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EDITED BY
Michael J. Jowers,
University of Granada, Spain

REVIEWED BY
Jeanne A. Mortimer,
Independent Researcher, Mahé, Seychelles
Jesse Erens,
University of Trier, Germany

*CORRESPONDENCE
Lyndsey K. Tanabe
Lyndsey.tanabe@ntu.edu.sg

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Identifying a high-use hawksbill turtle habitat in the central Saudi Arabian Red Sea using photo-ID

Lyndsey K. Tanabe[1,2]*, Jesse E. M. Cochran[1], Royale S. Hardenstine[1], Kirsty Scott[1] and Michael L. Berumen[1]

[1]King Abdullah University of Science and Technology, Division of Biological and Environmental Science and Engineering, Thuwal, Saudi Arabia, [2]Asian School of the Environment, Nanyang Technological University, Singapore, Singapore

Hawksbill turtles (*Eretmochelys imbricata*) face significant threats globally, exacerbated by historical exploitation for their ornate carapace. In the Red Sea, data are lacking on many aspects of hawksbill turtle ecology. The in-water distribution of the species throughout the basin is relatively unknown, and essential habitats, such as foraging areas, are not well described. Here, we addressed this gap through photo-identification surveys conducted from July 2019 to December 2021 at Rabigh, located on the central Saudi Arabian coast of the Red Sea. Turtles were identified based on their unique facial scute patterns and subsequent re-sightings were used to describe their individual behavior and residency patterns. We analyzed photos from 104 sightings and identified 46 individuals. The majority of identified individuals were hawksbill turtles (n = 36), while green turtles were only occasionally reported (n = 10). Individuals exhibited diverse behaviors, including foraging (19%), resting (18%), and swimming (60%). Despite the small survey area, 42% of all turtles were re-sighted, suggesting that this site could serve as an important foraging habitat for this species. Notably, even on the last sampling day, we identified four new turtles, suggesting that with increased sampling effort, more individuals would likely be observed. These results highlight the importance of this location for critically endangered hawksbill turtles in the Red Sea, providing support for its designation as a protected area. This study also emphasizes the applicability of photo-ID monitoring to inform conservation strategies amid expanding coastal developments and increasing tourism in Saudi Arabia.

KEYWORDS

conservation biology, endangered species, marine ecology, wildlife monitoring, residency patterns

Introduction

Hawksbill turtles (*Eretmochelys imbricata*) are among the most threatened sea turtle species, listed as Critically Endangered globally by the International Union of Conservation of Nature (IUCN, 2024). Historically, intense exploitation for their carapace (Mortimer and Donnelly, 2008), and more contemporary anthropogenic threats such as climate change,

coastal development, fisheries, and pollution (Wallace et al., 2011) have led to this conservation status. Effective conservation strategies depend on a comprehensive understanding of their ecology and movement patterns to identify key habitats, which include foraging and nesting sites.

Hawksbill and green turtles (*Chelonia mydas*) are known to nest along the Red Sea coastline (Mancini et al., 2015). Although nesting sites have been identified and limited monitoring of sea turtles has been conducted in Saudi Arabia (Shimada et al., 2021b), in-water research is still in its infancy (Al Ameri et al., 2022). For green turtles, there have been substantial tagging efforts to determine their inter-nesting (Shimada et al., 2021a; Tanabe et al., 2023a) and post-nesting movements (Al-Mansi et al., 2021; Tanabe et al., 2023a). However, for hawksbill turtles, knowledge of their foraging ecology is limited in the region, with insights provided by one satellite telemetry study (Tanabe et al., 2023c) and their species distribution recorded from opportunistic surveys (Garzon et al., 2022). The significant gap in research on hawksbill turtles in the Red Sea underscores the need for more focused studies on the species.

With increasing coastal development in Saudi Arabia, including large-scale tourism projects (PIF, 2017), the need to protect marine habitats has never been more urgent. In recent years, efforts to protect marine megafauna in the Saudi Arabian Red Sea have increased, including the establishment of a government agency dedicated to the conservation of sea turtles (SHAMS, 2024). Because of the conservation status of hawksbill turtles and the rapid rate of development in Saudi Arabia, it is important to identify key foraging areas for developing targeted conservation strategies.

Understanding population demographics, life history, movement patterns, and connectivity (Marshall and Pierce, 2012) is crucial for assessing population health and informing conservation management. While flipper tags have been conventionally used to identify individual sea turtles (e.g., Moncada et al., 2010), particularly for long-term monitoring on nesting beaches (e.g., Chan, 2010; Derville et al., 2015), the tagging process requires direct handling and tags can be lost over time (Reisser et al., 2008). Another technique, photographic identification (photo-ID), is often used for in-water studies (Jean et al., 2010; Chassagneux et al., 2013; Neves-Ferreira et al., 2023), as it offers a minimally-invasive approach by using natural permanent patterns and markings on animals to identify individuals. This technique has been successfully applied to a variety of marine taxa, including sharks (Cochran et al., 2016), rays (McIvor et al., 2024), fish (Speed et al., 2007), whales (Alessi et al., 2014), and sea turtles (Reisser et al., 2008).

Sea turtle photo-ID relies on clear images of the facial scute profile (Reisser et al., 2008) or flipper scutes (Gatto et al., 2018), ideally taken at a perpendicular angle. These images can then be analyzed manually or using automated software systems, including the "Pattern" package on the Interactive Individual Identification System (I^3S) (Van Tienhoven et al., 2007) and HotSpotter (Dunbar et al., 2021). These systems reduce analysis time compared to manual methods (Calmanovici et al., 2018) however, automated systems may miss matches, especially in low-quality photos, with one study finding up to 33% of matches were missed (Kelly, 2001).

Despite this, photo-ID remains a powerful tool for sea turtle monitoring, particularly for in-water assessments at specific locations over extended periods (Neves-Ferreira et al., 2023). It is valuable for data collection in regions with logistical challenges and limited resources, while also fostering public involvement and environmental awareness (Dickinson et al., 2010).

As Saudi Arabia undergoes rapid coastal development to increase tourism and diversify its economy (PIF, 2017), understanding and protecting important marine habitats has become increasingly urgent. Given the critical conservation status of hawksbill turtles, this study aims to provide essential data on their distribution and behavior in a previously understudied region of the Red Sea. The use of photo-ID allows us to track individual turtles, but more importantly, it offers critical insights into the ecological importance of the site as a potential key habitat for the species. In the future, incorporating citizen science photo-ID methods could further enhance data collection, helping to identify high-use habitats and guide conservation efforts to protect these vital ecosystems from the impacts of coastal development and tourism.

Materials and methods

Study site

The study took place on the northern tip of the Rabigh peninsula, located approximately 12 km north of the city of Rabigh (Figure 1). This site was chosen for its easy access to the reef, and local reports of frequent turtle sightings. Thirty kilometers south of the site is a petrochemical industrial plant and a deep-water port that exports petroleum products. The study site is characterized by a fringing reef with a steep reef wall, supporting a mix of both soft and hard corals, interspersed with sandy patches at a depth of around 10 meters. In the inner part of the peninsula, the Rabigh Lagoon hosts seagrass and mangrove communities (Touliabah and Elbassat, 2017).

Green turtles have been recorded to nest at sandy beaches near this site, whereas no hawksbill turtle nesting has been reported here. Hawksbill turtles have been recorded to nest in low densities at suitable nesting beaches along the Saudi Arabian Red Sea coast (Shimada et al., 2021b; Scott et al., 2022) (Figure 1). The largest known rookery in the Red Sea is in Sudan, approximately 500 km southwest of Rabigh, with 330 hawksbill turtles recorded nesting in 1976 (Groombridge and Luxmore, 1989). At present, there is no published literature on hawksbill turtle foraging habitats in the region.

Snorkel surveys

Photo-ID snorkeling surveys were conducted monthly from July 2019 to December 2021 at Rabigh, in the central Saudi Arabian Red Sea (22.9267°, 38.8566°). Surveys could not be completed every month from March 2020 through March 2021, due to restrictions

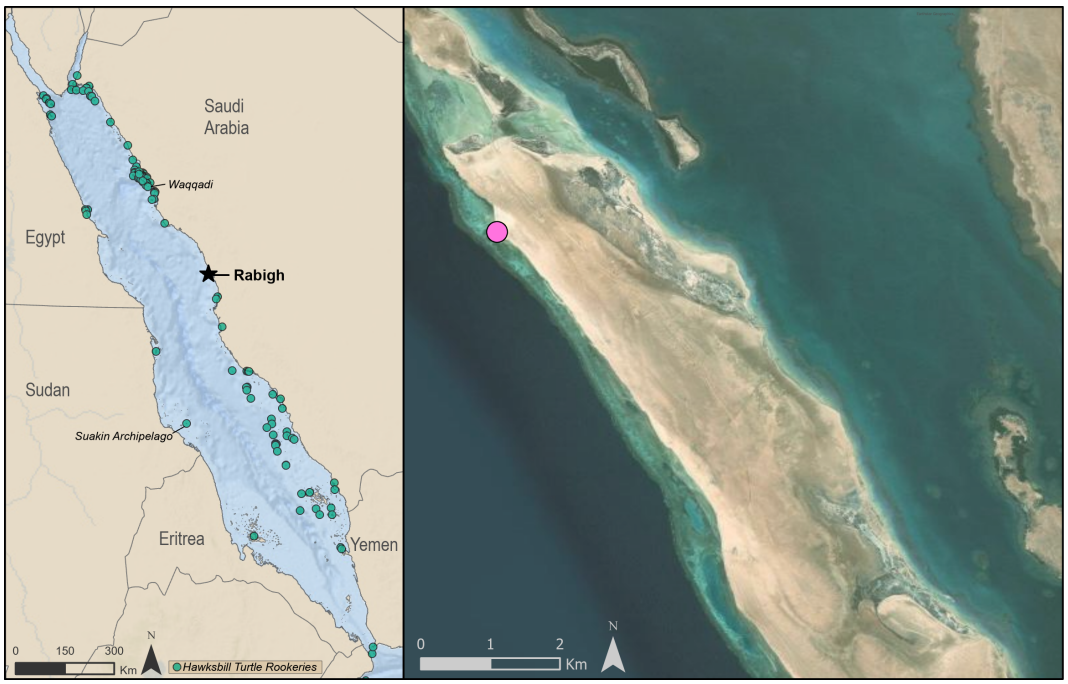

FIGURE 1
Left: Distribution of hawksbill turtle (*Eretmochelys imbricata*) rookeries (green points) throughout the Red Sea (Shimada et al., 2021b; Scott et al., 2022) and the location of the surveys undertaken in this study (star). Right: An aerial overview of the site, which was a coral reef adjacent to the sandy peninsula. Photo-identification surveys were conducted on the Rabigh peninsula (pink point: 22.9267° 38.8566°) in the central Saudi Arabian Red Sea, ~12 km north of the city of Rabigh.

and logistical challenges resulting from the Covid-19 pandemic. Two groups of 2-4 individuals snorkeled in opposite directions along the reef wall for 45 minutes (each group covering roughly 1-1.5 km, dependent on current conditions) before turning around and swimming back to the point of entry, for a total survey duration of 1.5 hours. Photographs of facial scutes were taken perpendicularly to the side of the face. The aim was to capture images of both the left and right sides of the face, as well as the carapace from above. During each turtle encounter, the time, depth, sex, species, behavior, and distinguishing characteristics were recorded. Photos were used to validate *in-situ* species identification using the number of prefrontal scale pairs on the head (greens have one pair and hawksbills have two pairs). The sex of adult individuals was determined by tail length (with adult males having longer tails extending well beyond their carapace). For subadults, sex was not determined. We classified subadult green turtles as approximately <90 cm straight carapace size (SCL) (following Bresette et al., 2009) and hawksbill turtles approximately <70 cm SCL (Witzell, 1983). This study received ethics approval from KAUST Institutional Animal Care and Use Committee under protocol 19IACUC07.

Image analysis

First, all images were sorted by date into individual folders for each turtle photographed. Each individual was manually identified using facial scute patterns and unique markings (scars, barnacles, etc.). For high quality photographs, these were verified using I^3S Pattern (Van Tienhoven et al., 2007). Poor quality photographs (e.g., blurry, out of focus, or lacking detail) and all photos taken from more than a 20° angle from the side of the turtle's head were omitted. Descriptive statistics were used to describe the species composition of the sightings over the study period, characterize behaviors, and quantify the percentage of individuals that were re-sighted. A discovery curve was constructed by comparing the cumulative number of unique individuals with the total number of sightings, allowing us to assess the rate at which new individuals were encountered over the course of the study.

Results

Between 2019 and 2021, a total of 149 sightings were recorded. After filtering and omitting low-quality photographs, 104 sightings remained for analysis. We found that I^3S, the computer-aided identification software, was less reliable compared to manual identification, primarily due to the limitations in image quality. To ensure that we included as many sightings as possible in the analysis, we opted to use manual identification, which allowed us to maximize the dataset. Out of 104 observations, 47 unique individuals were recorded between February 2019 and February 2020. However, due to Covid-19 restrictions, survey efforts were reduced from March 2020 to February 2021, resulting in only 9 sightings during that period. Surveys resumed in February 2021 and continued until November 2021, during which 48 additional

sightings were recorded. In total, 46 unique turtles were identified, comprising 10 green turtles and 36 hawksbill turtles (Figure 2A).

Among the 46 identified turtles, 27 were only encountered once (Supplementary Tables S1, S2), while others were observed on up to five different survey days, with the longest interval between sightings being 724 days (Table 1). Notably, hawksbill turtles were more likely to be re-sighted, accounting for 17 of the 19 re-sighted individuals (Table 1). When comparing residency patterns between the two species, 80% of green turtles were only photographed on a single survey day, compared to 53% of hawksbill turtles (Supplementary Tables S1, S2). Of the adult sea turtles from both species, the majority were females (n = 21), with only five mature males recorded (Supplementary Tables S1, S2).

The two species of sea turtles displayed distinct behavioral patterns. Hawksbill turtles exhibited a range of behaviors, including breathing (3%), resting (18%), foraging (19%), and swimming (60%) (Figure 2B). In contrast, green turtles were predominantly observed resting (60%) and swimming (40%) (Figure 2C). The average depth of sightings was 6.7 meters (SD = 3.6).

To assess the completeness of our dataset, we compared the number of unique turtles identified to the total number of sightings, generating a discovery curve (Figure 3). The curve did not reach an asymptote, suggesting that new individuals would continue to be identified with further survey effort. On the final survey day, four new individuals were recorded, highlighting that additional sampling could yield new encounters.

In addition to identifying individual turtles, photo-ID provides valuable insights into the health and threats facing the population. No instances of fibropapilloma tumors were observed in the turtles photographed for this study. However, we did document two concerning incidents: one hawksbill turtle was entangled in fishing line, and another hawksbill was observed ingesting a plastic bag (Supplementary Figure S1). Use of photo-ID in this way is multi-faceted, enabling individual recognition while providing valuable data to monitor health risks and environmental threats, supporting broader conservation efforts aimed at protecting sea turtles.

Discussion

Although hawksbill turtles have been widely studied in other regions, there is a significant lack of published research on their populations in the Red Sea. This knowledge gap makes our study an important contribution to understanding the status of this Critically Endangered species in this under-studied region. The high number of hawksbill turtle sightings and unique individuals recorded in our study suggest that Rabigh, Saudi Arabia, is an important site for this

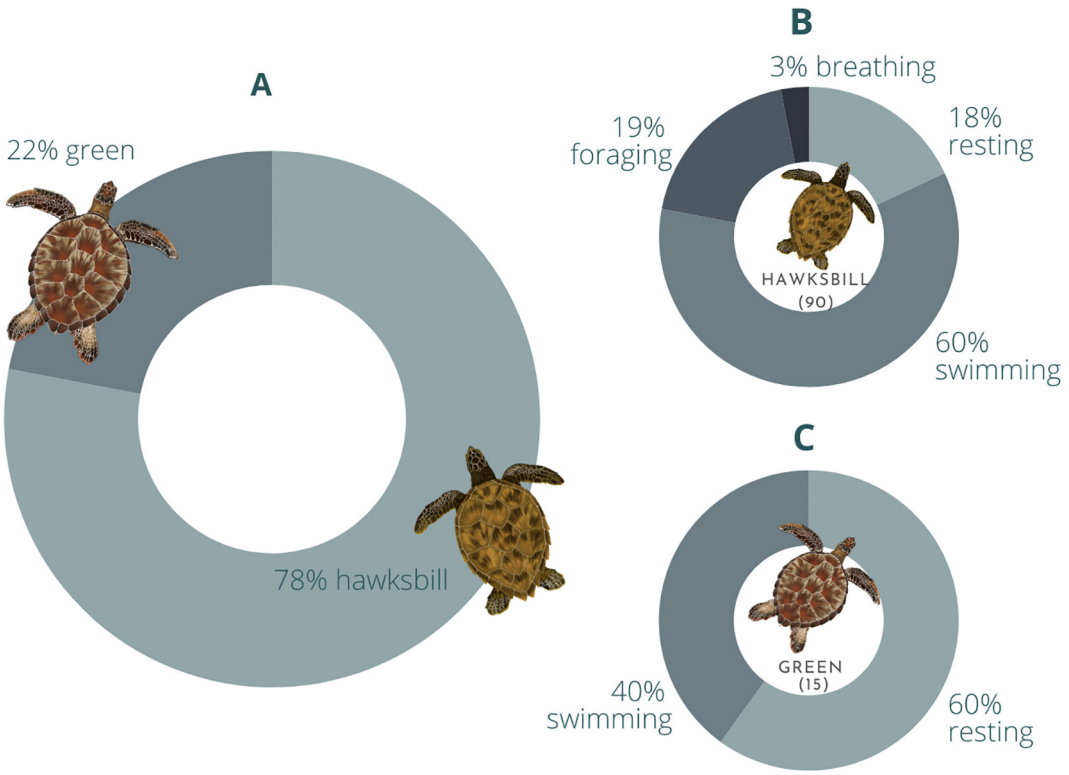

FIGURE 2
Over the 20 snorkeling surveys at Rabigh between July 2019 and December 2021, 46 turtles were uniquely identified, 22% (n=10) of which were green turtles (*Chelonia mydas*), and 78% (n=36) were hawksbill turtles (*Eretmochelys imbricata*) **(A)**. Out of 104 usable sightings, most of the behaviors recorded were swimming, when this was split by species, hawksbill turtles had more behaviors including breathing (3%), foraging (19%), resting (18%), and swimming (60%) **(B)**. Green turtles were only found resting (60%) and swimming (40%) **(C)**.

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TABLE 1 Metadata from hawksbill (*Eretmochelys imbricata*) and green turtles (*Chelonia mydas*) re-sighted at Rabigh.

ID	Species	Sex	# of Days Sighted	Date of First Sighting	Date of Last Sighting	Days Between First and Last Sighting
R003H	hawksbill	female	5	02/07/2019	18/03/2021	625
R001H	hawksbill	female	4	02/07/2019	16/04/2021	654
R005H	hawksbill	male	4	02/07/2019	25/06/2021	724
R009H	hawksbill	female	4	08/07/2019	28/02/2021	601
R011H	hawksbill	male	3	05/08/2019	20/02/2020	199
R016H	hawksbill	subadult	3	16/11/2019	25/07/2020	252
R021H	hawksbill	male	3	18/07/2020	25/06/2021	342
R022H	hawksbill	female	3	18/03/2021	27/11/2021	254
R017H	hawksbill	subadult	3	16/11/2019	20/02/2020	96
R026H	hawksbill	female	3	20/02/2020	25/06/2021	491
R007H	hawksbill	male	2	08/07/2019	16/04/2021	648
R012H	hawksbill	female	2	05/08/2019	24/01/2020	172
R020H	hawksbill	female	2	06/10/2019	20/02/2020	137
R024H	hawksbill	female	2	16/04/2021	27/05/2021	102
R029H	hawksbill	female	2	06/10/2019	21/07/2021	654
R032H	hawksbill	female	2	24/01/2020	18/03/2021	419
R015H	hawksbill	female	2	24/01/2020	20/02/2020	27
R023G	green	female	3	20/02/2020	16/04/2021	421
R002G	green	juvenile	2	18/03/2021	16/04/2021	29

Sex was determined based on tail length in adult turtles, with males identified by having tails that extend well beyond the edge of the carapace. Turtles were classified as adults if they had an estimated straight carapace length (SCL) exceeding 90 cm for green turtles and 70 cm for hawksbill turtles.

species. Given the increasing anthropogenic threats in the region—such as coastal development, pollution, and climate change—identifying and protecting such habitats is essential for informing effective conservation strategies. While photo-ID is a well-established tool in sea turtle research, its application here offers new insights into hawksbill turtles in the Red Sea, helping to fill an important gap in knowledge.

Sea turtle photo-ID studies have been used worldwide, with many focusing on green sea turtles (e.g., Philippines (Araujo et al., 2019), Malaysia (Chew et al., 2015), Japan (Tabuki et al., 2021), Reunion Island (Carpentier et al., 2016), and Kenya (Hancock et al., 2023)). A systematic review of population monitoring of sea turtles found both taxonomic and geographic biases, with most studies conducted on green turtles (40.2%), followed by loggerhead turtles (32.3%) and hawksbill turtles (21.4%) (Hendrix and Pérez-Espona, 2024). The majority of population monitoring studies have been conducted in the Caribbean Sea/Gulf of Mexico, followed by the Mediterranean Sea, and the Pacific Ocean (Hendrix and Pérez-Espona, 2024), highlighting a research gap in the North West Indian Ocean.

The observed differences in species abundances throughout our study are likely driven by species-specific foraging preferences. In the Red Sea, where sea surface temperatures exceed 25°C for ≥ 6 months annually, herbivory is dominant for green sea turtles (Esteban et al., 2020), which may explain their lower abundance at our coral reef study site. This was further supported by the absence of foraging behavior observed in green turtles during our surveys. In contrast, hawksbill turtles exhibit a more diverse diet, feeding on sponges, soft corals, algae, hard corals, and invertebrates (León and Bjorndal, 2002; Obura et al., 2010; Von Brandis et al., 2014). At Rabigh, they were observed eating sponges and soft corals (e.g., from the family Xeniidae), but current information on the diet of hawksbill turtles in the Red Sea is limited.

Our findings align with a photo-ID study conducted in the Perhentian Islands, Malaysia, where green turtles were observed more frequently on seagrass beds, while hawksbill turtles were predominantly recorded on coral reefs (Long and Azmi, 2017). While there are no published reports on hawksbill turtle migrations in the Red Sea, satellite telemetry research on green turtles indicates that they use the shallow coastal waters as a migratory corridor between nesting and foraging habitats (Attum et al., 2014; Al-Mansi et al., 2021; Tanabe et al., 2023a). It is likely that hawksbill turtles are also migrating along the coast, as demonstrated in telemetry studies in other regions (e.g., Fossette et al., 2021). The reef wall may be used as a migratory corridor, which could help explain the large number of turtles observed at this site but does not justify their high

residency on the reef. Furthermore, while there is evidence of sporadic green turtle nesting along Rabigh beach (Scott et al., 2022), no mating behavior was observed during our surveys or reported by citizen scientists.

Hawksbill turtles exhibited higher residency than green turtles, with 47% of individuals being re-sighted on multiple survey days, compared to just 20% of the green turtles. These findings are based on 104 sightings recorded over 20 survey days spanning two years. Although there is no published literature on hawksbill turtle sightings in other parts of the Red Sea, studies from other regions provide useful comparisons. For example, research from Malaysia, which gathered 1,826 sightings over 6 years from conservation projects and the public showed eight of 23 individual hawksbill turtles (35%) were re-sighted (Long and Azmi, 2017), while a study in Brazil which collected 576 sightings from social media over 15 years reported that seven of 32 individuals (22%) were re-sighted. Therefore, hawksbill turtles at our site showed a higher re-sighting proportion compared to similar studies from other regions.

The fringing reef at Rabigh stretches over 25 kilometers, offering a variety of reef structures that support high biodiversity and foraging resources for hawkbill turtles, which may be why hawksbill turtles had higher residency compared to green turtles. However, it is important to note that the surveyed area likely did not cover the entire home range of either species. A study from the northern Saudi Arabian Red Sea using high-accuracy Fast-Loc GPS technology, estimated that the foraging home ranges of two hawksbill turtles to be 14 and 0.8 km^2 (Tanabe et al., 2023c). This may mean that there are a greater number of turtles occupying the Rabigh foraging area than captured in these surveys.

The high re-detection rates indicate the site's importance for hawksbill turtles, but additional surveys are needed to generate robust population estimates and density metrics. Our discovery curve never reached an asymptote, indicating that additional survey efforts would likely continue to identify new turtles. Satellite tracking of these turtles could determine more fine-scale movements and define home ranges, while continued photo-ID surveys are warranted to better understand residency patterns.

During our surveys, we observed several threats to turtles, including ghost nets, discarded fishing line, and plastic pollution (Supplementary Figure S1). Notably, one hawksbill turtle was observed attempting to consume a plastic bag (Supplementary Figure S1), a threat previously documented in the region (Tanabe et al., 2023b). Another hawksbill turtle was temporarily stuck in fishing line (Supplementary Figure S1), and a separate report documented a hawksbill turtle temporarily trapped in a gillnet at this site (El-Khaled et al., 2023). A study on pollution in coastal environments found that litter along the Rabigh coast was common, presenting health hazards for humans and wildlife (Alharbi and Rangel-Buitrago, 2022). Common anthropogenic pollution included food packaging, bottles, and fishing nets (Alharbi and Rangel-Buitrago, 2022). These findings underscore the urgent need for targeted monitoring and mitigation strategies to address the impacts of marine debris and fisheries on sea turtles, particularly given the increasing development pressures in the region.

While no studies have quantified the impact of by-catch on turtles in the Red Sea, research from the Arabian Gulf estimated that over 4,700 turtles were accidentally caught per year (Abdulqader et al., 2017), further emphasizing the need for urgent intervention. Additionally, our surveys found no instances of fibropapilloma tumors in either species of turtle, a condition that has been observed in other regions using photo-ID (Hancock et al., 2023). To date, there have been no confirmed cases of fibropapilloma in Red Sea turtle populations, but ongoing monitoring is crucial to assess any emerging health threats.

Beyond anthropogenic pollution, another significant threat to the turtles in Rabigh is coral reef bleaching. Since the completion of this photo-ID study, the central Saudi Arabian Red Sea experienced large-scale bleaching events in 2023 and 2024, leading to

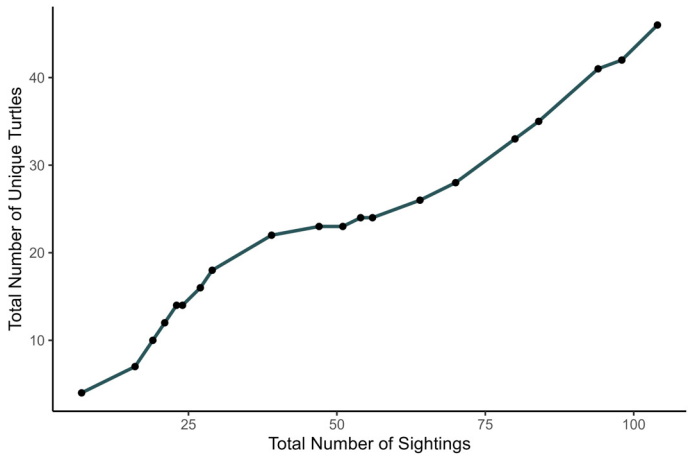

FIGURE 3
The discovery curve showing the cumulative number of uniquely identified individuals over the course of the study. New individuals continued to be identified even on the last survey day, indicating that the population was not fully sampled, and continued survey effort would likely result in the identification of new individuals.

FIGURE 4
Comparison of coral health at Rabigh, Saudi Arabia. The first image, taken in July 2021, shows a vibrant and healthy reef, rich in color and life. The second image, taken in September 2023, depicts the same reef site that was impacted by coral bleaching, with noticeable loss of color.

widespread coral mortality in shallow waters (Figure 4). These events present an additional challenge to hawksbill turtles, which rely on healthy coral reefs for food sources such as sponges and soft corals. The loss of these critical resources may affect the turtle population's foraging distribution and overall health. The bleaching event in Rabigh further highlights the vulnerability of marine ecosystems in the Red Sea, especially in light of ongoing coastal development and tourism expansion. As these pressures intensify, it becomes increasingly important to prioritize the protection and restoration of coral reef habitats, which play a vital role in supporting biodiversity and the health of species like the hawksbill turtle.

These findings add urgency to the need for targeted conservation strategies that address both climate-induced impacts, such as coral bleaching, and direct anthropogenic threats like pollution and overfishing. Long-term monitoring efforts are essential to assess how turtle presence, behavior, and residency may change in response to coral bleaching. By comparing data before and after the bleaching event, we can gain valuable insights into the resilience of both the turtle population and the coral reef ecosystem, informing future conservation actions aimed at mitigating the impacts of such events.

In the Red Sea, there is enormous potential to leverage citizen science in efforts to monitor endangered species and ecosystems due to the presence of ecotourism and daily diving activity (Montagna et al., 2018). A long-term sea turtle photo-ID project in Egypt (https://turtlewatchegypt.net) has identified more than 700 individual hawksbill and green turtles to date. Though data on hawksbill turtles is not yet published so we were unable to compare our findings. Nonetheless, data from the Egyptian photo-ID project were used to establish a connection between green turtle feeding grounds along the Egyptian Red Sea coast and the Saudi Arabian nesting area at Ras Baridi, as one of the photographed turtles was identified with a flipper tag indicating it had been tagged while nesting in Saudi Arabia (Montagna et al., 2023).

Collaborative efforts for photo-ID are needed among the countries surrounding the Red Sea to better understand movement patterns of these highly migratory species.

Platforms like Internet of Turtles (https://iot.wildbook.org/) provide a framework for unifying regional efforts by allowing researchers to share and analyze photo-ID data in a centralized database. We plan to contribute to these efforts by uploading our sightings to the Internet of Turtles, which will enhance data integration across the region and foster more comprehensive conservation strategies. Additionally, for large datasets, this method may be a more efficient than manual identification, which requires considerable time and effort.

Our photo-ID study highlights Rabigh as a potentially important foraging area for Critically Endangered hawksbill turtles in the Red Sea. Given its importance, we recommend prioritizing this area for protection to preserve reef health and support the regional turtle population. To draw more robust conclusions about the seasonality and temporal trends of turtle presence at this site, photo-ID efforts should be extended over a longer period. Future studies could also be expanded to include seagrass areas within the Rabigh lagoon, focusing on identifying food sources as well as their density and distribution for both hawksbill and green turtles. Furthermore, long-term monitoring of turtle populations through photo-ID surveys will be crucial to understand seasonal changes in abundance and residency. Additionally, continued photo-ID monitoring at Rabigh would help to understand the long-term effects of coral bleaching on hawksbill turtle residency at the site.

Beyond scientific value, photo-ID serves as an effective tool for raising awareness and promoting behavioral changes among tourists and local communities. Building on this initial database, a citizen scientist initiative (Red Sea Photo ID: https://redseaturtle.wixsite.com/home) has been established to encourage local and tourist participation in submitting photos of sea turtles, manta rays, and whale sharks from the Saudi Arabian Red Sea. This project aims to increase public awareness of the threats facing marine megafauna in the region and contribute valuable data to inform the development of regionally tailored conservation management plans. Continued and collaborative photo-ID efforts will be vital in addressing key knowledge gaps surrounding sea turtle distribution, foraging habitats, and movement patterns in the Red Sea.

Data availability statement

The raw data supporting the conclusions of this article will be made available upon reasonable request. Interested parties can contact the corresponding author via email to request access to the data.

Ethics statement

The animal study was approved by KAUST Institutional Animal Care and Use Committee (IACUC), permit no. 19IACUC07. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

LT: Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. JC: Conceptualization, Formal Analysis, Investigation, Methodology, Supervision, Writing – review & editing. RH: Conceptualization, Formal Analysis, Investigation, Methodology, Supervision, Writing – review & editing. KS: Data curation, Investigation, Methodology, Writing – review & editing. MB: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing.

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/famrs.2025.1540089/full#supplementary-material

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