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Systematic Literature Review: The Role of Earth's Magnetic Field in Dolphin Migration Navigation

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ABSTRACT

The urgency of this study arises from the need to understand how dolphins navigate long-distance migrations in marine environments where visual and acoustic cues are limited. The main problem addressed is the limited integration of scientific evidence on magnetoreception and the extent to which human-generated electromagnetic activities disrupt geomagnetic navigation. This study aims to synthesize recent findings on how dolphins detect and use the Earth's magnetic field as a natural orientation system and to identify factors that threaten its stability. A Systematic Literature Review (SLR) using PRISMA guidelines was employed to ensure a structured process of identifying, screening, and synthesizing relevant peer-reviewed publications from 2014 to 2025. Five studies that met the inclusion criteria were analyzed thematically. The results show that magnetite-based receptors in the dolphin nervous system allow detection of geomagnetic variations and support the formation of internal spatial maps. Magnetoreception is strengthened through its integration with echolocation and passive electroreception, forming a multisensory navigation system. The findings also indicate that artificial electromagnetic sources, such as submarine cables and sonar, can interfere with geomagnetic cues and reduce navigational accuracy. These results provide implications for conservation and biomimetic technology development.

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INTRODUCTION

Natural science examines natural phenomena through systematic and empirical investigation, enabling humans to understand and utilize natural processes responsibly. Scientific knowledge develops dynamically based on empirical evidence and logical reasoning, forming a foundation for technological advancement and environmental understanding (Nasution, 2020; Adi, 2018). Physics, as a core discipline within natural science, plays an essential role in explaining physical phenomena related to matter, energy, and their interactions. Many physics concepts, including magnetic fields, are abstract in nature and require integrative scientific approaches to be properly understood. Studies in physics education emphasize that contextualizing abstract concepts through systematic analysis improves scientific understanding (Al Fadhiel & Mufit, 2024; Tanjung et al., 2023).

The Earth possesses unique physical characteristics that support life, including gravitational stability, atmospheric protection, and a global magnetic field. The Earth's magnetic field is generated by electric currents in the molten outer core through the geodynamo mechanism and extends outward to form the magnetosphere (Ikhsab & Prasetyo, 2025). This magnetic field protects the planet from harmful solar radiation and charged particles. In addition, it provides directional and positional information that can be utilized by living organisms. As a result, the geomagnetic field plays a dual role in planetary protection and biological orientation.

From a physics perspective, the Earth's magnetic field can be modeled as a dipole field characterized by parameters such as declination, inclination, and intensity. These parameters vary across geographic locations and form a natural magnetic map. Although local anomalies may occur, the global geomagnetic structure remains relatively stable over geological timescales. This stability allows the geomagnetic field to function as a reliable reference for orientation. Consequently, it can be used for navigation in both natural and technological systems (Harefa & Humendru, 2024; Nasution, 2020).

In biological systems, many animal species utilize geomagnetic information for orientation and long distance migration. Research has demonstrated that animals are capable of detecting geomagnetic cues and using them as both a compass and a navigational map (Wiltschko & Wiltschko, 2022). This ability has been well documented in birds, fish, and sea turtles. However, studies focusing on large marine mammals remain limited. In particular, evidence related to dolphins is still fragmented and has not been systematically synthesized.

Dolphins migrate across vast marine environments where visual landmarks are limited and acoustic signals can be influenced by oceanographic conditions. Under such circumstances, the Earth's magnetic field is hypothesized to serve as a stable navigational cue. Previous studies suggest that dolphins may integrate geomagnetic information with echolocation and electroreception. This multisensory integration supports spatial orientation during migration. Nevertheless, the physiological mechanisms underlying this process are not yet fully understood (Naisbett-Jones & Lohmann, 2022)..

Increasing human activities in marine environments introduce artificial electromagnetic disturbances that may interfere with natural geomagnetic cues. Submarine power cables, sonar systems, and underwater communication technologies generate electromagnetic fields that can alter magnetic signals used by marine organisms. Such disturbances may reduce navigation accuracy and disrupt migration routes. Similar findings in environmental studies indicate that disruption of natural systems can weaken biological adaptability. This concern is increasingly relevant in the context of marine conservation (Balmori de la Puente & Balmori, 2023; Fahlevi et al., 2024).

In addition to ecological implications, geomagnetic navigation has inspired developments in biomimetic technology. Autonomous underwater navigation systems increasingly adopt principles derived from animal navigation strategies. These systems utilize geomagnetic cues to operate in environments with limited external references. Such technological approaches show strong conceptual similarities to biological navigation mechanisms observed in marine mammals. Therefore, understanding dolphin magnetoreception has relevance beyond biology (Zhu & Cui, 2025).

Based on these considerations, this systematic literature review aims to synthesize scientific evidence regarding the role of the Earth's magnetic field in dolphin migration navigation. This study focuses on the physiological basis of magnetoreception in dolphins. It also examines the integration of geomagnetic cues with other sensory systems. In addition, the review analyzes the impacts of anthropogenic electromagnetic disturbances. By integrating perspectives from physics, marine biology, and environmental science, this study contributes to conservation efforts and biomimetic navigation research.

METHODS

This study employed a Systematic Literature Review (SLR) design guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to examine the Earth's magnetic field role in dolphin migratory navigation through magnetoreception. The PRISMA framework was selected for its systematic, transparent, and standardized procedures in identifying and synthesizing scientific literature (Moher et al., 2009; Ridho & Dasari, 2023). A descriptive qualitative approach integrated multidisciplinary perspectives from marine biology, geomagnetic physics, and animal behavioral ecology. The central research question was: "How does the Earth's magnetic field facilitate dolphin migratory navigation, and how do anthropogenic activities affect this mechanism?". This methodology ensured a comprehensive, holistic understanding of magnetoreception phenomena in dolphins (Harefa & Humendru, 2024; Tanjung et al., 2023).

Articles were included if they were empirical or review publications dated 2014–2025 to capture current magnetoreception research developments. Second, all selected publications required peer-review status to guarantee scientific validity and methodological rigor (Kremers et al., 2014; Moher et al., 2009). Third, studies specifically addressed dolphin or marine mammal navigation via magnetoreception and geomagnetic fields. Fourth, articles written exclusively in English minimized translation bias and facilitated comparative analysis. Exclusion criteria eliminated non-relevant studies, non-peer-reviewed materials, methodologically unclear papers, and inaccessible full-text documents (Patil et al., 2022; Ridho & Dasari, 2023).

This review encompassed four principal aspects of dolphin magnetoreception within migratory navigation contexts. First, biophysical mechanisms featured magnetite (Fe_3O_4) crystals that transduce geomagnetic cues into spatial orientation signals (Kremers et al., 2014). Second, behavioral evidence demonstrated dolphins' ability to discriminate magnetic stimuli, establishing navigation prerequisites (Kremers et al., 2016). Third, magnetoreception integrated with echolocation and electroreception supported long-distance orientation in dynamic marine environments (Hüttner et al., 2023). Fourth, anthropogenic disturbances from submarine cables and sonar were analyzed alongside biomimetic applications for sustainable underwater navigation systems (Nyqvist et al., 2020).

A comprehensive literature search via Google Scholar employed keywords: "magnetoreception in dolphins," "marine mammals navigation magnetic field," "geomagnetic orientation dolphins," and "sensory adaptation in cetaceans," yielding 23 initial articles (Ridho & Dasari, 2023). The selection process followed PRISMA stages as illustrated in Figure 1 (Moher et al., 2009). Screening eliminated articles based on publication year, peer-review status, and title/abstract relevance to magnetoreception. Eligibility assessment evaluated full texts for methodological clarity and inclusion criteria compliance. The inclusion stage finalized five articles suitable for in-depth thematic synthesis (Hüttner et al., 2023).

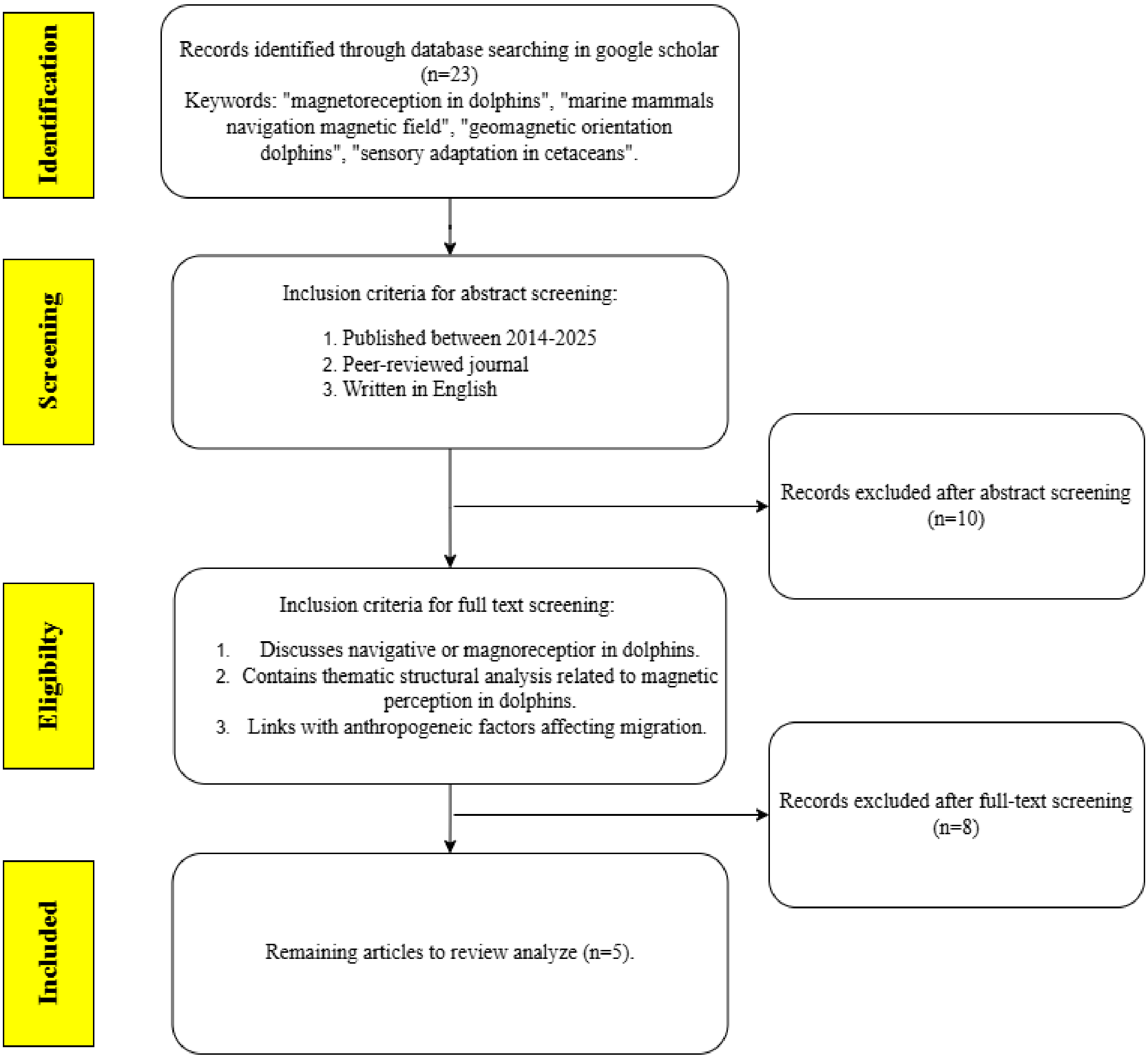

Figure 1. PRISMA Flow Diagram

Data analysis utilized descriptive qualitative thematic synthesis to identify patterns and core concepts across selected literature. Key information including authors, objectives, methods, and magnetoreception findings was extracted into a tabular matrix in Table 1 for structured comparison. Primary themes comprised biophysical mechanisms, magnetite sensor anatomy, multimodal navigation integration, and anthropogenic impacts. Critical appraisal assessed methodological quality, identified finding consistencies, and evaluated evidence limitations from biological and physical perspectives. Data triangulation across multidisciplinary studies enhanced the validity and robustness of conclusions (Handayani, 2017; Harefa & Humendru, 2024; Scientific Reports, 2024).

Synthesized findings were interpreted within ecological conservation and biomimetic technology contexts. Results underscored geomagnetic fields' critical role in successful dolphin migratory navigation. Anthropogenic disturbances such as naval sonar potentially induced disorientation and stranding events. This SLR methodology supported development of environmentally sustainable underwater navigation technologies. The PRISMA-guided approach ensured reproducibility and substantial contributions to marine mammal research (Kremers et al., 2016; Simamora et al., 2024).

RESULTS AND DISCUSSION

Results

Identification of Core Findings Related to Dolphin Magnetoreception

A comprehensive analysis of the selected literature revealed several key publications that specifically address the mechanisms of geomagnetic navigation in dolphins. These studies collectively demonstrate that dolphins possess biological structures capable of sensing variations in the Earth's magnetic field, allowing them to orient and migrate across long distances. Researchers employ diverse methodologies, including behavioral experiments, neurophysiological examinations, and environmental simulations, to understand how dolphins utilize magnetic cues. Overall, the literature consistently identifies magnetoreception as an essential internal sensory system that supports long-distance navigation in open-ocean environments. A summary of these findings is presented in Table 1.

Tabel 1. Summary of Selected Studies on the Role of Earth's Magnetic Field in Dolphin Migratory Navigation

Authors (Year)	Research Objectives	Key Findings on Magnetoreception	Methodological Approach	Strengths & Limitations
Patil et al. (2022)	Examine natural sensor systems used by dolphins for marine navigation and migration	Magnetite (Fe_3O_4) crystals in neural structures detect Earth's magnetic field lines, forming internal maps for long-distance orientation in low-visibility oceans	Conceptual review of biomimetic sensors and evolutionary adaptations	Strengths: Comprehensive synthesis; Limitations: Lacks primary data.
Nyqvist et al. (2020)	Assess electromagnetic field impacts on marine mammal migratory behavior	Dolphins detect regional magnetic variations as geographic markers for direction, feeding grounds, and breeding sites; maintains precise paths in open ocean	Literature review + ecological modeling of electric/magnetic senses	Strengths: Multi-species comparison; Limitations: Indirect evidence only
Hüttner et al. (2023)	Investigate electroreception and magnetoreception integration in dolphin orientation	Induction-based detection while swimming enables large-scale migration; resists minor geomagnetic disturbances (solar storms)	Controlled experiments measuring electroreceptive responses in bottlenose dolphins	Strengths: Direct behavioral data; Limitations: Small sample size

Kremers et al. (2014)	Test dolphins' ability to discriminate magnetic stimuli	Dolphins approached magnetized neodymium blocks 2x faster than controls; confirms behavioral magnetoreception prerequisite for navigation	Field experiments with magnetized vs. unmagnetized devices (n=12 dolphins)	Strengths: First direct evidence; Limitations: Controlled aquarium setting
Kremers et al. (2016)	Analyze complexity of cetacean sensory systems for survival	"Magnetic hills/valleys" (field anomalies) provide positional awareness; integrates with echolocation for hybrid navigation	Neuroanatomical review + behavioral correlation studies	Strengths: Multidisciplinary; Limitations: Relies on correlational data.

The studies summarized in the table show that the Earth's magnetic field plays an essential role in enabling dolphins to navigate long migratory routes with high accuracy. First, the identification of magnetite particles within neural structures provides a biological basis for perceiving changes in magnetic intensity. Second, behavioral experiments show that dolphins respond differently to magnetic and non-magnetic objects, indicating true perceptual discrimination rather than random behavior. Third, the persistence of migratory precision in low-visibility environments demonstrates that dolphins rely on more than acoustic or visual cues. Fourth, variations in geomagnetic gradients appear to act as natural geographic markers that guide dolphins across large-scale oceanic regions. Fifth, the consistency of findings across multiple studies strengthens the hypothesis that dolphins maintain an internal geomagnetic map. Sixth, the similarity of navigation patterns with other migratory species such as sea turtles and birds further supports the evolutionary development of magnetic-based orientation systems.

Discussion

Magnetoreception as a Primary Mechanism for Long-Distance Migration

Magnetoreception functions as the central navigational system that enables dolphins to maintain orientation across extensive migratory pathways, especially in offshore regions where visual or acoustic cues are insufficient. Research indicates that geomagnetic information provides a stable and predictable reference point that remains reliable despite fluctuations in light availability, water clarity, and weather conditions (Nyqvist et al., 2020; Burhanuddin, 2024). Neurological findings support the presence of magnetite-like particles within the cetacean nervous system, suggesting a biological mechanism capable of detecting magnetic inclination and polarity to form a natural compass (Hüttner et al., 2023). Tracking studies further reveal that changes in dolphin movement often correspond with geomagnetic anomalies, emphasizing the role of this sensory modality in route maintenance (Scientific Reports, 2024). Because the geomagnetic field is globally continuous and unaffected by environmental disturbances, magnetoreception provides dolphins with a dependable long-distance navigational framework. These findings confirm that magnetoreception is a primary mechanism rather than a supplementary aid for sustaining coordinated and precise migration.

Integration of Magnetic and Electro-Sensory Systems

Dolphins navigate efficiently through an integrated multisensory system in which magnetoreception operates in conjunction with passive electroreception. As dolphins move through geomagnetic fields, subtle electrical potentials are produced and detected by specialized electroreceptive structures, creating an interactive sensory network that enhances spatial detection (Hüttner et al., 2023; Nyqvist et al., 2020). Experimental evidence demonstrates that dolphins can distinguish magnetic objects from non-magnetic ones, indicating the presence of a dedicated neural pathway for magnetic processing. This integration allows dolphins to interpret fine variations in their environment, such as localized magnetic gradients near topographical features that serve as natural reference points. The combination of magnetic and electric cues provides stability when other sensory systems are limited, such as in deep or turbid waters where vision and sound propagation are compromised. This multisensory approach enhances navigational accuracy, reduces errors during long-distance travel, and represents an adaptive advantage for life in vast and complex marine ecosystems (Kremers et al., 2016).

Functional Limitations of Sonar and Its Complementary Role

Echolocation is essential for short-range environmental assessment, but it is not suitable as a primary long-distance navigational system due to rapid sound attenuation in seawater. High-frequency echolocation clicks weaken significantly as they travel, limiting their effective range and preventing dolphins from using them for large-scale orientation. Observational studies show that dolphins modify their click patterns primarily when nearing objects or prey, reinforcing the interpretation that sonar serves localized functions rather than broad-range navigation. Computational models further confirm that echolocation becomes ineffective over distances exceeding several hundred meters, which is insufficient for migratory purposes (Ladegaard et al., 2019; Recent Research, 2009; Wei et al., 2021). Environmental factors such as salinity gradients, temperature layers, underwater structures, and anthropogenic noise also influence sound propagation and increase uncertainty in acoustic detection. Consequently, dolphins rely on echolocation for precise short-range tasks such as identifying prey, avoiding obstacles, and maintaining group coordination, while magnetoreception provides the primary long-distance directional guidance. This complementary division of sensory roles ensures efficient navigation at multiple spatial scales (Baldachini et al., 2025; Ismadi, 2019).

Effects of Natural and Anthropogenic Magnetic Disturbances

The effectiveness of magnetoreception makes dolphins highly sensitive to disruptions caused by natural geomagnetic variability and human-generated electromagnetic activities. Natural events such as solar storms and geomagnetic fluctuations can temporarily alter magnetic intensity and direction, diminishing the accuracy of magnetic-based navigation and increasing the likelihood of disorientation. Although dolphins can compensate for minor disturbances through integrated sensory processing, severe anomalies may contribute to irregular movement patterns or stranding incidents. Anthropogenic sources pose a more persistent threat because of their increasing distribution in marine areas. Submarine communication cables, offshore wind farms, undersea mining infrastructure, and naval technologies emit localized electromagnetic fields that interfere with the natural magnetic landscape used by dolphins for navigation (Nyqvist et al., 2020; Fisher & Slater, 2010). Observational evidence indicates that regions with elevated electromagnetic emissions often show higher rates of cetacean disorientation and abnormal migration trajectories. These disturbances can also affect foraging routes and disrupt coordinated group movement. Mitigation efforts, such as regulating electromagnetic emissions and designating protected migration corridors, are necessary to reduce ecological risks and preserve species that depend on geomagnetic navigation (Adi, 2018; Januardi, 2025; Nurhaida et al., 2023.).

Evolutionary Adaptation and Biomimetic Technological Potential

The combined use of magnetoreception for large-scale orientation and echolocation for short-range spatial analysis demonstrates a highly refined evolutionary adaptation in dolphins. This dual sensory strategy supports a wide range of biological functions, including migration, foraging efficiency, predator avoidance, and group cohesion. Insights into these biological mechanisms have stimulated innovation in biomimetic engineering, particularly in the development of autonomous underwater vehicles that rely on geomagnetic cues to navigate without GPS (Burhanuddin, 2024; Kremers et al., 2016; Patil et al., 2022). Advances in marine tracking technology, such as minimally invasive tagging systems, enable researchers to analyze dolphin movement with greater precision while minimizing environmental disturbance. These innovations contribute to conservation planning, enhance understanding of habitat usage, and support the management of marine environments affected by climate change and industrial expansion. Overall, the study of dolphin navigation provides valuable insights not only into evolutionary biology but also into sustainable technological development inspired by natural systems (Wulandari et al., 2024; Ikhsan and Prasetyo, 2025; Scientific Reports, 2024).

CONCLUSION

Through the mechanism of magnetoreception, the Earth's magnetic field has been proven to play a major role in maintaining the accuracy of dolphin migration orientation, as magnetite in their nervous system allows them to detect geomagnetic changes, which are then translated into position and directional information during long-distance travel. Behavioral findings show that dolphins are able to distinguish objects based on their magnetic properties, confirming that the magnetic field functions as an internal map that works in conjunction with echolocation abilities for short-range navigation. The integration of these two sensory systems enables dolphins to adapt to complex ocean conditions. However, various human technologies such as sonar, submarine cables, and other electromagnetic devices can disrupt the stability of the ocean's magnetic field, potentially triggering migration disorientation. Overall, this research confirms that the Earth's magnetic field is not just a passive environmental element, but an important ecological component that supports the survival of dolphins while also inspiring the development of more environmentally friendly underwater navigation technologies.

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