records were obtained from the Global Biodiversity Information Facility (GBIF), conservation status and threat data from the IUCN Red List, and genetic barcode availability from the Barcode of Life Data System (BOLD) and GenBank. All datasets are publicly available without restriction, and the methodological steps are fully described, allowing complete replication of the analyses without the need to request data from the authors.

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## Appendix

**TABLE A1** | Threat Classification Scheme used by IUCN (2024), version 3.3.

| Threat code | Threat description                                               |
|-------------|------------------------------------------------------------------|
| 1           | Residential & commercial development                             |
| 1.1         | Housing & urban areas                                            |
| 1.2         | Commercial & industrial areas                                    |
| 1.3         | Tourism & recreation areas                                       |
| 2           | Agriculture & aquaculture                                        |
| 2.1         | Annual & perennial non-timber crops                              |
| 2.1.1       | Shifting agriculture                                             |
| 2.1.2       | Small-holder farming                                             |
| 2.1.3       | Agro-industry farming                                            |
| 2.1.4       | Scale Unknown/Unrecorded                                         |
| 2.2         | Wood & pulp plantations                                          |
| 2.2.1       | Small-holder plantations                                         |
| 2.2.2       | Agro-industry plantations                                        |
| 2.2.3       | Scale Unknown/Unrecorded                                         |
| 2.3         | Livestock farming & ranching                                     |
| 2.3.1       | Nomadic grazing                                                  |
| 2.3.2       | Small-holder grazing, ranching or farming                        |
| 2.3.3       | Agro-industry grazing, ranching or farming                       |
| 2.3.4       | Scale Unknown/Unrecorded                                         |
| 2.4         | Marine & freshwater aquaculture                                  |
| 2.4.1       | Subsistence/artisanal aquaculture                                |
| 2.4.2       | Industrial aquaculture                                           |
| 2.4.3       | Scale Unknown/Unrecorded                                         |
| 3           | Energy production & mining                                       |
| 3.1         | Oil & Gas drilling                                               |
| 3.2         | Mining & quarrying                                               |
| 3.3         | Renewable energy                                                 |
| 4           | Transportation & service corridors                               |
| 4.1         | Roads & railroads                                                |
| 4.2         | Utility & service lines                                          |
| 4.3         | Shipping lanes                                                   |
| 4.4         | Flight paths                                                     |
| 5           | Biological resource use                                          |
| 5.1         | Hunting & collecting terrestrial animals                         |
| 5.1.1       | Intentional use (species being assessed is the target)           |
| 5.1.2       | Unintentional effects (species being assessed is not the target) |

(Continues)

**TABLE A1** | (Continued)

| Threat code | Threat description                                                                        |
|-------------|-------------------------------------------------------------------------------------------|
| 5.1.3       | Persecution/control                                                                       |
| 5.1.4       | Motivation Unknown/Unrecorded                                                             |
| 5.2         | Gathering terrestrial plants                                                              |
| 5.2.1       | Intentional use (species being assessed is the target)                                    |
| 5.2.2       | Unintentional effects (species being assessed is not the target)                          |
| 5.2.3       | Persecution/control                                                                       |
| 5.2.4       | Motivation Unknown/Unrecorded                                                             |
| 5.3         | Logging & wood harvesting                                                                 |
| 5.3.1       | Intentional use: subsistence/small scale (species being assessed is the target)           |
| 5.3.2       | Intentional use: large scale (species being assessed is the target)                       |
| 5.3.3       | Unintentional effects: subsistence/small scale (species being assessed is not the target) |
| 5.3.4       | Unintentional effects: large scale (species being assessed is not the target)             |
| 5.3.5       | Motivation Unknown/Unrecorded                                                             |
| 5.4         | Fishing & harvesting aquatic resources                                                    |
| 5.4.1       | Intentional use: subsistence/small scale (species being assessed is the target)           |
| 5.4.2       | Intentional use: large scale (species being assessed is the target)                       |
| 5.4.3       | Unintentional effects: subsistence/small scale (species being assessed is not the target) |
| 5.4.4       | Unintentional effects: large scale (species being assessed is not the target)             |
| 5.4.5       | Persecution/control                                                                       |
| 5.4.6       | Motivation Unknown/Unrecorded                                                             |
| 6           | Human intrusions & disturbance                                                            |
| 6.1         | Recreational activities                                                                   |
| 6.2         | War, civil unrest & military exercises                                                    |
| 6.3         | Work & other activities                                                                   |
| 7           | Natural system modifications                                                              |
| 7.1         | Fire & fire suppression                                                                   |
| 7.1.1       | Increase in fire frequency/intensity                                                      |
| 7.1.2       | Suppression in fire frequency/intensity                                                   |
| 7.1.3       | Trend Unknown/Unrecorded                                                                  |
| 7.2         | Dams & water management/use                                                               |
| 7.2.1       | Abstraction of surface water (domestic use)                                               |
| 7.2.2       | Abstraction of surface water (commercial use)                                             |
| 7.2.3       | Abstraction of surface water (agricultural use)                                           |

(Continues)

**TABLE A1** | (Continued)

| Threat code | Threat description                                     |
|-------------|--------------------------------------------------------|
| 7.2.4       | Abstraction of surface water (unknown use)             |
| 7.2.5       | Abstraction of ground water (domestic use)             |
| 7.2.6       | Abstraction of ground water (commercial use)           |
| 7.2.7       | Abstraction of ground water (agricultural use)         |
| 7.2.8       | Abstraction of ground water (unknown use)              |
| 7.2.9       | Small dams                                             |
| 7.2.10      | Large dams                                             |
| 7.2.11      | Dams (size unknown)                                    |
| 7.3         | Other ecosystem modifications                          |
| 8           | Invasive & other problematic species, genes & diseases |
| 8.1         | Invasive non-native/alien species/diseases             |
| 8.1.1       | Unspecified species                                    |
| 8.1.2       | Named species                                          |
| 8.2         | Problematic native species/diseases                    |
| 8.2.1       | Unspecified species                                    |
| 8.2.2       | Named species                                          |
| 8.3         | Introduced genetic material                            |
| 8.4         | Problematic species/diseases of unknown origin         |
| 8.4.1       | Unspecified species                                    |
| 8.4.2       | Named species                                          |
| 8.5         | Viral/prion-induced diseases                           |
| 8.5.1       | Unspecified 'species' (disease)                        |
| 8.5.2       | Named 'species' (disease)                              |
| 8.6         | Diseases of unknown cause                              |
| 9           | Pollution                                              |
| 9.1         | Domestic & urban waste water                           |
| 9.1.1       | Sewage                                                 |
| 9.1.2       | Run-off                                                |
| 9.1.3       | Type Unknown/Unrecorded                                |
| 9.2         | Industrial & military effluents                        |
| 9.2.1       | Oil spills                                             |
| 9.2.2       | Seepage from mining                                    |
| 9.2.3       | Type Unknown/Unrecorded                                |
| 9.3         | Agricultural & forestry effluents                      |
| 9.3.1       | Nutrient loads                                         |
| 9.3.2       | Soil erosion, sedimentation                            |
| 9.3.3       | Herbicides & pesticides                                |
| 9.3.4       | Type Unknown/Unrecorded                                |
| 9.4         | Garbage & solid waste                                  |

(Continues)

**TABLE A1** | (Continued)

| Threat code | Threat description              |
|-------------|---------------------------------|
| 9.5         | Air-borne pollutants            |
| 9.6         | Excess energy                   |
| 10          | Geological events               |
| 10.1        | Volcanoes                       |
| 10.2        | Earthquakes/tsunamis            |
| 10.3        | Avalanches/landslides           |
| 11          | Climate change & severe weather |
| 11.1        | Habitat shifting & alteration   |
| 11.2        | Droughts                        |
| 11.3        | Temperature extremes            |
| 11.4        | Storms & flooding               |
| 11.5        | Other impacts                   |
| 12          | Other options                   |
| 12.1        | Other threat                    |