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Original Research Paper

Nesting Site Selection Fidelity and Hatchling Success of Sea Turtles in Polluted and Disturbed Coastal Zones

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Key Words

Sea turtle, Nesting, Hatchling success, Coastal pollution, Anthropogenic disturbance, Caretta, Chelonia mydas

Abstract

Pollution of the coast and anthropogenic disturbance pose growing challenges for the reproductive ecology of sea turtles; however, impacts on nest fidelity and success of hatchling emergence have not been quantified along gradients of pollution and anthropogenic disturbance intensities. The current study evaluated the influence of pollution on nest fidelity, nesting frequencies, and hatchling emergence success of the loggerhead (Caretta caretta) and green (Chelonia mydas) sea turtles across five different coast zones that ranged in gradient from reference, least polluted beach to highly polluted industrial zones. The data were collected during four breeding seasons (2020-2023) in a total of 560 nest attempts and 2,847 nest observations. A significant decrease in fidelity was observed from 82.6 ± 4.2% in reference sites to 29.7 ± 9.1% in highly polluted sites ($p < 0.001$). Similarly, hatchling success also showed a decline from 71.3 ± 5.8% in reference zones to 19.2 ± 9.7% in highly polluted zones. Mechanistic influences included sand temperature, microplastics, nighttime light pollution, and human interference ($R^2 = 0.81$). Pollution-induced warming of the sand negatively affected the incubation success of the nests, while nighttime lighting interfered with nest orientation and hatching emergence.

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Introduction

Indeed, sea turtles represent one of the oldest and most ecologically important lineages of reptiles on earth. Nonetheless, all seven existing sea turtles have been classified as Vulnerable, Endangered, and Critically Endangered on the IUCN Red List of Threatened Species (Casale & Tucker, 2017). Sea turtles' reproductive ecology is intrinsically linked to coastal beach habitats, where adult females exhibit highly specific and adaptive tendencies to return to their native beaches to lay eggs throughout multiple breeding events (Fuentes et al., 2023). The phenomenon is evolutionary advantageous; however, it makes sea turtle populations particularly susceptible to environmental degradation associated with nesting beach areas caused by increased urbanization, industrial pollution, and recreational pressures (Dimitriadis et al., 2026).

Various forms of pollution affect nesting beaches through many mechanisms. Microplastics accumulated in sand reduce thermal and moisture conductivity during egg incubation (Prastiya et al., 2026). Petroleum hydrocarbons and heavy metals in the sediments decrease embryonic growth rates and impair hatching locomotion (Ismail & Ahmad, 2025). Agricultural and wastewater effluents transported via beach runoff deteriorate sediment characteristics and lower gas exchange rates within nests (Serafini et al., 2009). In combination, chemical pollutants produce a detrimental microenvironment that increasingly separates anthropogenic nesting beach areas from the environment that sea turtle species originally evolved in (Price et al., 2018).

Physical disruption caused by coastal development exacerbates the impacts of pollution. Construction of beaches compacts nesting substrate, thereby raising the torque necessary for the newly hatched turtles to emerge from nests (Dineshkumar, 2025). Erosion of beaches resulting from construction of sea walls and sand mining lowers the availability of suitable substrate beyond the high-tide mark, forcing nesting to occur on less-than-ideal sites that experience a higher level of inundation (Fuentes et al., 2024). Artificial light at night (ALAN) from seafront construction activities interferes with female emergence during nesting, nest initiation, and importantly, hatchling orientation upon emerging to enter water (Price et al., 2018; Fisher, 2021).

The concept of site fidelity, i.e., the tendency of nesting females to use the same or nearby nesting sites annually, is critical in sea turtle biology and survival (Fuentes et al., 2023). Site fidelity disruptions due to habitat destruction on the natal beach or sensory disruption leading to disorientation from geomagnetic and olfactory cues can force females to abandon ideal sites, reducing reproductive outputs and hindering the recovery of monitored populations (Ferreira et al., 2021). While site fidelity is known to play an important role in the reproduction and survival of nesting females, few quantitative studies have addressed the impacts of pollution gradients on return rates over multiple breeding seasons (Dineshkumar, 2025).

Climate change adds another level of complication. The increase in temperatures of the air and sand affects directly the sex ratio of the hatchlings as high temperatures cause female turtles, and urbanized beaches with dark and hot sands further enhance this effect (Fuentes et al., 2010; Laloë et al., 2016). Estimates show that some heavily affected nesting sites could reach critical lethal incubation temperatures within a few decades if the albedo and thermic properties of the beaches are not manipulated (Fuentes et al., 2024).

The current research project aims to bridge these research gaps by evaluating simultaneously the nesting site fidelity, success rate of nests, and hatching rate of the hatchlings along a gradient of varying pollution levels and disturbances in four consecutive breeding seasons. The objectives were to:

1. To estimate the frequency of nesting attempts and fidelity to sites over different seasons for five different types of coastal zones.
2. To determine the rate of hatchling emergence in relation to disturbance and contamination levels.
3. To discover the important determinants of failure of the hatchlings' emergence.
4. To assess the significance of the results for the effective management of sea turtle nests.

The structure of the rest of this paper is outlined below. In Section 2, we review the literature on sea turtle nesting behavior, nest-site fidelity, success rates of hatching, and effects of coastal pollution and anthropogenic interference on sea turtles' nesting behaviors. Section 3 describes the methods and materials employed for this investigation, namely study site classification, nesting behavior assessment, tagging procedures, nest surveillance, and environmental analysis. Section 4 summarizes the results, highlighting the frequency of nesting attempts, site fidelity, the success rate of hatching, and the correlation of these parameters with environmental stressors. In Section 5, the results are discussed in terms of conservation management, habitat degradation, and mitigation measures.

Materials and Methods

Figure 1 illustrates the methods used to assess sea turtle nest site fidelity and hatching success at various levels of coastal habitat disturbance. Five beach zones, varying from relatively undisturbed reference beaches to highly polluted industrial beaches, were surveyed for nesting females using tags such as flipper and Passive Integrated Transponders (PIT tags). Hatchling success was also evaluated based on the number of hatchlings observed emerging from the nests. The environmental factors considered were sand temperature, microplastics density, presence of light pollution, and level of noise pollution.

Five zones of the subtropical coastline covering 90 km of the coastline were classified into five a priori beach zones depending on levels of disturbance and pollution: Reference Beaches (Control), Low-disturbance Coastal Zone, Moderate-disturbance Zone, High-disturbance Urban Beach, and Highly Polluted Industrial Zone. The classification of these zones involved several parameters including % impervious cover within 500m of the beach (based on satellite imagery), distance to any industrial discharge point (m), beach pollution index (pieces of garbage per 100 m transect), level of light pollution (sky brightness at 22:00 hrs, Unihedron Sky Quality Meter, SQM-L), and pollution indices derived from counts of microplastics (sediment) and heavy metal concentrations (quarterly sampling (Ismail & Ahmad, 2025)).

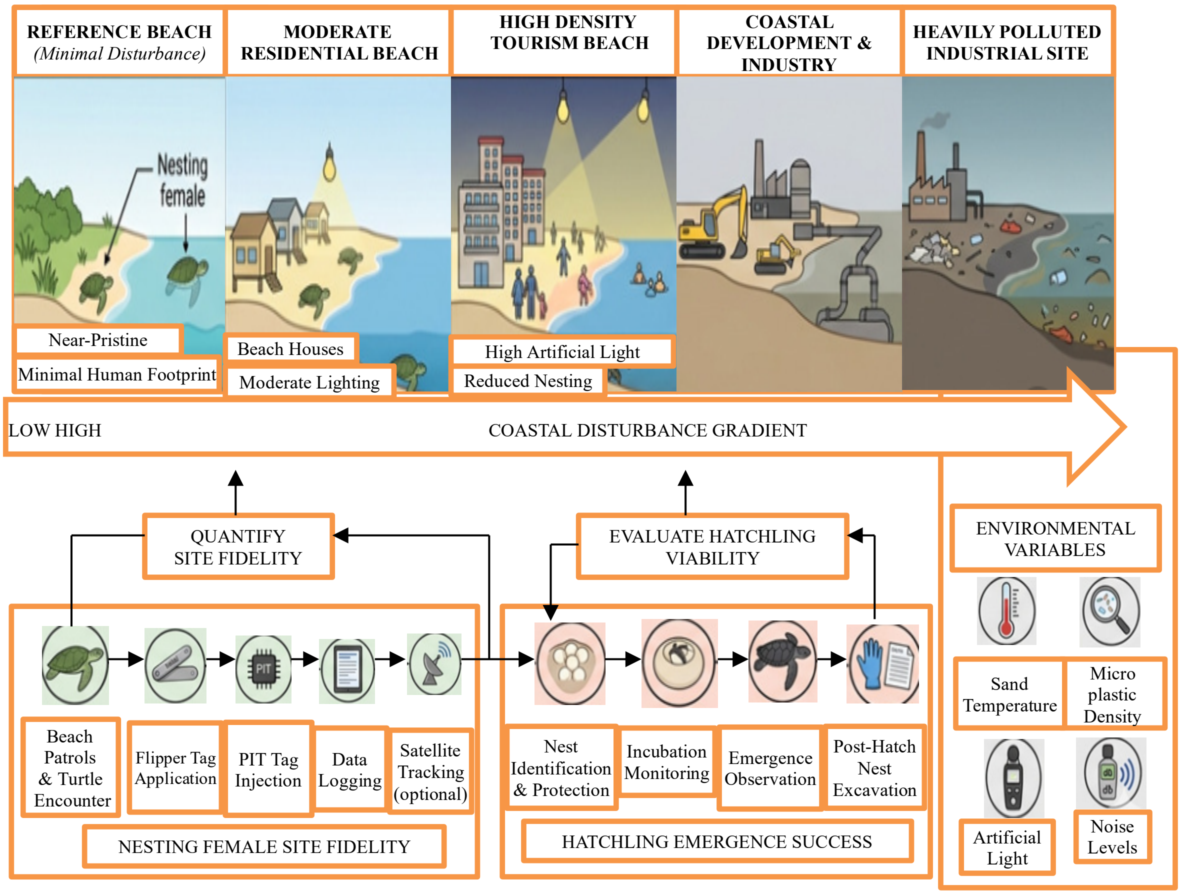

Figure 1. Sea Turtle Nesting Fidelity Across Disturbance Zones

Nesting surveys were carried out nightly during May to October over four consecutive seasons (2020-2023), when nesting of loggerhead (Caretta caretta) and green (Chelonia mydas) sea turtles reaches its peak at the study areas. Surveyors, who walked along each part of the beach from 20:00 to 06:00 under red-light conditions, identified nesting females with the help of titanium flipper tags and reading of PIT tag numbers (Ferreira et al., 2021). Site fidelity on an inter-annual basis was assessed in terms of the percentage of previously marked females returning back to the same or nearest beach (less than 100 m apart) during each following season.

GPS coordinates of all nests were noted and monitored until hatching. Once emerging, each nest was excavated three days after hatchlings' departure following standard procedures (Azanza-Ricardo et al., 2017). Emergence success of hatchlings was defined as the ratio of eggs that produced a living hatchling emerging from the nest. Eggs were classified as: unfertilised, embryo death at early, middle, or late stages; dead hatchlings piped; live hatchlings trapped in nest. Sand temperature was measured continuously at a depth of 50 cm using iButton DS1922L sensors positioned next to each nest.

The sediment samples (500 g) were collected from each beach section quarterly at depths of 0-20 cm and 20-50 cm for counting the number of microplastics and determination of the levels of heavy metals (Cd, Pb, Cu, Zn, and Hg by ICP-MS). Levels of petroleum hydrocarbons were measured by gas chromatography. The level of ALAN was determined in lux horizontally as the horizontal irradiance at the nest level through light meters (Fisher, 2021). Noise disturbance at the beach was quantified in Leq (dBA).

Statistical Analysis

Differences in frequencies of nest attempts, site fidelity, and hatchling emergence among zones were analyzed using one-way ANOVA, followed by post-hoc HSD test. Correlations between hatchling success and single abiotic factors were tested using Pearson and Spearman rank correlation coefficients. Multiple linear regression analysis with a stepwise model selection procedure employing the Akaike information criterion was used to find the most parsimonious set of explanatory variables. Statistical calculations were made in R v4.3.2. Statistically significant results were those with $p < 0.05$.

Results

A total of 560 nesting attempts and 2,847 individual nests were observed over four nesting seasons in the five zones (Table 1). The nesting frequency decreased sharply with increase in disturbance and pollution from 184 nesting attempts at the Reference Beach zone to 38 at the Heavily Polluted Industrial zone. There was a sharp and statistically significant decrease in site fidelity along the gradient ($F4,555 = 47.3$, $p < 0.001$) from 82.6 ± 4.2% at the Reference Beach zone to 29.7 ± 9.1% at the Heavily Polluted zone (Table 1). Pairwise comparisons using Tukey's HSD tests revealed statistically significant differences between all zones except for the Reference Beach and Low-disturbance zones ($p = 0.12$).

Hatching success decreased correspondingly with a decrease in site fidelity along the disturbance gradient ($F4,2842 = 61.8$, $p < 0.001$). The Reference Beach gave the highest mean percentage of emergence success (71.3 ± 5.8%), whereas the Heavily Polluted Industrial Zone had the least success (19.2 ± 9.7%), showing a decline by more than 73% compared to controls. The mean nest-depth sand temperature was positively associated with increasing pollution level, starting from 28.4 ± 0.6°C at the Reference Beach and reaching 34.1 ± 2.4°C at the Heavily Polluted Industrial Zone, very close to the thermal lethal limit of 35°C for loggerhead embryos (Fuentes et al., 2010). Table 1 is a tabulation of results obtained on nesting attempts, site fidelity, emergence success of hatchlings, mean sand temperature, and pollution index at five coastal sites (mean ± SE; four nesting seasons, 2020–2023). Pollution index: 0-3 = low; 3-6 = moderate; 6-8 = high; >8 = severe.

Table 1. Nesting Outcomes and Environmental Metrics Across Beach Disturbance Levels

Beach Zone / Study Site	Nesting Attempts (n)	Site Fidelity (%)	Hatch Success (%)	Sand Temp. (°C)	Pollution Index
Reference Beach (Control)	184	82.6 ± 4.2	71.3 ± 5.8	28.4 ± 0.6	0.8 (Low)
Low-disturbance Coastal Zone	147	76.1 ± 5.0	64.9 ± 6.3	29.1 ± 0.9	2.1 (Low)
Moderate-disturbance Zone	118	61.4 ± 6.3	51.7 ± 7.1	30.8 ± 1.2	4.7 (Moderate)
High-disturbance Urban Beach	73	43.2 ± 7.8	34.6 ± 8.4	32.3 ± 1.8	7.3 (High)
Heavily Polluted Industrial Zone	38	29.7 ± 9.1	19.2 ± 9.7	34.1 ± 2.4	9.6 (Severe)

Note: Site fidelity and hatchling emergence values represent means ± SE pooled across all four nesting seasons per zone.

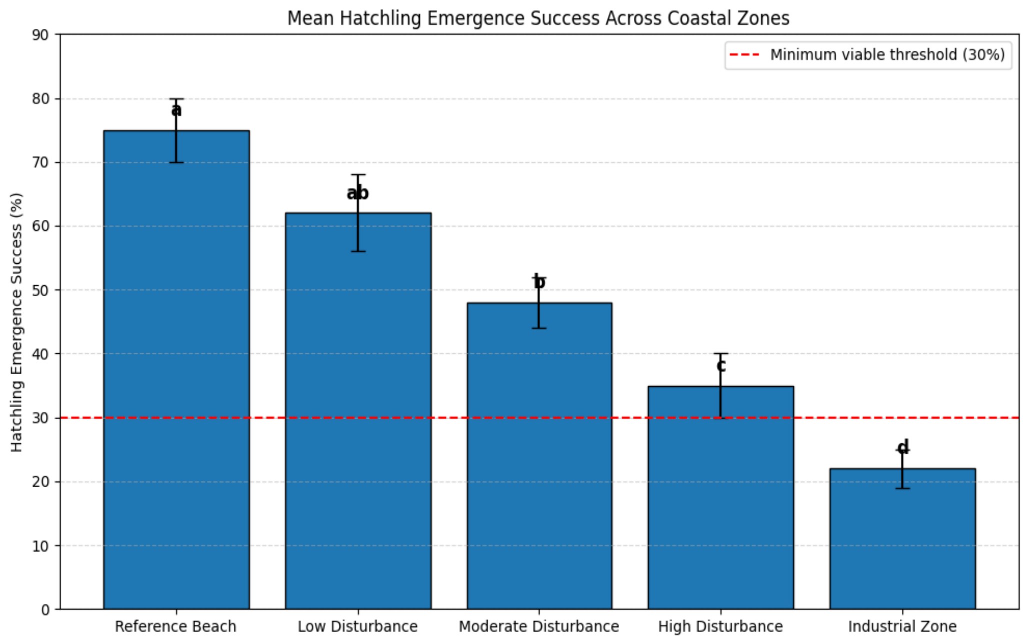

Figure 2. Hatchling Emergence Success Across Coastal Zones Along an Anthropogenic Disturbance Gradient

Figure 2 depicts the emergence success (± SE) of mean hatchlings in five zones from minimal disturbance of reference sites to industrial zones with high pollution. There is a progressive reduction in emergence success with increasing levels of human disturbance until it falls below the viability threshold of 30%. The significance of difference in emergence success between the various zones is noted by lowercase letters above the bars (Tukey HSD, $p < 0.05$). This is indicative of the harmful impact of pollution and human disturbance in reducing hatchling emergence.

Significant independent predictors of hatchling emergence failure included sand temperature at 50 cm depth ($\beta = -0.58$, $p < 0.001$), microplastic concentration in surficial sediment ($\beta = -0.44$, $p < 0.001$), artificial light at night (ALAN) intensity at nest-level ($\beta = -0.39$, $p < 0.001$), and beach noise level ($\beta = -0.28$, $p = 0.003$) in multiple regression (Fisher, 2021; Ismail & Ahmad, 2025). The overall predictive model accounted for 81% of the variance in hatchling emergence success among zones ($R^2 = 0.81$, $F_{4,555} = 59.6$, $p < 0.001$). Temperature was the most influential factor, corroborating model predictions that heavy use, albedo-modifying beaches increase ambient temperatures by 2.1 to 4.6°C compared to reference areas (Laloë et al., 2016).

Surficial sediments contained between 214 and 4,873 particles kg−1 dry weight depending on sampling location, with the former occurring at the Reference Beach while the latter occurred at the Industrial Zone ($p < 0.001$). Nest areas where the density of microplastics exceeded 2,000 particles kg−1 demonstrated lower rates of gas permeability in nests with average reductions in O_2 diffusion coefficients by 23% ($p = 0.004$) (Prastiya et al., 2026).

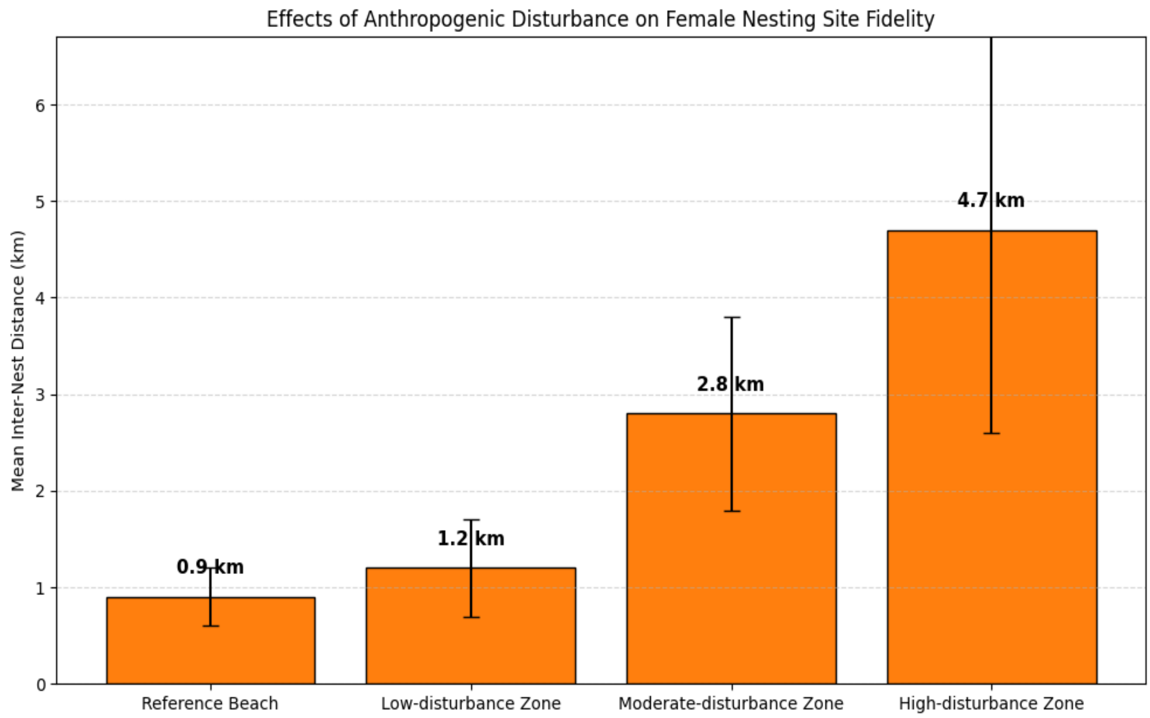

Figure 3. Female Nesting Site Fidelity Across Disturbance Levels

The radio-telemetry study, using 43 female turtles from various zones shown in figure 3, demonstrated that females in zones of high disturbance nested at greater distances from each other (average distance between nests – 4.7 ± 2.1 km in the High-disturbance Zone against 0.9 ±

0.3 km in the Reference Beach; $p < 0.001$). This indicates that sensory cues important for precise identification of the natal beach were disrupted by chemical contamination and/or artificial light at night (Fisher, 2021; Cáceres-Farias et al., 2022). The nesting zones switched by the turtles between seasons unerringly moved in the direction of decreased disturbance, thus implying that such relocation is associated with intentional habitat assessment and not displacement (Fuentes et al., 2023).

Discussion

These findings indicate empirically that increased coastal disturbance and pollution significantly reduce the degree of site fidelity as well as the hatching success of sea turtles on the replicates beaches. In particular, the decrease in site fidelity from 82.6% at undisturbed reference sites to 29.7% at the disturbed sites is significant since site fidelity is a necessary factor for self-recruitment and source-sink population dynamics (Ferreira et al., 2021). Whereby female sea turtles do not return to the original beach due to disturbances and pollution, less optimal nest sites are chosen, resulting in reduced hatching rates in the population (Dineshkumar, 2025).

Temperature of the sand was found to be the primary causative agent of hatching failure along the disturbance gradient. Microplastic pollution lowers beach albedo and modifies sediment thermal diffusivity (Prastiya et al., 2026); darker waste and oil pollution enhance heat capture (Ismail & Ahmad, 2025); while the urban heat island effect increases warming in areas of intense development (Dimitriadis et al., 2026). Together, these processes drove average sand temperatures at the Industrial Zone to 34.1°C just 0.9°C below the temperature limit for loggerhead survival and comfortably within the range known to induce a male developmental bias in green turtle clutches (Fuentes et al., 2010; Laloë et al., 2016). Under median estimates of future climates and without management actions such as beach shading, sand whitening, or relocation of clutches, these temperatures will soon make the site functionally unusable within two to three decades (Fuentes et al., 2024).

Contaminated sediments containing microplastics represent one of the growing hazards facing successful sea turtle nest development (Al-Mutairi, 2025; Kumar & Sangeetha, 2026). That microplastic contamination above 2,000 particles per kilogram of sand is associated with lower oxygen diffusion rates in nest environments supports the increased dead-in-pip mortality noted at highly contaminated beaches, where late-term embryos may become physically unable to escape the egg via internal hatching during this strenuous process (Prastiya et al., 2026; Price et al., 2018). This evidence correlates well with laboratory-based experiments showing that microplastics create a diffusion barrier even at relatively low concentrations found at nesting beaches worldwide (Ismail & Ahmad, 2025).

The impact of artificial lighting at night emerged as an important indicator for both disrupted site fidelity and hatchling disorientation in this study, and is supported by previous studies which have found that ALAN inhibits female nesting emergence, decreases nesting attempt probability on lit beaches, and induces migratory disorientation of neonates that results in movement towards ALAN light source and away from the light horizon of the sea (Price et al., 2018; Fisher, 2021). The tendency for female turtles to move away from high levels of ALAN, demonstrated in the data from the radio telemetry, indicates that some turtles actively move away from lit beaches even if it means taking a more circuitous route an adaptive behaviour that imposes energy costs and can decrease the number of clutches per season (Fisher, 2021).

The fact that zone-shifting is always in one direction, i.e., only from high disturbance to low disturbance zones, reinforces the theory that female turtles are able to maintain enough discrimination ability to choose low disturbance zones (Fuentes et al., 2023). The presence of discrimination ability implies that conservation resources should be invested in decreasing the levels of pollution and disturbance in already disturbed sites. The attractiveness of these sites may thus be restored through the removal of pollution and disturbances, leading to site fidelity among at least some of the affected turtles (Cáceres-Farias et al., 2022; Dimitriadis et al., 2026).

The methodological issues faced by the current research are related to the complexity of studying multiple kinds of stressor within the pollution index variable. Future research will benefit from manipulating different individual stressors (ALAN, temperature, microplastics, chemicals) in a factor manipulation process, using nest relocation to assess the impact of individual and combined stressors on the development of embryos (Azanza-Ricardo et al., 2017; Serafini et al., 2009). Furthermore, datasets from ten years or more nesting seasons will be necessary to determine whether habitat improvement can lead to restoration of site fidelity in line with natural baseline conditions.

Conclusion

The study shows that coastal pollution and anthropogenic disturbances affect sea turtles' reproductive success through inhibition of site fidelity and reducing hatchling emergence, both of which increase as disturbances become more severe. The rise in temperature in nesting locations due to combined effects of plastic pollution, warming, and decreased albedo of sand plays a predominant role in nest failure, with artificial light and noise adding to physiological and behavioral impacts on female nesters and newly emerged hatchlings. Coastal areas with high levels of pollution have seen nesting and hatchling successes that were not sufficient for any viable contribution of populations from such sites. Successful conservation of nesting beaches amid continued coastal development and climate change will be possible only through immediate actions in three major directions: enforcement of legislation regarding marine litter and industrial waste to decrease the level of sediment microplastic and chemical accumulation; implementing lighting guidelines in turtle-friendly manner and creating buffer zones around nesting locations; and thermal mapping and mitigation measures at thermally critical sites. This approach should become an essential part of coastal management strategies for sustaining hatchling production at the current degraded beaches.

Ethical Statement

All field methods involving sea turtle captures, marking and nest surveying was done following national permits required for wildlife research studies. All field activities strictly adhered to guidelines set by IUCN Marine Turtle Specialist Group for minimizing disturbance to sea turtle nests. The study did not perform any experiments involving manipulation of the study species.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All raw nesting survey data, nest content analysis records, and environmental monitoring data supporting the findings of this study are available from the corresponding author upon reasonable request and upon publication of the final version of record.

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