Artificial Night Lighting in the Mediterranean: Management Priorities and Constraints for Sea Turtle Conservation

Charalampos Dimitriadis [a], *Nikolaos Simantiris* [b c], *Fulvio Maffucci* [d], *Mustapha Aksissou* [e], Mouloud Benabdi [f], Piero Carlino [g], Paolo Casale [h], *Simon Demetropoulos* [i], *Wayne J. Fuller* [j], *Marc Girondot*[k], *Brendan J. Godley* [l m n], *Abdulmaula Hamza* [o], *Imed Jribi* [p], *Yakup Kaska* [q], *Yaniv Levy* [r s], *Jonathan R. Monsinjon* [t], *Ayse Oruc* [u], *Aliki Panagopoulou* [v], *Vilma Piroli* [w], *ALan F. Rees* [x], *Jesús Tomás* [y], *Oguz Turkozan* [z], *Sandra Hochscheid* [d], *Antonios D. Mazaris*[aa]

[a] *Management Unit of Zakynthos and Ainos National Parks and Protected Areas of Ionian Islands, Natural Environment and Climate Change Agency, 29100 Zakynthos, Greece*
[b] *MEDASSET (Mediterranean Association to Save the Sea Turtles), 10672 Athens, Greece*
[c] *Department of Aerospace Science and Technology, National and Kapodistrian University of Athens, 34400 Psachna, Greece*
[d] *Stazione Zoologica Anton Dohrn, Villa Comunale, 80121 Napoli, Italy*
[e] *Faculty of Science, University Abdelmalek Essaadi, Tetouan, Morocco*
[f] *Applied Zoology and Animal Ecophysiology Laboratory. Faculty of Natural and Life Sciences. University of Bejaia, Algeria*
[g] *Sea Turtle Research, Rescue and Rehabilitation Center of Salento Natural History Museum, 73021 Calimera, Italy*
[h] *Dept. of Biology, University of Pisa, Via A. Volta 6, 56126 Pisa, Italy*
[i] *Mediterranean Turtle Research and Conservation Society (MedTRACS), Paphos, Cyprus*
[j] Faculty of Veterinary Medicine, Near East University, Nicosia, Cyprus
[k] Laboratoire Ecologie, Societé, Évolution - Université Paris Saclay, CNRS, AgroParisTech, Gif-sur-Yvette 91190, France
[l] Centre for Ecology and Conservation, Faculty of Environment, Science and Economy, University of Exeter, Penryn, Cornwall, TR10 9FE, UK
[m] College of Marine Science and Aquatic Biology, University of Khorfakkan, Sharjah, UAE
[n] Sharjah Marine Sciences Research Centre (SMSRC), University of Khorfakkan, Sharjah, UAE
[o] Biology Department, Faculty of Education Tripoli, University of Tripoli, Tripoli, Libya
[p] Faculty of Sciences of Sfax, University of Sfax, Sfax, Tunisia
[q] Pamukkale University, Sea Turtle Research Center (DEKAMER), Denizli, Türkiye.
[r] Israel Sea Turtle Rescue Center, National Nature and Parks Authority, Gan Leumi Beit Yannay, Kfar Vitkin, Israel
[s] Department of Marine Biology, Leon H. Charney School of Marine Sciences, University of Haifa, Haifa 3498838, Israel
[t] Laboratory of Marine Environmental Sciences (LEMAR), IUEM - Univ Brest, CNRS, IRD, Ifremer - 29280 Plouzané, France
[u] WWF-Türkiye, Asmalı Mescit Mah. İstiklal Cad. No: 136 Kat: 4 Beyoglu, İstanbul, Türkiye
[v] ARCHELON, the Sea Turtle Protection Society of Greece, Athens, Greece
[w] University of Shkodra "Luigj Gurakuqi",Albania
[x] Turtles from Above, Plymouth, UK
[y] Marine Zoology Unit, Cavanilles Institute of Biodiversity and Evolutionary biology, University of Valencia, Valencia, Spain.
[Z] Aydın Adnan Menderes University, Faculty of Science, Department of Biology, Aydın, Türkiye
[aa] Department of Ecology, School of Biology, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

Corresponding author: Charalampos Dimitriadis (xdimitriadis@marine.aegean.gr)

1. Introduction

Artificial Light at Night (ALAN) has emerged as a rapidly expanding and pervasive form of pollution threatening global biodiversity and challenging conservation efforts (Falchi et al., 2016; Gaston et al., 2021). ALAN is detectable along a significant portion of the world's coastline (more than 22% in 2010, Davies et al., 2016) further extending across the sea surface, subsurface, and seafloor, altering the natural photic zones of the oceans (Davies et al., 2020; Smyth et al., 2021; Davies & Smyth, 2025) and impacting coastal and marine ecosystems (Gaston et al., 2014). This form of pollution represents a major ecological concern, as it introduces artificial illumination characterized by temporal patterns, spectral range, and intensities that are absent under natural conditions. Yet, its influence extends beyond the directly illuminated areas, as scattered and reflected light can alter the natural nocturnal environment over large spatial scales, disrupting many ecologically relevant processes in a wide range of wildlife species (Longcore et al., 2018; Tidau et al., 2021; Hirt et al., 2023). The progressive erosion of natural nocturnal darkness imposes profound consequences for ecological systems and a wide spectrum of taxa, including invertebrates, fish, amphibians, reptiles, birds and, mammals, whose life-history strategies are fundamentally contingent upon ambient light regimes (Hölker et al., 2010; Gaston et al., 2013; Karan et al., 2023). In this context, the attenuation of darkness triggers pervasive disruptions to essential ecological processes across species, encompassing foraging dynamics, reproductive success, recruitment patterns, orientation and navigational capacity, dispersal mechanisms, consumer–resource interactions, migratory behaviour and overall fitness (Sanders et al., 2021; Marangoni et al., 2022; Burt et al., 2023 and references therein).

Sea turtles are among the species most acutely impacted by ALAN, as their ontogenetic transitions and reliance on multiple coastal and marine habitat types make them highly susceptible to light-induced disturbance (Limpus & Kamrowski, 2013; Fuentes et al., 2023). Exposure of sea turtles to ALAN is particularly pronounced at nesting sites and nearshore coastal areas situated in proximity to urban, touristic or industrial developments (Kamrowski et al., 2014; Pendoley et al., 2016; Dimitriadis et al., 2018; Colman et al., 2020). Although the magnitude and extent of ALAN impacts may vary across different spatial and temporal scales, substantial evidence indicates they are predominantly associated with on-beach nesting behaviour and site selection by adult females, hatchling orientation during sea-finding, and offshore dispersal capacity (Salmon, 2003; Thums et al., 2016; Silva et al., 2017; Shimada et al., 2023; Attum & Nagy, 2024). These disruptions can ultimately reduce reproductive success, population resilience, and recruitment (Lorne and Salmon 2007; Dimitriadis et al., 2018; Wilson et al., 2019).

On a global scale, the Mediterranean region is among the areas most exposed to ALAN, primarily as a result of concentrated human population and activities along its coastal and nearshore zones, including urbanization, coastal development, tourism, industrial operations, shipping and transport networks (Piante & Ody, 2015; Marangoni et al., 2022; Polinov 2023). The region sustains significant populations of two sea turtle species the loggerhead turtle (*Caretta caretta*) and the green turtle (*Chelonia mydas*) which currently rely on approximately 52 and 13 major nesting sites, respectively, in addition to numerous minor nesting sites distributed around the Mediterranean basin (Casale et al., 2018). The overlap of coastal areas of intense ALAN exposure with these critical nesting and nearshore hatchling dispersal areas renders the Mediterranean a hotspot for potential light-induced ecological disruptions (Biddiscombe et al., 2020). Notwithstanding, knowledge of the threat posed by ALAN and its associated ecological impacts on sea turtles in the Mediterranean remains limited, being largely confined to a small number of sites and timeframes (e.g. Mazor et al., 2013; Dimitriadis et al., 2018; Leader et al., 2024; Simantiris et al., 2025; Jribi, 2025).

While natural dark skies become less common, important limitations and knowledge gaps persist in evaluating the ecological footprint of ALAN on sea turtles and in adopting the best management practices at nesting sites and nearshore areas (Rivas et al., 2015; Rees et al., 2016; Gomez Isaza et al., 2025). From a management perspective, the considerable heterogeneity in ALAN properties and sources across coastal and nearshore marine environments complicates not only the design and implementation of standardized monitoring protocols, but also the establishment of effective conservation measures. Nevertheless, identifying and prioritizing suitable strategies and measures towards the mitigation of ALAN effects on sea turtles is critical for enhancing the conservation effectiveness of their populations, recognizing current knowledge gaps and strengthening evidence-based management (Schofield et al., 2013; Fuentes et al., 2023).

Based on the perceptions of the experts involved in the monitoring and conservation of marine turtles in the Mediterranean, we aimed to: (a) evaluate the perceived impacts of ALAN on sea turtle nesting sites and nearshore marine habitats; (b) identify the principal research gaps; (c) determine critical limitations; and (d) establish priorities for strategies and mitigation measures to alleviate ALAN effects. By integrating research and practice, this study highlights critical ALAN-related knowledge gaps and management priorities for sea turtles, offering guidance and insights with broad applicability to marine conservation globally.

2. Material and Methods

In February 2024, members of the Marine Turtle Specialist Group (MTSG) (https://www.iucn-mtsg.org) with a focus on the Mediterranean Regional Management Units of loggerhead and green turtles (Wallace et al., 2023), together with additional experts in sea turtle monitoring and conservation, were invited to participate in an online survey. The objective of this survey was to assess and prioritize existing knowledge gaps, management priorities, and constraints, as well as to evaluate the ecological impacts of artificial light at night (ALAN) on sea turtles across the Mediterranean region. Experts that were invited to participate in the online survey consisted of diverse representatives in marine turtle monitoring and conservation across the Mediterranean coasts: managers (e.g. representatives of MPAs that implement activities focusing on sea turtle conservation, produce scientific articles and contribute to research projects), and researchers (e.g. personnel of academic or research centers).

A two-step process was followed to develop and disseminate the online survey. In the first step, the structure of the questionnaire was designed by the core team (S. Hochscheid, F. Maffucci, A.D. Mazaris, C. Dimitriadis). These experts were exclusively involved in the design phase and did not participate in the survey itself, thereby minimizing any potential bias. In the second step, the questionnaire was distributed to members of the Marine Turtle Specialist Group (MTSG), resulting in 22 completed responses. To ensure broad spatial and institutional representation, the survey was also circulated to additional stakeholders beyond the MTSG. These included researchers and/or managers working on sea turtles in the Mediterranean region, as well as members of other relevant initiatives (e.g., the Mediterranean Marine Protected Area Turtle Working Group – https://medpan.org/en/projects/conservation-marine-turtles-mediterranean-region). Additional potential participants were identified through scientific publications, technical reports, and attendance lists from relevant conferences and meetings. This process yielded 5 further responses. In total, 27 completed questionnaires were collected in 2024.

2.1. Survey sampling methods and design

The online survey was implemented through a structured questionnaire employing a five-point Likert scale (1–5). The questionnaire consisted of four sections: (1) participants' expertise and country of work on sea turtles; (2) general perceptions of ALAN monitoring at critical nesting sites and nearshore marine areas; (3) perceptions of ALAN impacts on sea turtle nesting sites and nearshore areas across different life stages, including identification of research gaps and limitations in monitoring and impact assessment; and (4) perceptions of 11 strategies and mitigation measures aimed at reducing the effects of ALAN on sea turtles in nesting and nearshore habitats. The proposed strategies and mitigation measures were grouped into two thematic categories: (a) species monitoring, assessment, and conservation planning, and (b) law and policy. Within Sections 3 and 4, both impacts and mitigation measures were assessed in terms of adequacy, practical applicability, financial cost, and societal cost. Similarly, questions addressing the limitations of implementing monitoring protocols were evaluated against multiple criteria, including effectiveness, carrying capacity (e.g., expertise and equipment constraints), practical applicability, and financial cost.

2.2. Data analysis

For the questions related to strategies and mitigation measures (Section 4), we merged the perception scores of the four components (i.e. adequacy, practical applicability, financial cost, and societal cost) to create a composite score (i.e. average) for each question (Bennett et al., 2020). These composite scores allowed us to treat the original ordinal values of the Likert scale as continuous values. Ranking of importance of strategies and mitigation measures was determined using quartile analysis. Responses were categorized into three groups based on their distribution. Items falling within the upper quartile (≥75th percentile) were classified as of high importance, those within the lower quartile (≤25th percentile) as of lower importance, and the remaining items were designated as of moderate importance. Kendall's tau correlation coefficient was employed to evaluate the degree of consensus among experts in their ranking assessments on the importance of strategies and mitigation measures counteracting ALAN effects. This nonparametric statistic quantifies the strength and direction of agreement among multiple raters by providing the pair-wise level of probability of concordance minus discordance. Values approaching 1 and -1 denote a perfect direct agreement or disagreement, respectively while values close to 0 suggest no agreement.

3 Results

3.1 Characteristics of survey sample

Twenty-seven people working on sea turtle conservation across 16 Mediterranean countries (Albania, Algeria, Croatia, Cyprus, Egypt, France, Greece, Israel, Italy, Lebanon, Libya, Morocco, Spain, Syria, Tunisia, and Türkiye) participated in the online – survey. Among the respondents, 25 identified their expertise as encompassing nesting beach monitoring and the conservation - management of sea turtles, of whom 12 additionally reported expertise in marine protected area management.

3.2 Base line information for ALAN and Sea turtles

The majority of the respondents concur that ALAN could jeopardize the reproductive output of sea turtles (with severe and high level of impact evaluation collectively representing 63% of responses), and that monitoring of its effects is necessary (81% of responses). Nonetheless, over 60% of respondents reported lacking access to, or awareness of, a standardized monitoring protocol for

ALAN effects at sea and nesting beaches, while more than 80% indicated that they had never applied such a protocol either at sea or on nesting beaches (Fig. 1).

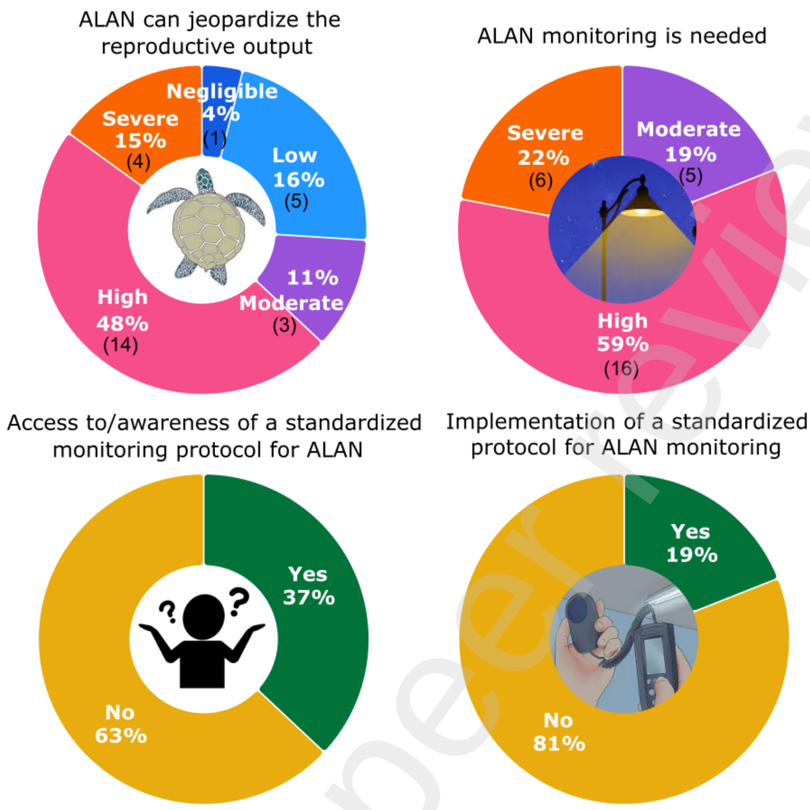

Fig. 1: Responses (n = 27) of the survey participants regarding the impact of ALAN on the reproductive output, the necessity for monitoring ALAN at sea and nesting beaches, the availability of monitoring protocols and their use in the field (donut size represents % of responses; numbers in brackets show response counts)

3.3 Impacts of ALAN on sea turtle nesting sites and nearshore marine areas

Overall, based on their experience, researchers reported that the greatest impact of ALAN occurs on hatchling orientation during the sea-finding transit from the nest to the sea, whereas the lowest impact is observed in adult females returning to the sea after emerging onto the beach to nest (Fig. 2a). This indicates that respondents consider hatchlings to be the life stage most affected by ALAN.

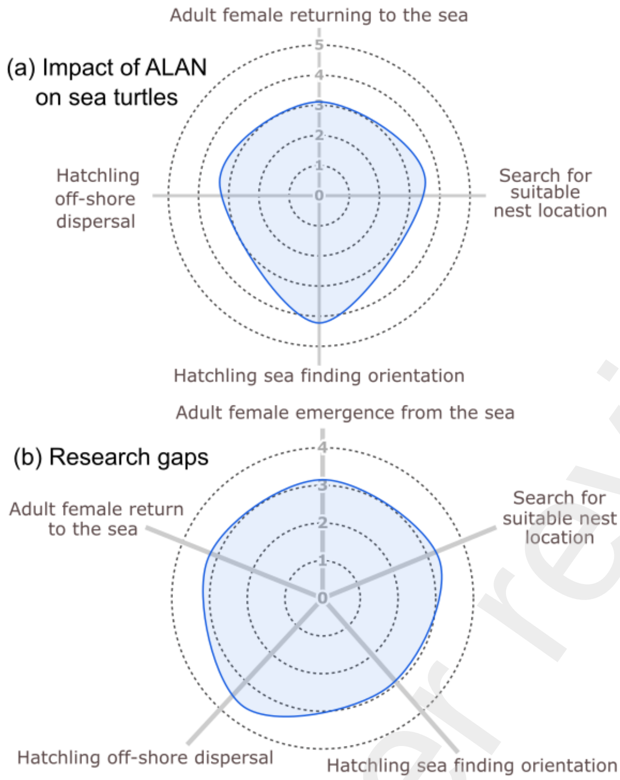

Fig. 2: Evaluation of the (a) impacts of ALAN and (b) associated research gaps on sea turtle nesting sites and nearby marine environment.

3.4 Research gaps

Considering the impacts of ALAN on different sea turtle reproductive stages, the most critical knowledge gap appeared to concern the offshore dispersal of hatchlings, followed by the return of adult females to the sea and their location of suitable nesting sites (Fig. 2b).

3.5 Limitations

Application of ALAN monitoring protocols

The primary limitation in implementing a standardized methodology and monitoring protocol for ALAN, across wide spatial scales (all sea turtle life stages and nesting locations) and temporal coverage (throughout the nesting period and across nesting seasons), was reported to be primarily associated with financial costs, rather than constraints related to carrying capacity, effectiveness, or practical applicability (Fig. 3a). By contrast, limitations related to communication and education, update of monitoring protocols to include ALAN as well as policy-related constraints, were primarily associated with issues of adequacy followed by practical applicability (Fig. 3b, Fig. 4a, Fig. 4b).

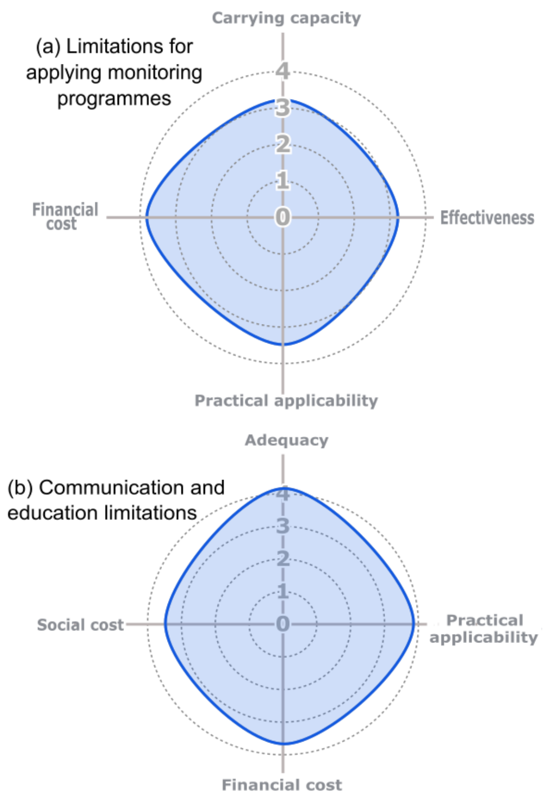

Fig.3: Evaluation of limitations related to ALAN issues focusing in applying (a) monitoring, (b) communications and education programmes on sea turtle nesting sites and nearby marine environment.

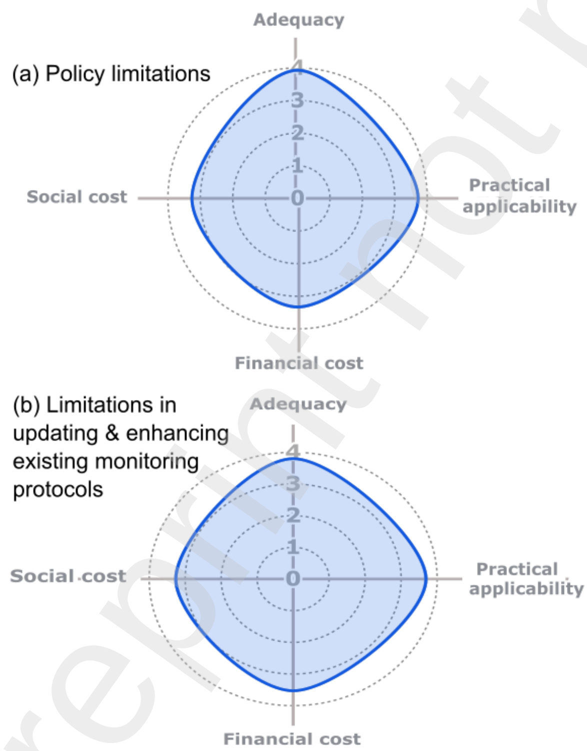

Fig.4: Evaluation of limitations to ALAN issues focusing to (a) policy and (b) the update and enhancement of existing monitoring protocols for sea turtle nesting sites and nearby marine environment.

3.6 Priorities for strategies and mitigation measures to alleviate ALAN effects

Based on the ranking of strategies and mitigation measures for ALAN effects on sea turtles above the 75th percentile, the three highest-ranked measures were related to species monitoring, assessment, and conservation planning. These included: (1) updating monitoring programs to incorporate ALAN measurements; (2) implementing measures to reduce ALAN exposure on nesting beaches, such as creating shaded corridors for hatchlings, eliminating direct light sources, minimizing remote light visible from the beach through the use of light-blocking fences or vegetation, use of motion-activated lights, and redirecting public and private lighting downward, as well as reducing sky glow from nearby human settlements, tourism facilities, and industries; and (3) updating conservation measures to integrate state-of-the-art interventions, new technologies, and nature-based solutions aimed at mitigating the impacts of ALAN (Fig 5). Measures and strategies of moderate importance included the: 1) identification of tipping points of abrupt change, indicators and alarm threshold for ALAN effects on sea turtles, 2) Enhancement of cooperation (exchange of experience and good practices) among managers and conservation practitioners, 3) establishment or increase of communication across policy makers-managers-researchers, 4) monitoring and assessment of the efficacy of existing management strategies for mitigating ALAN effects.

Measures below the 25th percentile, which were ranked to have lower importance, were linked to: 1) fitness check (i.e. evaluate efficacy and potential overlaps) and review of existing Laws, Regulations, and Policies, 2) enhance public awareness on ALAN impacts on sea turtle nesting habitat and wildlife in general, 3) adapt scenario-based planning (i.e. identify management actions that would be justified under proper ALAN impact assessment and 4) reform or revision of legislative pieces and agreements to tackle emerging pressures and activities.

Fig. 5: Ranking and grouping of the importance of strategies and mitigation measures for ALAN effects on sea turtles with color differentiation based on the 25th (lower than 25th colored yellow) and 75th (higher than 75th colored red) percentile.

With respect to the ranking of the relative importance of strategies and mitigation measures, no significant convergence was observed among most expert responses. Specifically, 88% of the pairwise comparisons (286 out of 325) yielded non-significant Kendall's tau coefficients ($p > 0.05$). Among the remaining 12% that showed statistically significant results, a strong negative association predominated, indicating substantial disagreement among experts.

Discussion

Base line information for ALAN and Sea turtles

Artificial light at night (ALAN) has emerged as a pervasive anthropogenic driver of ecological change in coastal ecosystems (Gaston et al., 2021; Tidau et al., 2021; Stanton & Cowart, 2024). However, its effects on Mediterranean sea turtles remain insufficiently characterized and have been circumstantially translated into management, systematic monitoring, or conservation practices. (Peters & Verhoven, 1994; Turkozan 2000; Rees 2005; Margaritoulis et al., 2025). Our expert survey across 16 Mediterranean countries confirmed broad recognition of ALAN as a threat, with most respondents rating impacts on reproductive output as high or severe and emphasizing the urgent need for standardized monitoring protocols. More than 80% indicated that they had never applied a standardized monitoring protocol, either at sea or on nesting beaches, regarding ALAN effects on sea turtles. Recent reviews of research trends and conservation priorities indicate that ALAN is understudied compared to other threats (Robinson et al., 2023), despite being ranked as a high conservation priority in some regions (Rees et al., 2016; Fuentes et al., 2023) in line with the finding of our study. In the Mediterranean, ALAN has been previously identified as a significant threat requiring conservation focus (Casale et al., 2018), but only a moderate amount of knowledge is currently available (Marsili et al., 2025). Globally, knowledge on ALAN impacts remains concentrated on loggerhead (*Caretta caretta*) and green turtles (*Chelonia mydas*), the two species that nest widely in the Mediterranean, and is heavily biased toward regions such as North America and Australia (Robinson et al., 2023; Gomez Isaza, 2025). This geographic and taxonomic imbalance underscores the importance of synthesizing Mediterranean perspectives, given the basin's dense overlap of nesting habitats with some of the world's most intensively developed and illuminated coastlines (Piante & Ody, 2015; Falchi et al., 2016; Polinov, 2023).

Life-Stage-Specific Impacts at Nesting and Nearshore Habitats

Our findings indicate that hatchlings are the life stage most vulnerable to ALAN, particularly during the sea-finding phase on the beach and, to a lesser extent, during the frenzy period of nearshore dispersal to open ocean waters. Exposure to artificial light during these critical windows results in high rates of disorientation, exhaustion and prolonged residence in predator-rich coastal waters (Lorne & Salmon, 2007; Thums et al., 2016; Wilson et al., 2018, 2022). Such outcomes compromise recruitment, population resilience and may have population-level consequences when compounded across nesting cohorts (Dimitriadis et al., 2018). Adults were evaluated as less sensitive but not immune to ALAN, as illumination can deter nesting on bright beaches, modify nest site selection, and reduce reproductive output (Silva et al., 2017; Hu et al., 2018). Despite their importance, the effects of ALAN on nesting site selection and offshore dispersal remain underexplored (Price et al., 2018).

Our findings align with previous studies documenting life-stage-specific vulnerabilities to artificial lighting (Salmon, 2003; Thums et al., 2016; Silva et al., 2017), emphasizing the need for management strategies tailored to ontogenetic sensitivities.

Despite the substantial knowledge gaps regarding the impacts of ALAN across different life stages and nesting process phases identified in this study, the Mediterranean represents a high-risk scenario. Coastal development, tourism, industrial activities, and urban lighting collectively intensify ALAN pressures in nearshore zones, rendering the region a potential hotspot for light-induced ecological disruption (Biddiscombe et al., 2020). Expansion of ALAN could increase the proportion of illuminated beaches, including within protected areas, eroding the effectiveness of conservation designations or plans for MPA expansion (Kamrowski et al., 2014; Davies et al., 2016). While estimates of exposure to ALAN in regions such as Brazil and the United States range from 60% to 98% of nesting sites (Fuentes et al., 2016; Colman et al., 2020), comparable data for the Mediterranean are limited to the main *Chelonia mydas* nesting areas, where approximately 65% of nests occur on beaches influenced by ALAN (Leader et al., 2024). However, in the Mediterranean context, major nesting rookeries are situated near densely populated and tourism-developed coastlines (Casale et al., 2018), suggesting that even modest increases in lighting could affect a disproportionately large share of regional nesting populations.

Knowledge Gaps and Monitoring Limitations

Despite significant advances in sea turtle research over recent decades (Mazaris et al., 2018) and evidence of population rebounds worldwide (Hays et al., 2025), several uncertainties limit the translation of scientific knowledge into conservation practice. One of the most striking gaps identified herein is that ALAN assessments are rarely integrated into monitoring plans, and standardized protocols are consistently absent, particularly across wide spatial scales encompassing all life stages and nesting locations and across temporal coverage throughout the nesting period and across nesting seasons. Salmon and Witherington (1995) proposed a standardized protocol—the fan mapping method—along with threshold criteria to systematically evaluate disrupted hatchling sea-finding orientation using directional data (Kamrowski et al., 2015). To date, only a single study has been published that applied this protocol in the Mediterranean to quantify ALAN effects on hatchlings (Dimitriadis et al., 2018). This limited application highlights the urgent need for broader adoption of standardized monitoring protocols to generate comparable data across sites and seasons, a necessary approach for monitoring all anthropogenic threats (Casale et al., 2025).

Financial constraints were identified as the primary barrier to implementing ALAN monitoring programs, limiting both spatial and temporal coverage. Additional challenges, related to communication, education, updating protocols, and policy uptake, stemmed from inadequate resources, knowledge, tools, and institutional frameworks, followed by practical applicability issues. These combined limitations hinder both the adoption of mitigation strategies and the generation of standardized, actionable data. At a policy level, laws, standards, and codes regulating ALAN in marine environments are rare globally, with uptake in Mediterranean conservation programs being particularly limited (CMS, 2020b; Rees et al., 2016). Further research gaps include the impacts of skyglow on hatchlings, physiological consequences of misorientation, and the identification of light mitigation measures effectiveness (Tidau et al., 2021; Gomez Isaza et al., 2025).

Conservation Priorities and Mitigation Strategies

Maintaining naturally dark coastal habitats remains the most effective safeguard against the impacts of artificial light at night (ALAN) (Rivas et al., 2015). Experts have emphasized the need to update monitoring programs to incorporate ALAN parameters and to minimize light exposure on nesting beaches. This objective can be achieved through the implementation of targeted management measures, including the installation of shielding structures, the use of downward-directed and long-wavelength lighting, the elimination of superfluous light sources, the regulation of illumination intensity to essential levels, and the establishment of shaded transit corridors for hatchlings (Salmon, 2003; Di Bari et al., 2023). The integration of advanced technologies and nature-based solutions into conservation interventions was also identified as a priority. Such measures may involve the use of automated lighting systems triggered by the movement of vehicles or people at night, as well as the restoration of sand dune systems and coastal vegetation to reduce light dispersion (Pendoley & Kamrowski, 2016; Simantiris et al., 2025). Policy reform, public awareness campaigns, and scenario-based coastal planning were considered relevant but of moderate priority, indicating that practical, site-based interventions may provide the most immediate conservation benefits (Kamrowski et al., 2014). Integrating ALAN considerations into marine protected area (MPA) management and coastal spatial planning is equally critical, particularly given that nearly one-third of MPAs globally already experience nighttime illumination (Davis et al., 2016). Recent advances in remote sensing and real-time light mapping offer promising opportunities to monitor illumination dynamics and to assess the effectiveness of mitigation measures (Falchi et al., 2016; Stare & Kyba, 2019). Another important finding highlighted in our study was the considerable lack of convergence among experts regarding the scoring of light impact mitigation measures. This divergence in expert opinions likely reflects broader uncertainties within the scientific and management communities. In particular, it may be attributed to the limited understanding of the actual ecological impacts of light pollution across the Mediterranean region and the scarcity of empirical assessments evaluating the effectiveness of mitigation strategies on nesting beaches and adjacent nearshore habitats. These gaps, as identified in our study, underscore the need for region-specific, evidence-based research to inform adaptive management frameworks and guide the prioritization of effective ALAN mitigation actions.

Several limitations of the study must be acknowledged. First, a potential source of bias may originate from the disproportionate representation of researchers compared to managers among the expert respondents. As a result, expert perceptions may have been skewed toward issues related to research, knowledge gaps, and inconsistencies in translating scientific findings into management practices. Yet, the relatively modest sample size, although spanning 16 Mediterranean countries, may limit the generalizability of rankings for specific strategies and mitigation measures, reflecting fine-scale variability in perceptions or local context. Future research should prioritize empirical quantification of ALAN impacts across multiple life stages, map vulnerable to ALAN areas, standardize monitoring protocols and ALAN intensity measurements, rigorously assess the effectiveness of mitigation interventions under field conditions, and investigate skyglow impacts and the physiological consequences of disorientation (Gomez Isaza et al., 2025).

Synthesis and Implications

Taken together, our results emphasize that ALAN is an established (Leader et al., 2024) but under-addressed threat to Mediterranean sea turtles, with disproportionate impacts on hatchling survival and recruitment. Conservation efforts are currently hampered by gaps in monitoring, methodological limitations, and limited policy uptake. Addressing these challenges requires a dual approach: a) advancing empirical research to resolve gaps and limitations, and b) scaling up evidence-based mitigation at nesting and nearshore habitats. Switching off, dimming, or shielding lights, preserving naturally dark landscapes, and limiting ecologically harmful spectra have been suggested as practical measures to reduce artificial light exposure (Falchi et al., 2011; Gaston et al., 2013; Davies et al., 2014). Implementing these strategies will not only safeguard regional sea turtle populations but also confer broader ecological benefits for a wide range of species and habitats (Marangoni et al., 2022), while simultaneously providing a globally relevant framework for managing ALAN in other coastal ecosystems.

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