# What if Traditional Ecological Mangrove Knowledge Eroded over Decadal Time Scales?

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**Abstract:** Long-term monitoring of mangrove ecosystem changes and their impact on local communities is challenging due to the need for decades of fieldwork. Gazi Bay, Kenya, has become a model site for studying long-term mangrove dynamics and social-ecological transitions, thanks to ongoing scientific research since the 1980s. This study analyzes mangrove use in the 2000s, 2010s, and 2020s through 262 semi-structured ethnobiological interviews covering mangrove utilization, fisheries, and environmental perceptions. Findings reveal a local ecological taxonomy based on mangrove species traits, with usage patterns evolving over time. While some species remained constant or increased in use for construction and fuelwood, others declined significantly in applications such as construction, medicine, material treatment, and food/fodder (including fisheries). These shifts, along with changing gender roles, signal a loss of Traditional Ecological Knowledge (TEK). Community members reported perceived increases in mangrove cover, attributing them to natural regeneration, planting efforts, cutting bans, and conservation awareness. Continued research is essential to inform sustainable management, understand evolving human–mangrove relationships, and navigate the trade-offs between conservation and TEK erosion.

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**Abstract in Kiswahili:** Kukusanya matukio ya mabadiliko kwa kutumia ufuatiliaji wa muda mrefu ya mifumo ikolojia ya mikoko kwa jamii sio rahisi kwa sababu inahitaji kazi ya nyanjani ya muda wa miongo. Shukrani kwa utafiti wa kisayansi tangu miaka ya 1980 huko Gazi eneo la bahari ambalo limekua kielelezo cha utafiti wa muda mrefu na, baadaye, mabadiliko ya ikolojia-jamii ya mikoko. Utafiti huu umeangazia matumizi ya mikoko huko Gazi katika miaka ya 2000, 2010, na 2020 kwa kukusanya maoni kuhusu maisha ya jamii, viumbe na mazingira kutoka kwa watu wapatao 262, pia shughuli za uvuvi, na fikra kuhusu mabadiliko ya mazingira. Matukio ya utafiti huu unadhihirisha njia asili za jamii katika kutambua aina za mikoko na mabadiliko ya matumizi maalum ya mikoko hii. Ikiwa matumizi ya baadhi ya aina ya mikoko katika ujenzi au kutumika kama kuni imeongezeka au kutobadilika, matumizi mengine ya aina zingine za mikoko zimepungua kwa kiwango kikubwa katika ujenzi, kama dawa na tiba, na kama chakula kwa mifugo na kwa binadamu kupitia uvuvi. Madiliko haya sambamba na shughuli za kijinsia ni dalili ya kupotea kwa Elimu Ikolojia ya Asilia (Traditional Ecological Knowledge - TEK). Jamii ya Gazi imeshuhudia mabadiliko ya sehemu za mikoko kuongezeka kwa sababu ya kuchipuka kwa miche, upandaji wa mara kwa mara, marufuku ya kutokata mikoko, na ufahamu wa kuhifadhi mikoko katika jamii. Utafiti wa kina wa matumizi ya mikoko katika jamii unahitajika ili kuchangia usimamizi endelevu na sera ili kujua uhusiano wa watu na mabadiliko ya maeneo ya mikoko kwa wakati, na iwapo baina ya uhifadhi mikoko na kudorora kwa EIA inakubalika.

## Introduction

Mangrove forests in over 120 countries are highly productive ecosystems, providing diverse goods and services through various ecological processes and functions (Mukherjee et al. 2014). These range from wood products such as construction materials and fuelwood, including firewood and charcoal; non-timber forest products such as medicinal or material treatment uses, foods, and drinks; mineral raw materials such as mined sand; to others like fishing, coastal protection, socio-cultural, aesthetic, and spiritual values (Dahdouh-Guebas et al. 2021). Certain nature-based contributions, such as mangroves supporting fisheries (zu Ermgassen et al. 2025), protecting coasts from ocean surges (Feagin et al. 2010), and storing carbon (Wolswijk et al. 2026) are exceptionally important and often surpass those of other plant species (cf. Díaz et al. 2018). Mangrove areas, as social-ecological systems, are home to valuable Local Ecological Knowledge (LEK) and Traditional Ecological Knowledge (TEK). Following Grimm et al. (2024), LEK is defined as the "knowledge, practices, and beliefs gained through extensive personal observation of, and interaction with local ecosystems, and shared among local resource users" and TEK as a "cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (see also Berkes et al. 2000).

While mangrove forest types vary in the goods and services they offer (Ewel et al., 1998), even naturally species-poor mangrove forests can be socio-ecologically rich in the benefits they provide (Dupont et al. 2026). Therefore, the need to conserve and protect mangroves is high. However, mangroves continue to decline due to multiple global and local pressures, including harvesting due to human utilization and coastal development (Goldberg et al. 2020; Hamilton and Casey 2016), even in protected areas (Heck et al. 2024). These human factors continue to cause loss and degradation of mangroves, although less so than circa 20 years ago (Duke et al. 2007; Friess et al. 2020). Climate change poses additional threats through sea-level rise and coastal erosion, temperature changes, and the increased recurrence and strength of climate-induced disasters (Alongi 2015; Gilman et al. 2008; Krauss et al. 2014; Lovelock et al. 2015, 2017; Osland et al. 2018; Ward et al. 2016; 2017).

Monitoring long-term mangrove changes and their impacts on communities is challenging, requiring decades of fieldwork, ideally in regions with historical records of local dependence on mangrove forests. One such region is Kenya, where mangroves have been reportedly used for wood products and harvested for subsistence and commercial uses (GoK 2017; Kokwaro 1985; Walter and Steiner 1936). Their uses include construction, firewood, charcoal production, boat building, as a source of medicine, dyes/tanning, and for beekeeping for honey (Dahdouh-Guebas et al. 2000; Owuor et al. 2017). Rising coastal populations have increased pressure on mangroves and associated fisheries due to growing demand for settlement, agriculture, and coastal development (Kairo 2024; McGranahan et al. 2007; Samoilys et al. 2015). Governance challenges include randomly issued harvesting permits and illegal extraction (Kairo 2003; UNEP 2011), compounded by a shortage of wardens and equipment that limits the Kenya Forest Service's capacity to enforce regulations and manage mangrove harvesting effectively (Murungi 2017).

Ethnobotanical research on mangrove utilization has been conducted in Kenyan bays and lagoons (e.g. Dahdouh-Guebas et al. 2000; Jung and Huxham 2018; Okello et al. 2019). However, comparative studies on mangrove knowledge and utilization patterns over time in Kenya or elsewhere remain scarce. Yet, such comparisons over decadal scales are essential for identifying social-ecological transitions and environmental change. Long-term research supports mangrove management aimed at social-ecological resilience and sustainability (Dahdouh-Guebas et al. 2022a, b). Further research is needed into mangrove wood and non-timber forest products (NTFPs), including their monetary value and value chains (Dahdouh-Guebas et al. 2022a, b; Odhiambo and Goodman 2025).

This study addresses the following questions: (i) What mangrove knowledge and nomenclature exists?; (ii) How has local utilization of mangroves for timber and NTFPs evolved over time?; (iii) What is the current status of artisanal fisheries in and around mangroves?; and (iv) How do local communities perceive changes in the mangrove ecosystem?

We analyze the socio-economic importance of mangroves across age, gender, education, occupation, and local knowledge. Changes in mangrove use in Gazi Bay are examined across the 2000s, 2010s, and 2020s, represented by 2003, 2014, and 2021, respectively, focusing on how direct human impacts have shaped forest structure and utilization. This study offers a novel perspective on the temporal dynamics of mangrove TEK within a social-ecological system and situates its findings within two contrasting interpretations of the "what if" question posed in the title.

## Material and Methods

### Study Site

This study was conducted in Gazi Bay (04° 25′S and 039° 50′E), along Kenya's south coast in Kwale County, about 50 km south of Mombasa (Fig. 1). This is one of the world's most intensively researched mangrove sites, with over 200 peer-reviewed publications, primarily in ecology and environmental sciences. Ongoing scientific presence since the 1980 s has made it a model site for studying long-term mangrove dynamics and social-ecological transitions. The bay receives freshwater from Mkurumuji and Kidogoweni rivers. Since river discharge changes seasonally, the mangroves are not always directly influenced by freshwater. In addition, seepage points provide freshwater input to the bay (Signa et al. 2017; Tack and Polk 1999). The climate in Gazi Bay is controlled by the monsoon winds, particularly the northeast monsoon, NEM, or kaskazi (October–March) and the southeast monsoon, SEM, or kusi (April–September), known to impact both mangrove fisheries and other mangrove-dependent activities (Ndarathi et al. 2020). In the region and in Gazi, the presence of migratory fishermen from Pemba (Zanzibar, Tanzania) also depends on the season.

In Gazi Village, the majority of livelihoods are based on small scale fishing, palm leaf weaving (e.g., coconut leaf thatching for roofing and fencing tiles, locally known as makuti), and subsistence crop farming (Kairo et al. 2018). Politically and administratively, Gazi "Village" is part of Kinondo "Ward", within Msambweni "sub-County", under Kwale "County." Before

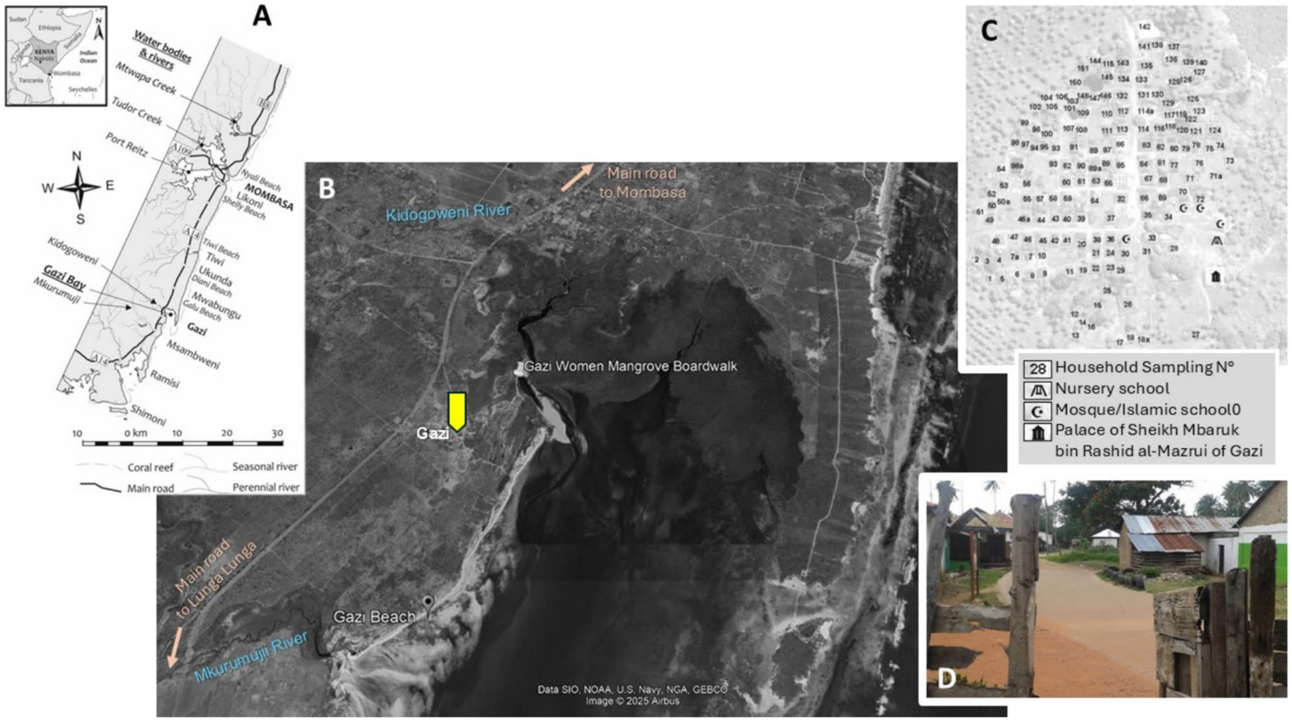


**Fig. 1**. Study sites. **A** Map inset of East-Africa showing Kenya and its southern coast, highlighting Gazi Bay. **B** Satellite image of Gazi Bay from Google Earth with the surveyed village of Gazi marked by a yellow placemarker. **C** Map of house locations in 2003 (numbers were not recorded during the interviews to preserve anonimity). **D** Street view of Gazi from 2016, looking east from approximately house number 37, with the nursery school visible in the background

the 2010 constitution, Gazi was a "Sublocation" (*mtaa mdogo*) in Kinondo "Location" (*mtaa*), situated in Msambweni "Division" (*taarafa*), within Kwale "District" (*wilaya*) of the Coast "Province" (*mkoa*). The mangrove forest of Gazi Bay covers around 703 ha (Kairu et al. 2018, 2021) and contains all ten species of mangroves commonly found in the Western Indian Ocean (WIO) region (Okello et al. 2024). Around Gazi Bay, communities are involved in mangrove awareness and conservation efforts. Through community forest associations (CFAs) and payment for ecosystem services (PES) projects such as Mikoko Pamoja and the Gazi Women Mangrove Boardwalk (GoK 2017; Huff and Tonui 2017), community members restore mangroves, sell carbon credits, guide visitors, and self-organize micro-financing loans among others.

## Data Collection and Analysis

### Ethnobiological Surveys

Primary data on mangrove nomenclature, knowledge and utilization/use for timber and non-timber forest products, artisanal fisheries and perception of change by local communities were collected from community households living within and around Gazi Bay. The research was cleared by the Kenyan Ministry of Education, Science and Technology and the National Commission for Science, Technology and Innovation under research permits MOEST 13/001/33C 123/2 and NACOSTI/P/21/9898 and upheld ethical standards in ethnobiology (cf. Vandebroek et al. 2025).

Household interviews were systematically sampled to cover the entire village, following the methodology of Dahdouh-Guebas et al. (2000, 2004, 2006). Prior to the interviews, permission was obtained from the Village Chairman and elders, followed by a well-attended village meeting (approx. 50–70 participants from neighborhoods across the village) to introduce the research and researchers. The oral face-to-face interviews were conducted from July to August 2003 ($n = 82$), May to June 2014 ($n = 82$), and May to June 2021 ($n = 98$) by or under the supervision of the authors. Where the selected house did not have occupants, the next one was chosen. When occupants were unavailable, follow-up visits were scheduled outside busy hours spent on work or household duties. Generally, per household, one person was interviewed. The survey targeted household heads, which often were men. Before each interview, oral informed consent was obtained, explaining the study's purpose, voluntary participation, and confidentiality. Respondents remained anonymous, with no personal identifiers recorded (not even the house numbers from Fig. 1C). Those unwilling to participate were excluded from the study. All surveys during the study periods were conducted using Kiswahili language, even if not the mother tongue of all respondents. Translators facilitated two-way translation (English-Kiswahili), and interviewers were trained by the authors.

Our semi-structured interviews using a questionnaire were conducted to capture data from the household surveys. The questionnaire addressed socio-economic background; ethnobotany with quantitative and qualitative data on plant parts, importance, and dependency; fishery practices including species names, fishing areas, gear, and fish income; and opinions and perspectives on mangrove forest changes over time (for the full questionnaire see Electronic Supplementary Material, hereafter referred to as "ESM," 1). The semi-structured interview design was shaped by prior field experience, particularly in ecology and landscape dynamics through vegetation science and remote sensing (Dahdouh-Guebas et al. 2004) as well as relevant literature (see also "Experiential observations"). Strong relationships between the lead author and the Gazi community through ongoing research, professional and personal involvement in village projects, participation as an observer in the procurement process for formal projects (tenders) among other engagements, also enabled effective community engagement. All questions were a priori open-ended, but pre-testing in Kenya and elsewhere enabled us to pre-print common responses on survey forms for interviewers to easily encircle during the oral interviews, without sharing these forms with respondents. All questions were asked to every participant; however, if a specific use was not mentioned, related subquestions were skipped. The importance of and the dependency on mangroves was asked on a Likert scale type, resp. a binary Yes/No question. These seemingly repetitive questions are part of a methodological approach to assess consistency in responses. The metric for mangrove use was defined as the number of respondents identifying a specific use. Mangrove knowledge refers to recognition of a specific number of functional species (see ESM 1 and Dahdouh-Guebas et al. 2000).

The questionnaire was refined after a pilot phase involving pre-testing. Sensitive questions on background, income, and wealth were asked at the end of each interview but appear at the top of the questionnaire form for encoding purposes, as they often informed analysis of other responses (see ESM1). Flexible probing was used during interviews, allowing deviation from semi-structured questions and adaptation of our questioning style based on respondent's answers. This included all probe types described by Robinson (2023): descriptive, ideographic memory, clarifying and explanatory. For example, an ideographic memory probe was used in the question "Do you catch more or less than 10 years ago?" by referencing a well-known local event from that time, such as the 2004 Indian Ocean tsunami during interviews in 2014. Such reference events may vary and include political milestones (e.g., presidential elections), infrastructural changes (e.g., installation of streetlights), or other significant local occurrences. Our questioning style adapted to the length of respondents' narratives, requiring respectful listening, especially when detailed anecdotes were shared. These stories often provided valuable insight into the respondent's worldview.

We, or specialists in the field, identified species using their diagnostic features (see also next section). Scientific and vernacular nomenclature and vernacular synonymy for identification of plants follows Dahdouh-Guebas et al. (2000), Dale and Greenway (1961), Tomlinson (2016), Williams (1949) and World Register of Marine Species – WoRMS (www.marinespecies.org), whereas that for fish and shellfish follows Anam and Mostarda (2012), Mohamed et al. (2007) and WoRMS. All Latin names have been checked on the WoRMS to retrieve the only accepted name, and, if available, the English vernacular names. Additional vernacular names can be retrieved from FishBase (www.fishbase.se) and SeaLifeBase (www.sealifebase.se). Scientific plant nomenclature has been cross-checked in the World Flora Online (WFO) Plant List (www.wfoplantlist.org).

### *Experiential observations*

To immerse ourselves in mangrove-related occupations like wood collection and fishing, we regularly joined stakeholders, with their permission, and visited local markets, documenting our observations through verbal and visual records. For instance, we accompanied fishermen during fishing excursions and sales at the landing site and markets partly to identify fish species. Matching vernacular species names to specimens, sharing anecdotes with local stakeholders and visualizing traditional practices would not have been possible without these visual and verbal experiential observations. Importantly, the latter were also done before, in between and after the aforementioned fieldwork expeditions, i.e., in Jul–Sep 1993, Jul–Sep 1997, Mar–Jun 1999, Aug–Sep 2000, Jul–Aug 2003, Jul–Aug 2005, Feb 2007, Jun–Aug 2009, May–Jun 2014, Aug 2016, Jul–Aug. 2018, May–Jun 2021, and Jul–Aug 2021.

### *Data analysis*

Descriptive analysis was completed using MS Excel, and statistical tests were computed using the R programming version 4.1.1 software (R Core Team 2021) and packages *lme4* and *glmmTMB*. Generalized Linear Mixed Modeling (GLMM) was applied to assess the association among categorical variables related to mangrove knowledge, with knowledge as response variable and survey year, residence time in the village, age class, gender, occupation, and education level as predictor variables. To account for similarities among respondents from the same location, village was included as a random effect. To verify if there was a significant difference in mangrove use categories by year (2003, 2014, and 2021), Chi-square tests ($\chi^2$) were performed. Post-hoc pairwise comparisons (Bonferroni) were conducted following the overall Chi-square test to confirm any significant difference between the years (2003, 2014, and 2021). For all tests, the statistical significance level was set at $p = 0.05$.

For responses to questions related to money, we used the local currency, i.e., Kenyan Shilling

(KES). During the data collection in 2003, the exchange rate for 1 United States Dollar (USD) was 75.75 KES in 2003, 89.05 KES in 2014, and 111.85 KES in 2021. (https://www.xe.com/currencytables/). We also converted KES to the Geary-Khamis Dollar (G-K$), also named International Dollar, which involves dividing the KES value by the set purchasing power parity (PPP) exchange rate. In turn, PPP equals the amount in KES necessary to purchase a similar amount of goods and services in the local market as the USD would buy in the USA. The PPP is mainly determined by the World Bank, the International Monetary Fund (IMF) and the Organization for Economic Co-operation and Development (OECD). One G-K$ was equal to 19.54 KES in 2003, 34.41 KES in 2014, and 42.33 KES in 2021 (data extracted from https://data.imf.org/ under Indicator name: Rate, Domestic currency per international dollar in PPP terms, ICP benchmarks 2017–2021).

## Demographic and Cultural Background of the Communities

Throughout the study period (2003, 2014, and 2021), nearly half of the respondents had never received formal education (Table 1). Data from 2014 and 2021 covered comparable mean or median ages of respondents, but these were higher than those for Msambweni sub-County or Kwale County (Table 1). Fishing was the source of livelihood reported by most of the respondents in 2003, small businesses in 2014, and service jobs such as driver, teaching, and boat operation, were most reported in the year 2021 (Table 1). The respondents' residence times in the village were grouped into three categories and strongly varied among years (Fig. 2), the median residence time dropping from 35 in 2003 to 24 in 2021. Most respondents aged 60 and above appear in the 2003 survey (Fig. 3). The household purchasing power in Gazi Village has decreased by almost 75% between 2003 and 2021 (Table 1). Finally, we consider the significant differences in respondent gender ratio irrelevant, because we never asked questions about individual use (e.g., "Do you collect…?"); whoever responded, men or women, always responded to the questions relative to the household ("Who collects…?").

All respondents lived and/or worked in and around Gazi Bay, historically named Maftaha Bay, with the majority residing in Gazi Village, sometimes spelled and pronounced as "Gasi" or "Gassi." Gazi, historically linked to the slave trade and often appearing on historic maps (cf. Krapf 1860), shared a legacy common to coastal East-Africa and the Western Indian Ocean, where such trade dates back to at least the first millennium (Gilbert 2002). Its related historic sites like palaces, prisons, or caves reported as such by local residents along with related anecdotes, can still be found in Gazi and elsewhere along the Kenyan and Tanzanian coastline. On the Kenyan south coast, communities often comprise individuals of Swahili and/or Digo origin, the latter being one of the Mijikenda tribes. Together with the Pokomo and Taita, the Mijikenda and Swahili form four Bantu-speaking clusters, all tracing their origins to Shungwaya, a mythical heartland in the Tana-Juba region (Hoorweg et al. 2000). The Swahili encompass and define a larger coastal identity with a distinct economic and social organization as an (often) urban and Muslim community, whereas the Mijikenda were traditionally farmers and coconut growers and had or have fortified settlements known as kaya and spiritual sites (Hoorweg et al. 2000). The Mijikenda sacred forests have been recognized as UNESCO World Heritage (https://whc.unesco.org/en/list/1231/). A third group of people, particularly fishers, have immigrated or have been regularly visiting from the neighboring island of Pemba, one of the two islands constituting Zanzibar, which was the historic regional center of the slave trade. Today most indigenous Gazi Mswahili, Wadigo and Wapemba, the names denoting the peoples, are merchants, agriculturists and/or fishers.

## Caveats

Our study has some limitations. One involves potential translation loss in distinguishing mangroves as trees (sg. *mkoko*, pl. *mikoko*) versus as ecosystems (*mikokoni*), with the Kiswahili locative suffix *-ni* indicating place. While terms like *sokoni* (marketplace) or *dukani* (shop location) are common when referring to a market (*soko*) or a shop (*duka*), *mikokoni* is preferred when referring to the mangrove forest, not individual trees. This may have caused some ambiguity, similar to the dual meaning of "mangrove" in

**Table 1.** Demographic description of respondents during the survey period of July–August in 2003, and May–June in both 2014 and 2021, alongside the closest Kenya Population and Housing Census data from 1999, 2009, or 2019 for Gazi (Central Bureau of Statistics 2001a, 2001b; KNBS 2010a, 2010b, 2010c, 2019a, 2019b, 2019c). MS = Data for Msambweni sub-County when data for Gazi Village or Kinondo Ward were not available; KW = Data for Kwale County when data for Msambweni sub-County or its subdivisions were not available; * = Estimated value; N/A = Not applicable. Percentages are expressed as integers; KES = Kenyan Shilling; USD = United States Dollar; G-K$ = Geary-Khamis Dollar (= International Dollar). Conversion rates as mentioned in the text under 'Data Analysis'

| | Census 1999 | Fieldwork 2003 | Census 2009 | Fieldwork 2014 | Census 2019 | Fieldwork 2021 |
|---|---|---|---|---|---|---|
| **Survey respondents** | 3,845 | 82 | 288,393^MS | 82 | 6,733 | 98 |
| Men | 51% | 73% | 49%^MS | 44% | 52% | 67% |
| Women | 49% | 27% | 51%^MS | 56% | 48% | 33% |
| Households in Gazi Village | 809 | 82 | ±1,100* | 82 | 1,399 | 98 |
| Households in Msambweni Sub-county | 43,622 | N/A | 59,484 | N/A | 45,374 | N/A |
| Households in Kwale County | 92,594 | N/A | 122,047 | N/A | 173,176 | N/A |
| Mean age (yrs) | 26^MS | 44 | 21^KW | 36 | 24^MS | 38 |
| Median age (yrs) | 30–34^MS | 40 | 34^KW | 32 | 21^MS | 36 |
| Maximum age | >60^MS | 90 | >80^MS | 64 | >100^MS | 65 |
| Minimum age | 0^MS | 20 | 0^MS | 18 | 0^MS | 20 |
| **Education** | | | | | | |
| Nursery or no formal education (N) | 49%^KW | 50% | 37%^MS | 25% | 16%^MS | 11% |
| Primary (P) | 39%^KW | 38% | 50%^MS | 44% | 52%^MS | 46% |
| Secondary (S) | 8%^KW | 13% | 10%^MS | 28% | 29%^MS | 35% |
| University (U) | 0%^KW | 0% | 2%^MS | 2% | 2%^MS | 6% |
| Not known or not stated | 3%^KW | 0% | 0%^MS | 0% | 1%^MS | 0% |
| **Profession of respondents** | | | | | | |
| Fishing | N/A | 44% | N/A | 18% | N/A | 25% |
| Small sales (sale of fruits, vegetables, etc. by women) | N/A | 15% | N/A | 30% | N/A | 22% |
| Fishmonger | N/A | 8% | N/A | 9% | N/A | 12% |
| Farming | N/A | 3% | N/A | 1% | N/A | 1% |
| Makuti making (i.e., thatched coconut for roofing and fencing tiles) | N/A | 6% | N/A | 13% | N/A | 2% |
| Firewood/timber selling | N/A | 1% | N/A | 1% | N/A | 2% |
| Tree logger | N/A | 4% | N/A | 0% | N/A | 0% |
| Other (driver, teaching, boat driving/sailing, business and other jobs in the service sector) | N/A | 21% | N/A | 24% | N/A | 31% |
| **Annual household income (reported)** | | | | | | |
| Kenyan Shilling | N/A | 163,886 KES | N/A | 112,443 KES | N/A | 97,935 KES |
| Euro | N/A | 1,956.61 EUR | N/A | 952.91 EUR | N/A | 759.95 EUR |
| United States Dollar | N/A | 2,163.51 USD | N/A | 1,262.70 USD | N/A | 875.60 USD |
| Geary-Khamis Dollar | N/A | 8,387.21 G-K$ | N/A | 3,267.74 G-K$ | N/A | 2,313.61 G-K$ |

**Table 1.** (continued)

| | Census 1999 | Fieldwork 2003 | Census 2009 | Fieldwork 2014 | Census 2019 | Fieldwork 2021 |
|---|---|---|---|---|---|---|
| **Type of houses** | | | | | | |
| Wood and mud | 66%[KW] | 36% | 49%[MS] | 54% | 20%[MS] | 19% |
| Wood and coral stone | 9%[KW] | 0% | 8%[MS] | 16% | 4%[MS] | 18% |
| Quarried fossil coral stone or limestone (white) | 12%[KW] | 55% | 19%[MS] | 10% | 49%[MS] | 51% |
| Cement bricks (grey) | 10%[KW] | 13% | 21%[MS] | 26% | 15%[MS] | 14% |
| Other | 1%[KW] | 0% | 3%[MS] | 0% | 12%[MS] | 0% |

**Fig. 2.** Residence time of respondents in the study area in 2003 ($n=80$), 2014 ($n=82$), and 2021 ($n=95$)

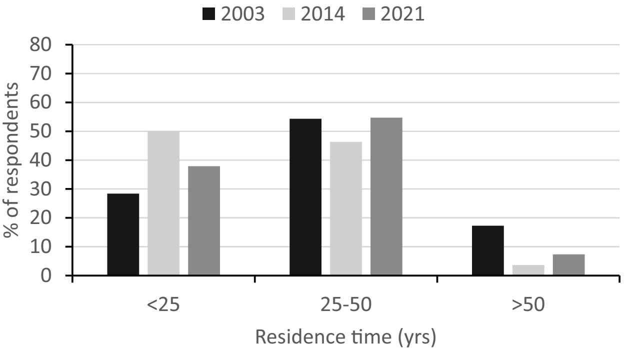


**Fig. 3.** Relationship between respondents' age and their residence time in Gazi Bay during the ethnobiological surveys conducted in 2003, 2014, and 2021. The yellow area represents their "knowledge age" defined as the minimum requirements to respond to questions about the local situation 10 years prior (cf. ESM 1), i.e., being at least 18 years old and having lived in the village for at least 10 years, based on the assumption that relevant memories begin around age 8. This threshold is conservative, considering that even younger children are exposed to local knowledge transfer through activities like collecting firewood or accompanying relatives (pers. obs. by the authors)

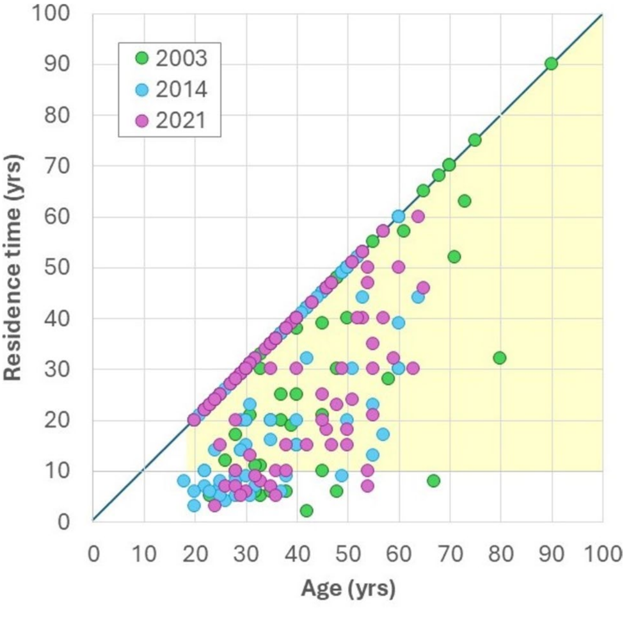

**Table 2**. Level of knowledge on mangrove tree species from respondents in 2003 ($n=82$), 2014 ($n=82$), and 2021 ($n=97$). This knowledge level should not be seen as a scholarly grade or evaluation, but simply ensures inclusion of data from respondents familiar with the tree species under study

| Number of mangrove species recognized | Knowledge level | % of respondents | | |
|---|---|---|---|---|
| | | 2003 | 2014 | 2021 |
| <3 | Low | 25 | 45 | 16 |
| 3–4 | Fair | 24 | 32 | 58 |
| <5 | Low and Fair | 49 | 77 | 74 |
| 5–6 | Good | 37 | 19 | 20 |
| 7–9 | Very good | 14 | 4 | 6 |
| ≥5 | Good and Very good | 51 | 23 | 26 |

English. However, since most respondents referred to mangroves as vegetation, the impact appears minimal.

Beyond the nearly 75% decline in household purchasing power in Gazi Village between 2003 and 2021, major global crises, such as the 2007–2008 financial crash, the 2020 COVID-19 recession, the 2021–2023 energy crisis, armed conflicts, and the climate and biodiversity crises, rarely emerged as key discussion topics in our surveys. We advocate for more social research on this issue, as it has been largely overlooked in over 25 years of work in the social sciences and humanities (cf. Cormier-Salem 1999; Dahdouh-Guebas et al. 2022a, b).

## Results

### Knowledge and Nomenclature of Mangroves

The interpretation of "mangrove" varied slightly across the three periods, with an increasing number of respondents defining it as vegetation (64% in 2003, 77% in 2014, and 80% in 2021). A minority, mainly fishers and firewood collectors, understood it as an ecosystem.

The nine mangrove species that respondents reported knowing were grouped into four categories based on the minimum number of species recognized in each (Table 2). The Generalized Linear Mixed Model (GLMM) test (ESM 2) showed that in 2003, respondents had significantly very good knowledge of mangrove species as opposed to the years 2014 and 2021 when knowledge of mangroves had decreased significantly (2014: $z_{-0.47631}=-4.363$, $p<0.0001$; 2021: $z_{-0.07334}=-0.796$, $p=0.426$). About 51%, 23%, and 26% of the respondents, in 2003, 2014, and 2021, respectively, stated that they had good to very good knowledge of mangrove species (Table 2). This reveals a significant decrease in good to very good knowledge levels as opposed to low and fair ones, between 2003 on one hand and 2014 and 2021 on the other ($\chi^2=13.20$, df = 1, $p=0.00028$), the latter 2 years being not significantly different from one another ($\chi^2=0.24$, df = 1, $p=0.74$). When pooling the data across all surveys, additional insights were revealed on mangrove knowledge and demographic background data. First, significant relationships were observed between the knowledge of the species and the respondent's residence time (>50 years: $z_{0.37485}=2.761$, $p=0.006$; 25–50 years: $z_{0.23606}=2.690$, $p=0.007$). About 19%, 59%, and 38% of the respondents who lived in the village for <25 years, 25–50 years, and >50 years, respectively, had good to very good knowledge of the mangrove species. Second, although age class generally had no significant relationship with the knowledge of mangroves by respondents, we found that two age classes, 41–50 years ($z_{0.6875}=2.273$, $p=0.023$) and 71–80 years ($z_{0.8458}=2.162$, $p=0.031$), had significantly higher good to very good knowledge of the mangrove species. Also note that in more recent times there were fewer people >50 years old in the village (Fig. 2). Third, we found that gender had no significant relationship with a respondent's knowledge of mangrove species ($z_{-0.14775}=-1.732$, $p=0.083$). Fourth, fishers ($z_{0.27772}=3.104$, $p=0.002$) and mangrove wood sellers ($z_{0.51039}=2.250$, $p=0.024$) had significantly good to very good knowledge of mangrove species compared to those who worked in other occupations. Fifth, our results showed no significant difference between mangrove species knowledge and the level of education, namely primary ($z_{0.01812}=0.182$, $p=0.855$), secondary ($z_{-0.07862}=-0.665$, $p=0.506$), and university ($z_{0.20276}=0.851$, $p=0.395$).

It is important to note that Gazi inhabitants use functional rather than Linnean nomenclature to identify plants and animals (ESM 3). A single biological tree species may have different vernacular names depending on its maturity or local interpretation. However, some believed that *Bruguiera* and *Rhizophora* were the young and adult stages of the same species. In contrast, two different biological fish species receive the same vernacular name, presumably because they are both toxic in a similar way. For instance, *bunju* is used to denote different fish species and genera belonging to the extremely toxic Tetraodontidae and Diodontidae.

Finally, some vernacular fish names seem to be used as a metaphor for the location where they were caught or known to be abundant or at least present. For instance, Chale, Dagasi, Kinondo, and Kiunga may correspond resp. to Chale Island, Gazi Village, Kinondo Village, and Kiunga Town or Kiunga Marine National Reserve. However, note that the latter, located over 500 km north, was too far away to be confused with the location per se, and to our knowledge and verification no nearby Kiunga location exists.

## Local Utilization of Mangroves

Most respondents reported more intensive uses of mangrove for construction and fuelwood in all years 2003, 2014, and 2021 than for other uses (Fig. 4).

### *Fuelwood*

Fuelwood use in 2003, 2014, and 2021 showed a significant variation ($\chi^2=10.20$, df$=2$, $p=0.006$). The use was confirmed by the Post-hoc tests to be significantly higher in 2003 than in 2014 ($p=0.01$) and in 2003 than in 2021 ($p=0.030$). A total of eight out of ten species of mangroves in Gazi were reported to be used for fuelwood in both 2003 and 2021, although some species were used to a limited extent in 2021. *Xylocarpus moluccensis* and *Pemphis acidula*, which are rare and/or small in the region, were not used for firewood. *Avicennia marina* (Forssk.) Vierh. and *Xylocarpus granatum* König showed higher usage in 2021 than in 2003, whereas the usage of *Rhizophora mucronata* Lamk. was nearly similar to that of 2003 (Fig. 5). In 2003, respondents collected firewood an average of eight times per month, traveling an average of 1 km each time. In 2021, this decreased to five trips per month averaging 1.2 km. No significant difference was found in collection frequency ($\chi^2=23.89$, df$=15$, $p=0.07$).

There is also an interesting change in reported gender division concerning firewood collection, with 27% women, 66% men, and 6% child collectors in 2003, over 59% women, 11% men, and 30% child collectors in 2014, to 57% women, 14% men, and 28% child collectors in 2021. We only observed women and child firewood collectors during our visual observations.

### *Construction*

The use of mangrove for construction wood showed significant variation between 2003, 2014, and 2021 ($\chi^2=12.84$, df$=2$, $p=0.002$), with Post-hoc tests showing a higher extent of the use in 2003 than in 2014 ($p=0.001$), and in 2003 than in 2021 ($p=0.001$).

Respondents distinguished between mangrove species used for pillars, horizontal and vertical framework, ceiling and roof construction. For pillars, *Ceriops tagal* (Perr.) C.B., *Rhizophora mucronata*, *Xylocarpus granatum* showed increased usage in 2021 compared to 2003. There was decreased usage of the species used for horizontal and vertical framework and for ceiling in 2021, and an increased usage of *Avicennia marina*, *Rhizophora mucronata*, *Xylocarpus granatum* for roofing (Fig. 6). Different mangrove wood diameter classes (*fito* 2.5–3.5 cm, *pau* 4.0–7.5 cm, *mazio* 7.5–11.5 cm, *boriti* 11.5–13.5 cm, *nguzo* 14.0–20.0 cm) were used to construct the different parts of a house (Dahdouh-Guebas et al. 2000; Roberts and Ruara 1967) (see ESM 4). In 2003, respondents collected construction wood six times per month, traveling on average 1 km each time; by 2021, this had dropped to two trips per month over the same distance. No significant difference was in collection frequency and distance travelled for mangrove construction wood ($\chi^2=9$, df$=5$, $p=0.11$).

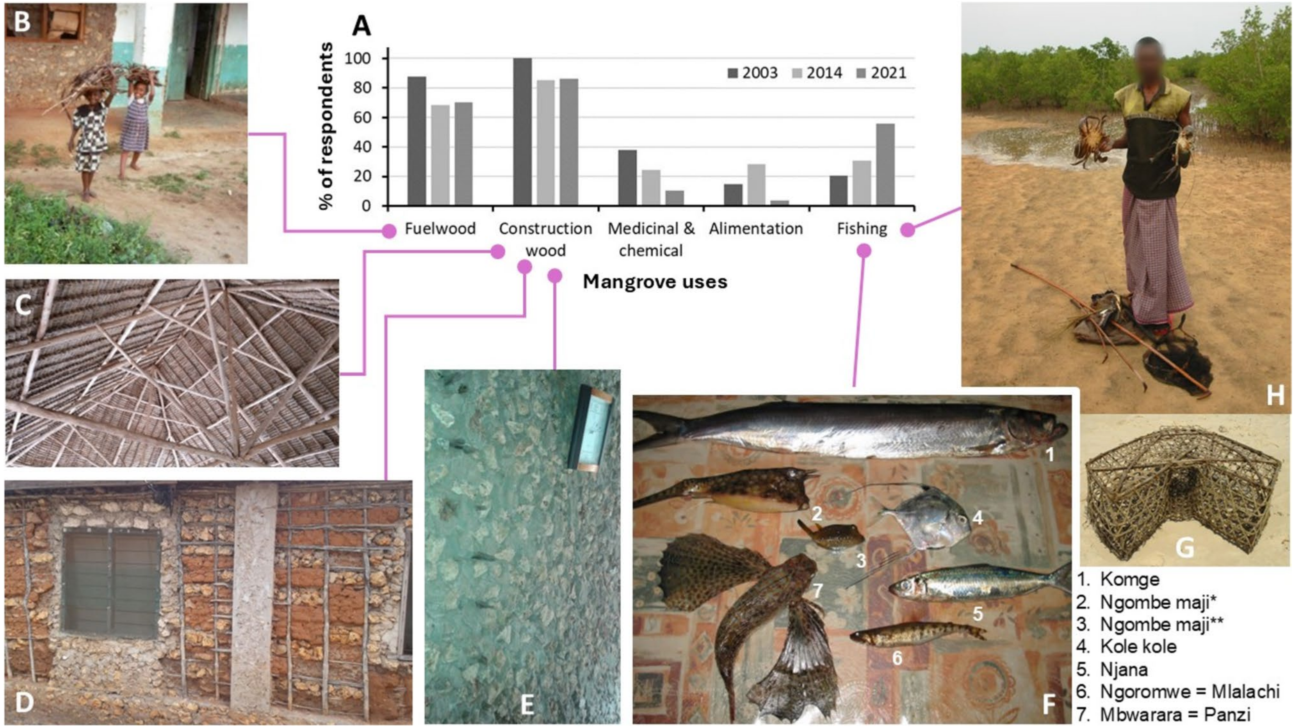


**Fig. 4**. **A** Graphical representation of the main uses of mangroves reported by respondents in 2003 ($n = 82$), 2014 ($n = 82$), and 2021 ($n = 88$), with illustration of **B** firewood (Dahdouh-Guebas et al. 2000 Economic Botany back cover), **C** beams used for roof construction (see also Fig. 6e), and **D** house of mangrove wood filled with mud, cement, and coral stone. **E** Even when inside or outside walls appear cemented, the internal wooden mangrove frame is revealed by horizontal poles protruding from the structure. **F** Some of the fish catches from boat landings. Note the same local name for two different toxic fish (2,3): *Rhino boxfish *Ostracion rhinorhynchos* (Bleeker, 1851) and **Whitespotted box fish *Ostracion meleagris* (Shaw, 1796). Refer to ESM 3 for full species list. **G** Basket trap (sg. *lema*; pl. *malema*) made from leaves of the (non-mangrove) East African Doum palm (*Hyphaene compressa* H. Wendl.) or Lala palm (*Hyphaene coriacea* Gaertn.), named *Mkoma*, *Mkoche*, *Mlala*, *Mnyaa*, or *Muaa* in Kiswahili (Maundu and Tengnäs 2005), to catch the Mangrove mud crab *Scylla serrata* (Forskål, 1775). **H** Fisherman foraging through mangrove creeks by foot showcasing his wooden fishing gear and his catch (also *Scylla serrata*)

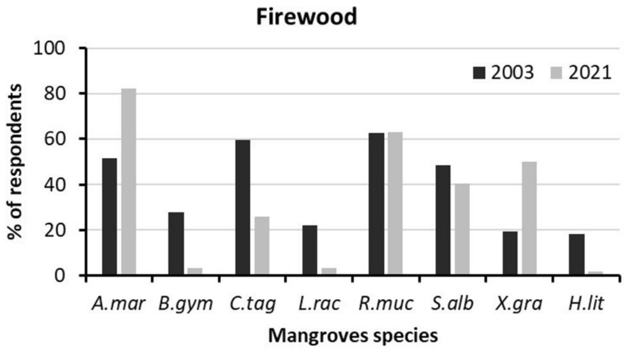


**Fig. 5**. Mangrove species used for firewood (fuelwood) in 2003 ($n=72$) and 2021 ($n=62$). *A.mar=Avicennia marina; B.gym=Bruguiera gymnorhiza; C.tag=Ceriops tagal; H.lit=Heritiera littoralis; L.rac=Lumnitzera racemosa; R.muc=Rhizophora mucronata; S.alb=Sonneratia alba;* and *X.gra=Xylocarpus granatum.* N.B. Mangrove tree species *Xylocarpus moluccenis* and *Pemphis acidula*, which are rare in the region, were not used for firewood

### *Uses for medicinal and chemical properties*

We differentiated between mangrove plants used to treat health issues (medicinal) and plants used for chemical properties (e.g., dying fishing nets). In all years, mangroves were used for medicinal and material treatment, but to a limited extent. The species preferred for medicinal use in 2003, which showed a drastic decrease by 2021, were *Avicennia marina*, *Rhizophora mucronata*, *Xylocarpus granatum* and *Heritiera littoralis*, whereas those mostly used for purposes based on chemical properties in 2003 were *Ceriops tagal* and *Rhizophora mucronata* (ESM 5). There was variation in their use as medicine between 2003, 2014, and 2021 ($\chi^2=17.81$, df=2, $p=0.0001$), with a significant decrease between 2003 and 2021 (Post-hoc test p=7.2e-05). Over half of the respondents reported first visiting a physician when ill (63% in 2003; rising to 93% in both 2014 and 2021).

### *Alimentation (animal fodder and food for humans)*

Mangrove species were used for animal feed to a limited extent, with 12% of respondents reporting this in 2003, 28% in 2014, and only 3% in 2021. The use of mangroves as fodder for animals showed a significant decrease ($\chi^2=20.14$, df=2, $p= <0.0001$), with post-hoc tests indicating higher significance in 2003 than in 2021 ($p=0.04$) and in 2014 than in 2021 ($p= <0.0001$).

In 2003 and 2021, no mangrove species were used directly or indirectly for human food. In 2014, three respondents reported obtaining honey from mangroves.

## Mangrove Artisanal Fisheries

Respondents reported 266 local names for marine animals, including fish, decapods (crabs, shrimps and lobsters), and mollusks (bivalves, gastropods, and cephalopods), corresponding to at least 272 English vernacular names and 163 scientific species (ESM 3). The results indicate that participants practiced significantly variable fishing in the mangrove area over time ($\chi^2=24.14$, df=2, $p= <0.0001$). An increase in mangrove creek fishing was observed between 2003 and 2021 (Post-hoc pairwise test $p= <0.0001$), and between 2014 and 2021 (Post-hoc test $p= <0.0001$). The types of fishing gear also varied over the years (see ESM 6). Respondents reported that the decrease in fish catches over the past 10 years, i.e., 64% decrease between 1993 and 2003; 70% between 2004 and 2014; 85% between 2011 and 2021, resulted from increased number of fishers, climate change, illegal fishing, and degraded habitats. A minority of respondents reported, however, increased fish catches (13% in 2003; 14% in 2014; 3% in 2021), albeit without significant difference ($\chi^2=3.08$, df=2, $p=0.210$).

A notable gender division exists in fisheries: while men primarily catch fish and shellfish, the small Golden shrimp *Plesionika martia*

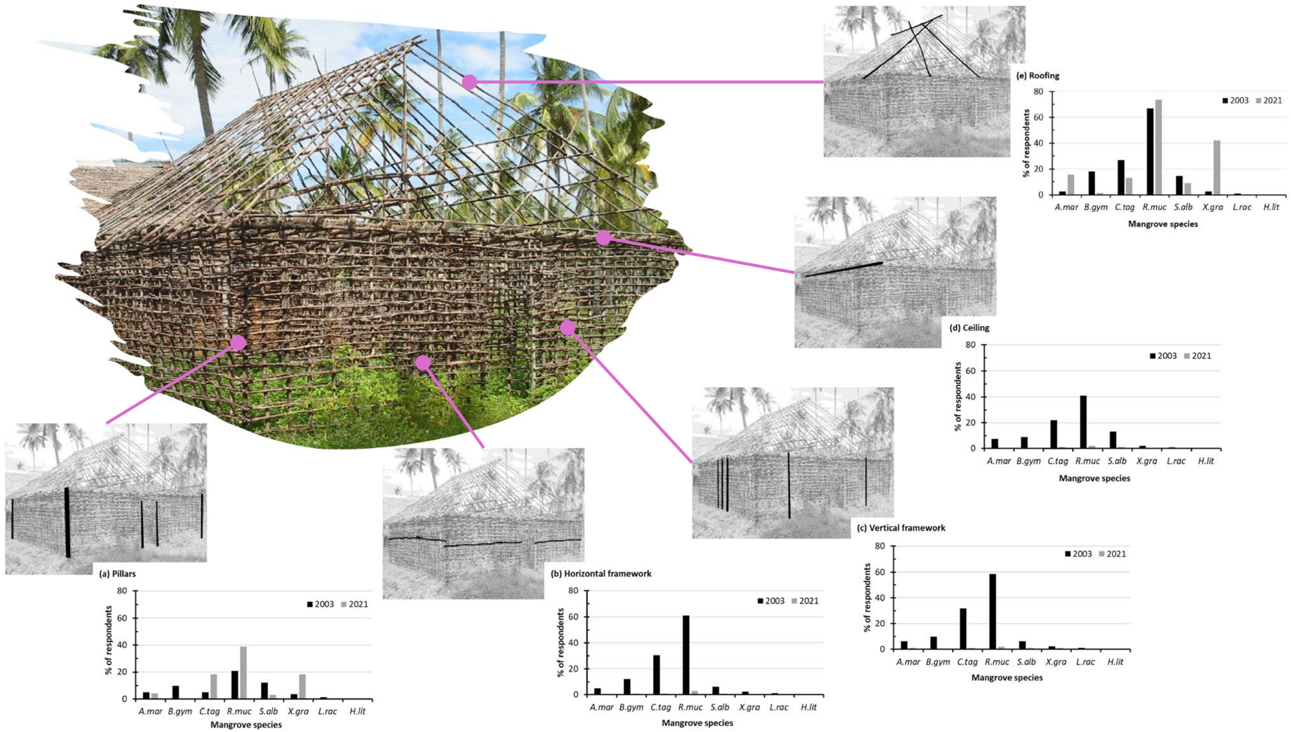


**Fig. 6**. Mangroves species used in house construction for (**a**) pillars, (**b**) horizontal framework, (**c**) vertical framework, (**d**) ceiling, and (**e**) roof construction in 2003 (n = 82) and 2021 (n = 76). Greyscale photographs highlight some of the beams (in black) corresponding to the each category. Explanation of abbreviations see Figure 5. Photograph by Griet Neukermans (Dahdouh-Guebas et al. 2020)

TABLE 3. The importance of and the dependency on mangroves reported by the respondents in 2003, 2014, and 2021. Importance was asked on a Likert scale type, whereas the dependence was a binary Yes/No question. These seemingly repetitive questions are part of a methodological approach to assess consistency in responses. The answers show clear consistency, as similar proportions of respondents who rated mangroves as "Very important" also reported dependency

| | 2003 ($n=81$) | 2014 ($n=82$) | 2021 ($n=94$) |
|---|---|---|---|
| **A. Importance** | | | |
| Very | 91% | 84% | 56% |
| Little | 5% | 9% | 30% |
| Not much | 2% | 4% | 4% |
| Not at all | 2% | 3% | 10% |
| **B. Dependency** | 89% | 79% | 56% |

(Milne-Edwards, 1883), locally known as duvi, is almost exclusively harvested by women (pers. obs. by the authors).

### Local Perceptions on Mangrove Dynamics

Changes in mangrove area over time were reported. Around 15% of respondents in 2003, 66% in 2014, and 69% in 2021 reported mangrove area increases due to natural regeneration, regular planting, and bans on cutting, alongside growing conservation awareness. In total, 77% of the respondents in 2003, 18% in 2014, and 25% in 2021 reported a decrease that resulted from the view that "if mangroves are not cut, they will not grow," illegal cutting of mangroves, and climate and climate change impacts such as from sea level rise and El-Niño Southern Oscillation. In light of the latter, residents of Gazi Village reported Maasai transhumance into coastal areas during extended drought periods to cause conflicts over natural resources (also pers. obs. by the authors). Respondents' views about perceived expansion in mangrove area significantly increased between 2003, 2014, and 2021 ($\chi^2=47.3$, df$=2$, $p<0.0001$).

Mangroves are considered important by Gazi Village residents, with at least 50% in each decade reporting high importance of mangroves to their daily lives. However, a significant decline in dependency on mangroves was reported ($\chi^2=64.4$, df$=2$, $p<0.0001$) (Table 3).

Linking demographic background, mangrove uses and changes, we recall four important observations. First, in recent times, there seem to be fewer people over 60 years old in the village (Fig. 3). Second, although the median residence time declined, the number of respondents with residence times below or above 30 years, the median age in 2021, or 10 years, the threshold for some retrospective questions, did not differ significantly between 2003 and 2021 (resp. $\chi^2=2.51$, df$=1$, $p=0.113$ and $\chi^2=0.02$, df$=1$, $p=0.884$). They were, however, significantly different when including 2014 data (resp. $\chi^2=9.70$, df$=2$, $p=0.0078$ and $\chi^2=4.51$, df$=2$, $p=0.052$). Third, professions shifted from artisanal fisheries to jobs in the service sector (Table 1). Fourth, from our observations, there were clear shifts in house construction (Fig. 7). All of these suggest that TEK and LEK in Gazi have been eroding over decadal time scales.

## Discussion

Documenting biocultural dynamics, social-ecological transitions, and changes in biological and cultural diversity requires urgent, long-term investment in fundamental research (Vandebroek et al. 2020). Studies on TEK erosion resulting from compounding climate-development effects and associated transitions in land tenure, education, globalization, migrations, and non-indigenous institutions and development policies exist for other ecosystems in Asia, Africa, and the Americas (cf. Athayde et al. 2017; Hedges et al. 2020; Sujarwo et al. 2014; Tran et al. 2025). However, such long-term ethnobiological approaches are still new to mangrove research.

### Knowledge and Traditional Ecological Taxonomy of Mangrove Biota

While most Gazi Village respondents identified mangroves as vegetation (wood, trees), knowledge levels on the number of mangrove tree species declined over time, with a rise in low to fair knowledge levels and a drop in good to very good levels. In 2003, fishers and

**Fig. 7.** Top: Traditional house constructed with mangrove wood (see also Fig. 6), filled with mud or coral pieces are gradually being replaced by structures using quarried natural white coral (rubble) stones (or grey cement bricks; not shown). Building coral brick houses no longer requires knowledge of mangrove tree species, their utilization classes in construction, or the architectural roles and properties of mangrove wood in traditional Swahili or Digo village houses (cf. Tables 1 and 2 and Figs. 5, 7 and 8 in Dahdouh-Guebas et al. 2000), potentially leading to TEK erosion. Photograph by Griet Neukermans. Bottom: Street view of Gazi in 2017, showing completed houses with makuti, i.e., thatched coconut leaf tiles, or iron sheet roofs. Mangrove poles, coral bricks, and coral stones used for construction are visible in front, some intended for export. Photograph by Nico Koedam

mangrove wood sellers had better knowledge of mangroves than other occupation types. This can be explained by fishers and mangrove wood sellers visiting mangrove forests more frequently, leading to their greater familiarity with the species. Similar results were found by Dahdouh-Guebas et al. (2000) in Mida Creek where specialist users recognized mangrove species using various characteristics and morphological properties of the plants, and those with a thorough understanding of mangroves were able to distinguish between different species through the root system. Mangrove wood harvesters have been reported to possess knowledge of mangrove species and their uses, and fishers were knowledgeable about the services mangroves offer (Murungi 2017). The essence of and the search for knowledge can, however, be different in science and society. Crona (2006) claims that knowledge sometimes appears to be largely related to the maximization of resource extraction rather than reflecting a deep understanding of ecological processes and causal links. Rist and Dahdouh-Guebas (2006) also noted that indigenous forms of knowledge often focus on why questions, whereas scientific approaches primarily address how questions.

A functional, pragmatic vernacular taxonomy for classifying plant and animal species by their beneficial or harmful traits is, or was, a reality in traditional communities such as Gazi Village. Ethnobotanical research indicates that properties of plant parts can differ between juvenile and mature stages, supporting the use of distinct vernacular names for the same species. In the Mangrove fern *Acrostichum aureum* L., for instance, mature fronds are used in roof construction (Yong et al. 2010), while only the young, tender leaves are consumed in vegetable curry (Satyanarayana et al. 2013) or salads (Yong et al. 2010). This suggests TEK regarding potential toxicity, as the species contains flavonoids, phenols, sterols, phenol, and polyphenol (Nabeelah Bibi et al. 2019). However, no toxicological studies have examined how toxicity in *Acrostichum* changes with plant age.

Ethnobiological research also confirms the existence of a unique vernacular name to denote different scientific species with similar negative or positive properties, such as the venomous fish in the present study. The Tetraodontoidei suborder, to which the Tetraodontidae and Diodontidae families belong, contain tetrodotoxin, the toxicity of which is known to have a 10% to 60% fatality rate after ingestion in humans (Ellenhorn and Barceloux 1988; Varini et al. 2025). A functional, pragmatic ethnoichthyological nomenclature that uses a single term to warn both children and adults against consuming toxic fish is entirely logical. Some studies also underscore the call for restoring indigenous names in Linnean taxonomy (Gillman and Wright 2020). This highlights that also the essence of naming can be different in science and in society.

## Utilization of Wood and Non-timber Forest Products

Changes in the use of mangrove species for fuelwood between 2003, 2014, and 2021 can be linked to various reported factors. Respondents were aware of the ban on mangrove logging and the requirement for a legal license, which may explain the reduced use of mangrove species for firewood (ESM 7). If given the choice to resort to free firewood or purchased charcoal, which corresponds to the 2003 situation, users seem to opt for firewood. The reported shift from firewood collection being man-dominated in 2003 to woman-dominated in 2021 remains unexplained, though it may relate to the end of mangrove tree logging as a formal profession (see below). Possible contributing factors include the cutting ban and related increased law enforcement (ESM 7), the COVID19 pandemic (Vandebroek et al. 2020; Yue et al. 2026), demographic changes due to migration (cf. Mbaye et al. 2021; Teye and Nikoi 2022; pers. obs. by the authors and pers. communication by respondents), and differing risk perceptions when violating the ban, especially among children. Identifying the causal reasons necessitates further research. In this context, differing gender-based harvesting practices can impact mangrove ecology as evidenced by variations in scale (small vs. large), target tree age (young vs. adult), and harvesting frequency and intensity (Feka et al. 2011), but also the flow of ecosystem services in general (Nyangweso Ochieng et al. 2023).

Mangrove conservation efforts may have been supported by awareness-raising activities from Kenya Marine and Fisheries Research Institute's (KMFRI) Gazi field station and civil society groups (Murungi 2017), as well as education, research, and outreach via social media and serious gaming by international scientific teams (Dahdouh-Guebas et al. 2020; 2022a, b). Locally available and reliable alternatives to mangrove utilization can reduce harvesting pressure, provided they integrate and respect LEK and TEK and align with the community's socio-cultural, economic, environmental, and climatic realities (Dahdouh-Guebas et al. 2022a, b).

Respondents identified *Rhizophora mucronata* as the preferred firewood species due to its high calorific value and long burn time, consistent with findings by Gallup et al. (2020) in Senegal, Nfotabong Atheull et al. (2009; 2011) in Cameroon and Satyanarayana et al. (2021) in Malaysia on *Rhizophora* spp. Increased use of *Avicennia marina* and *Xylocarpus granatum* from 2003 to 2021 was attributed to their low-smoke combustion, availability and convenient size. Warui et al. (2020) also found *Avicennia marina* to be well-suited for domestic firewood in Mida Creek, Kenya. In Kenya, mangrove wood for construction is sold in scores, i.e., 20 poles, corresponding to specific diameter classes, each of which has a traditional name (see also Dahdouh-Guebas et al. 2000; Roberts and Ruara 1967). Despite a ban on mangrove cutting (ESM 7), mangrove wood was still used for construction in Gazi in 2021, though less intensively than in 2003, likely due to awareness of the ban (N.B. there were no official tree loggers in Gazi Village in 2014 and 2021; cf. Table 2). The Kenya Population and Housing Census of 1999, 2009, and 2019 also showed a decrease in houses made out of wood and/or mud and an increase in houses made out of limestone (Central Bureau of Statistics 2001b; KNBS 2010c, 2019c; Table 2). The continuous use of *Rhizophora mucronata*, especially for roof construction and for building pillars, could be because of lack of affordable alternatives or utilization preference. Dahdouh-Guebas et al. (2000) reported that in Kenya, *Rhizophora mucronata* can grow long, thick and straight, making its hard wood ideal for house construction. However, while users prefer these properties, harvested mangroves do not necessarily regenerate similarly. In Kenya, cleared *Rhizophora* patches were often replaced by the less valued *Ceriops tagal* (Kairo et al. 2002), weakening the mangrove social-ecological system's natural, built and human capital (cf. Prabakaran et al. 2025).

The frequent use of *Xylocarpus granatum* for roof construction likely stems from its well-known valuable timber (Raju 2003). The reduced usage of species for horizontal and vertical framework and for ceiling in 2021 could be due to increased management interventions or to alternatives found by the communities.

Some studies reported the use of various mangrove species to cure different ailments such as in Mexico (Kovacs, 1999), in Kenya (Dahdouh-Guebas et al. 2000), in Southeast Asia (Bandaranayake, 1998) and beyond. We confirm this for Gazi Bay, but emphasize that over time, the TEK on this use, like on the aforementioned use of house building, has eroded. A study by Kovacs (2000) in Mexico also reported that some respondents acknowledged utilization of *Rhizophora* for medicinal purposes as something of the past. Modern medicine, modern facilities and industrialization could be the source of neglect of traditional medicinal practices and related TEK erosion (Gómez-Baggethun 2009; Turner and Turner 2008).

Many studies reported mangrove NTFP use as food, fodder, alcohol, sugar, and honey (e.g., Ahouangan et al. 2022; Dahdouh-Guebas et al. 2000, 2006; Dahdouh-Guebas 2013; FAO 1994, 2007a, 2007b; Gnansounou et al. 2022; Hernández-Cornejo et al. 2005; Walters et al. 2008). Regarding fodder, some findings on mangrove consumption by livestock contradict our 2021 results, which indicate that livestock primarily feed free ranging on leaves from terrestrial vegetation other than mangroves, though goats have occasionally been observed feeding on *Avicennia marina* fringing Gazi Village (pers. obs.).

## Mangrove Artisanal Fisheries

The mangrove ecosystem acts as a refuge for fish (Carrasquilla-Henao et al. 2019; zu Ermgassen et al. 2021, 2025). Gazi Village fish landing sites support a small-scale multi-gear and multi-species fishery (Crona 2006; Kimani et al. 1996; Ndarathi et al. 2020). Several respondents attributed the decline in catches over the past 10 years to lower rainfall, scarcity of fish, illegal fishing practices, and the Mkurumuji river being diverted for other uses by a nearby titanium mining company. Overfishing in nearshore areas caused depletion of fisheries resources (Josphat Nguu, pers. comm.), though none of this has been corroborated by research. Increased fishing could also be due to the increased human population. In Kenya, catches in artisanal fisheries are reported to have decreased over the past few decades (Crona 2006; Samoilys et al. 2017), although small-scale fisheries still provide a considerable contribution to local communities (Fondo et al. 2025). Likewise, a study in India by Dahdouh-Guebas et al. (2006) reported a decrease in catches due to offshore trawling that caused overharvesting of both juvenile and adult shrimps.

Given the observed gender division in fisheries and fish processing, particularly by Mama Karanga, women who process and cook the fish before selling it (Ndarathi et al. 2020), declining catches risk eroding fisheries TEK broadly, and especially among women. In Guinea-Bissau, children's traditional knowledge about fish and fishing is disappearing, especially in ways that affect boys and girls differently (Keleman et al. 2023), i.e., gendered erosion. This loss threatens both the cultural identity of local communities and efforts to protect fish species and use natural resources sustainably in mangrove ecosystems.

## Perceptions on Changes in the Mangrove Forest and its Biota

Understanding vegetation dynamics for the purpose of conservation and sustainable exploitation is important (Dahdouh-Guebas et al. 2004). In contrast to remote sensing studies (Kirui et al. 2013), the respondents in this study reported an overall increase in mangrove cover. In our study area, the human population and the infrastructure development in the villages have increased (more houses, more constructions using coral rubble and stones, larger village extent, more shops, paved roads, installation of street lights, new schools, etc., pers. obs. by the authors). Relating these changes in human population to usage of natural resources requires additional research.

Although local communities report increased mangrove surface, satellite data and previous studies suggest that mangrove extent has remained stable or even declined in Gazi Bay (Kirui et al. 2013). This apparent contradiction may point to a form of cryptic social-ecological degradation, whereby reductions in traditional mangrove uses and associated ecological knowledge are obscured by perceived increases in mangrove area. Given earlier reports of subtle ecological degradation in mangrove flora (Dahdouh-Guebas et al. 2005a, 2005b; Koedam and Dahdouh-Guebas 2008; Triest et al. 2021) and fauna (Bartolini et al. 2011), this phenomenon warrants closer scrutiny. Compared to our 2003 survey, the 2021 survey lacked respondents over 65 (Fig. 3), suggesting cryptic social-ecological degradation that conceals the decline in traditional mangrove uses and TEK, some of which will be irretrievably lost as current village elders pass away. Traditional house construction (Fig. 6) and the potential loss of this knowledge (Fig. 7) carry added significance in light of UNESCO's World Heritage List, which includes 1223 sites based on cultural or natural criteria (https://whc.unesco.org/). Mangroves feature in 44 of these, but only two, Lamu Old Town (Kenya, site dossier 1055) and Stone Town of Zanzibar (Tanzania, site dossier 173rev), are recognized for their 'cultural' use of mangrove timber (criteria ii, iii, iv and vi; https://whc.unesco.org/en/criteria/). In Gazi, which is summarily recorded in historical records (Aldrick 2022; Berg 1968), this heritage appears to be gradually eroding (Fig. 7). If this trend is widespread, it may signal a turning point in the TEK linked centuries-old mangrove wood trade from East-Africa to the Arabian/Persian Gulf, dating back to the first millenium A.D. (Pouwels 2002; Spear 2000), which potentially involved millions of trees (Breen and Lane 2003). Mangrove poles, alongside gold, ivory, and ambergris, but also enslaved persons, were traded from East Africa to Sohar (Oman), Siraf (Persia) and onward to China (Spear 2000) since the sixth century, long before the Mazrui Arabs settled in Gazi and elsewhere along the Kenyan coast in the nineteenth century (Berg 1968).

## What if There is Mangrove TEK Erosion?

### "What if" seems to become reality

What if traditional ecological mangrove knowledge eroded over decadal time scales? We would welcome the chance to respond to this title question that TEK erosion in mangroves is not a concern, but unfortunately, it no longer seems to be a "what if": it appears to be happening. This paper presents findings from ethnobiological surveys conducted in the 2000s, 2010s, and 2020s using a consistent methodology. This comparative approach reveals significant shifts in the use of mangrove goods and services in Gazi Bay, pointing to a concerning erosion of TEK and transmission to future generations. While some knowledge may have been passed on to individuals who later emigrated, the lack of clear evidence of such transmission raises concern about the continuity of TEK and the preservation of valuable insights into endangered mangrove forest ecosystems.

### "So what" as a response

Another way to approach the "what if" title question is by asking "so what?", challenging ourselves to consider whether the erosion of mangrove TEK over decadal time scales is truly problematic. Gazi Village has a decades-long history of mangrove awareness, conservation, and restoration (Kairo et al. 2001), and is home to Mikoko Pamoja, the world's first certified mangrove carbon credit project, launched in 2012 (Chisika and Yeom 2023; Huff and Tonui 2017), built on over two decades of restoration ecology research (Bosire et al. 2008). The Kenya Marine and Fisheries Research Institute (KMFRI) and Kenya Wildlife Service (KWS), along with the international research community, contributed much to awareness raising through the long-standing presence in Gazi of a research field station and forest management. Long-term curiosity-, need- and demand-driven scientific research has made Gazi Bay one of the world's most intensively studied mangrove sites. All these initiatives, with their benefits and challenges, may have helped shape mangrove forest policy and laws that restricted and controlled harvesting of mangrove forest resources (cf. Huxham et al. 2023). Sounding the alarm on eroding TEK may seem ironic in Gazi's context, where conservation efforts are strong. Yet, there may be a trade-off: safeguarding mangroves to ensure continued ecosystem services for local livelihoods could inadvertently contribute to TEK erosion, potentially weakening the social-ecological resilience in an era of change and uncertainty.

Our authorship consortium is divided on what trade-offs regarding mangrove TEK are acceptable. We do not take a definitive stance, but we aim to open the debate. Research has long shown that TEK cannot be sustained in its current form due to globalization, industrialization, and lifestyle changes. Instead, it must be integrated with legal and regulatory frameworks for sustainable natural resource management (Abdullah & Khan 2023). Studies from Africa and Asia demonstrate that sustainable forest use is unfeasible under rapid population growth without major policy interventions (Alam et al. 2024; Maja & Ayano 2021). Gazi Village, where the population increased by 75% between 2003 and 2021, may reflect similar dynamics (ESM 7). This suggests a need to enforce fisheries regulations to ensure fisheries viability and promote alternative livelihoods to reduce fishing pressure.

More research on the local use of mangroves should continue to feed into policies for sustainable mangrove management. We acknowledge that advancement for the ecological transition and a more inclusive and just world must be an objective of all ethnobiological research (Albuquerque et al. 2024). While promoting science-based conservation, it can be important to integrate elements of TEK and practices of the local communities into conservation (cf. Dahdouh-Guebas et al. 2006; Palmer and Finlay 2016).

## Conclusion

This study demonstrates that mangrove forests have consistently supported the Gazi Village community, with over 50% of respondents in 2003, 2014, and 2021 recognizing their livelihood value. Mangrove products such as fuelwood, construction materials, and fisheries resources were regularly used. However, overall usage declined in 2014 and 2021 compared to 2003. TEK related to house construction and firewood use appears to be eroding, marked by fewer users and shifting gender roles, particularly in firewood collection. The use of mangroves for (ethno)medicinal purposes and livestock fodder has also declined.

Fisheries supported by the mangroves continue to be exploited using various methods, but declining catches, linked to destructive practices and ecosystem degradation, raise concerns. As with firewood, the erosion of TEK, especially gender-specific knowledge, underscores the need for gender-inclusive resource management (cf. Keleman et al. 2024).

Despite a reported increase in mangrove area due to natural regeneration, planting, a legal ban on cutting and conservation awareness, illegal harvesting persists, driven by weak law enforcement.

The present study documents changes in ethnobiological traditions, fisheries practices, and local perceptions within three decades (2000s, 2010s, and 2020s). TEK is at risk of being lost to modernization, migration, and conservation policies that, while biologically necessary, reduce opportunities for knowledge transmission. Long-term, longitudinal studies are essential to track TEK and promote the integration of bio-cultural and gendered values into conservation and policy. The ethical debate around trade-offs, such as species conservation versus TEK preservation, must be addressed, alongside mitigation strategies like education.

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## Author Contribution

Farid Dahdouh-Guebas: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization, Supervision, Project administration, Funding acquisition. Saumu Rumba: Validation, Formal analysis, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization. Anneleen Van Tendeloo: Validation, Formal analysis, Investigation, Data Curation, Writing—Review & Editing, Visualization. Cosmas N. Munga: Validation, Resources, Writing—Review & Editing, Supervision. Nico Koedam: Conceptualization, Methodology, Validation, Writing—Review & Editing, Supervision, Project administration, Funding acquisition. Jean Hugé: Methodology, Validation, Writing—Review & Editing, Supervision, Funding acquisition.

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## Data Availability

Data (except personal data) are available on request from the corresponding author at Université libre de Bruxelles (ULB).

## Declarations

**Ethics Approval** All interviews were conducted with the permission of local authorities under the National Commission for Science, Technology & Innovation's research licenses MOEST 13/001/33C 123/2 and NACOSTI/P/21/9898, and with prior oral informed consent. The latter explained to all respondents the purpose of the research and the voluntary participation in this study, as well as the confidentiality of their responses to be used anonymously for research. Once written by the authors, the text of the paper was corrected and shortened using suggestions from the editorial office in combination with the language editor in M365 Word and Copilot. After publication, the results of the study will be presented to the local community in Gazi to wrap up the project cycle.

**Competing interests** The authors declare no competing interests.

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