*Review Article*

Biological Impacts of Climate Change on Sea Turtles: A Review

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ABSTRACT

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| Climate change poses significant threats to sea turtle populations, affecting reproduction, migration, and survival. This review explores the impacts of rising global temperatures, greenhouse gas emissions, and oceanic disruptions on these species. Elevated sand temperatures result in female-biased sex ratios, jeopardizing genetic diversity and long-term population stability. Rising sea levels and extreme weather events further reduce available nesting sites, while altered ocean currents disrupt migratory routes and food availability, endangering species viability. To mitigate these effects, robust conservation strategies are essential, including nesting site protection, sand temperature regulation, and bycatch reduction. Policies aimed at habitat preservation and carbon emission reduction are also critical for enhancing species resilience. Future research should prioritize adaptive strategies to ensure population sustainability in the face of ongoing climate change. This review emphasizes the urgency of integrated conservation efforts to safeguard these ecologically vital marine reptiles. |

*Keywords:* Sea turtles, climate change, conservation, marine ecosystems, greenhouse gases.

1. INTRODUCTION

Climate change is one of the greatest challenges facing humanity, with profound implications for ecosystems, biodiversity, public health, the economy, infrastructure, and global supply chains. Rising temperatures and the increasing frequency of extreme events, such as droughts and floods, are already reshaping the planet [1]. Global warming, driven by the excessive accumulation of greenhouse gases (GHGs) in the atmosphere, is primarily linked to carbon dioxide (CO₂), the most abundant, followed by methane (CH₄) and nitrous oxide (N₂O), which are 28 and 265 times more potent than CO₂, respectively [1].

Although GHGs have natural sources, such as organic matter decomposition, volcanic activity, and respiration, their atmospheric concentrations have surged due to anthropogenic activities, including fossil fuel combustion, deforestation, and intensive agriculture [2]. These processes release CO₂, CH₄, and N₂O at rates far exceeding the regulatory capacity of natural cycles. The resulting global warming accelerates polar ice melting, drives sea-level rise, and threatens biodiversity, pushing many species toward extinction [2]. In 2024, the global average temperature exceeded 1.5°C above pre-industrial levels for 11 consecutive months, reaching 1.6°C, making it the hottest year on record since 1850, according to the World Meteorological Organization (WMO) and other global meteorological institutions [3].

Climate change impacts biota and ecosystems by altering species distribution, habitats, and ecological cycles [3,4]. Rising global temperatures, driven by greenhouse gas emissions, force species to migrate to cooler regions, while others face population declines and extinction [4]. In marine environments, warming and acidification threaten coral reefs and disrupt food chains. Extreme events such as droughts and wildfires further degrade ecosystems and heighten biodiversity vulnerability [1]. Ectothermic organisms, including amphibians and reptiles, are particularly sensitive to these changes, making them highly susceptible to population declines [5].

Sea turtles comprise seven species across two families: Dermochelyidae and Cheloniidae, with five species occurring in Brazil (Table 1) [6]. These include the Green Turtle (*Chelonia mydas*), Hawksbill Turtle (*Eretmochelys imbricata*), Olive Ridley (*Lepidochelys olivacea*), Loggerhead (*Caretta caretta*), and Leatherback (*Dermochelys coriacea*) [6]. *C. mydas* has a grayish-green carapace and is found in Costa Rica, Guinea-Bissau, Mexico, Ascension Island (UK), Suriname, and Trindade Island (Brazil). *E. imbricata* has a brown carapace and inhabits subtropical and tropical waters of the Atlantic, Pacific, and Indian Oceans. *L. olivacea* is the smallest species found in Brazil, with an olive-green carapace and a light-yellow underside, occurring in the Indian, Pacific, and Atlantic Oceans (French Guiana, Brazil, and Africa) [7]. *C. caretta* has a yellowish-brown carapace, a disproportionately large head, and is found in the southeastern United States, Cape Verde, and Brazil. *D. coriacea* lacks scutes, has a black carapace with white, pink, or bluish spots, and is distributed across Congo, the Caribbean, the southern United States, and even temperate and subpolar waters [7].

Among the biological groups most affected by the consequences of climate variability, sea turtles stand out due to their complex life cycle, which involves migrations between coastal and oceanic habitats, and their reliance on specific environmental conditions for reproduction and feeding [8, 9]. As a result, they are highly sensitive to these changes. Studying the effects of climate change on sea turtles is crucial because they play key roles, such as maintaining coral reefs. These species already face multiple threats, including pollution, bycatch, and habitat degradation. Sea turtles are ideal indicators as they respond to environmental changes; for example, increasing temperatures of nesting beaches can lead to a female-biased population, compromising genetic diversity and future reproduction [8, 9].

This study examined the impacts of greenhouse gas emissions on the biology and ecology of sea turtles, specifically focusing on how these emissions influence sex ratio, the reduction of nesting areas, and changes in the species' dispersion and distribution. The research was conducted through a literature review assessing the effects of climate change on the survival and reproduction of sea turtles. The hypothesis proposed that increased GHG emissions intensify global warming, leading to significant threats for sea turtles, including I. Alterations in the sex ratio, caused by rising sand temperatures, which compromise reproduction; II. The reduction of nesting areas due to rising sea levels and the increased frequency and intensity of extreme weather events such as tropical storms, hurricanes, and coastal erosion; III. Changes in the species' dispersion and distribution, driven by altered ocean currents, disrupting their life cycle. This work contributes to a broader understanding of these climate-driven impacts, offering essential knowledge to inform conservation strategies and support evidence-based policy development.

**Table 1.** Characteristics and geographical distribution of the main sea turtle species found in Brazil.

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| **Species** | **Vernacular Name** | **Family** | **Carapace Characteristics** | **Distribution** |
| *Chelonia mydas* | Green Turtle | Chelonidae | Grayish-green | Costa Rica, Guinea-Bissau, Mexico, Ascension Island (UK), Suriname, Trindade Island (Brazil) |
| *Eretmochelys imbricata* | Hawksbill Turtle | Chelonidae | Brown | Subtropical and tropical waters of the Atlantic (Caribbean, Brazil), Pacific, and Indian Oceans |
| *Lepidochelys olivácea* | Olive Ridley Turtle | Chelonidae | Olive-green dorsally, light yellow ventrally, smallest among Brazilian species | Indian, Pacific, and Atlantic Oceans (French Guiana, Brazil, Africa) |
| *Caretta caretta* | Loggerhead Turtle | Chelonidae | Yellowish-brown, disproportionately large head | Southeastern USA, Cape Verde, Brazil |
| *Dermochelys coriacea* | Leatherback Turtle | Dermochelydae | Black with white, pink, or bluish spots; lacks scutes on the carapace, fins, and head | Congo, Caribbean, southern USA, temperate and even subpolar waters |

**2. GREENHOUSE EFFECT AND CLIMATE CHANGE**

The greenhouse effect is a fundamental natural phenomenon that sustains life on Earth. It occurs when atmospheric gases, including carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and water vapor, absorb and retain part of the heat radiated by the Earth's surface, preventing its complete dissipation into space [10]. This process regulates the planet’s temperature, creating conditions conducive to life. Without it, the global average temperature would be approximately 33°C lower, rendering most known ecosystems unviable [10].

However, the unchecked rise in greenhouse gas (GHG) emissions, largely driven by human activities, has amplified this natural mechanism, leading to global warming and accelerating climate change [11]. Since the Industrial Revolution, atmospheric CO₂ levels have steadily increased due to fossil fuel combustion, deforestation, and unsustainable agricultural practices [12]. This excess accumulation of heat-trapping gases intensifies global temperatures, driving extreme weather events, biodiversity loss, sea level rise, and ocean acidification [13].

Climate change stands as one of the greatest threats to global biodiversity, exerting particularly severe impacts on marine ecosystems [13,14]. Rising ocean temperatures, acidification, and sea level rise are among the most profound consequences of global warming, directly affecting sensitive species such as sea turtles, which depend on stable environmental conditions for survival and reproduction [14].

For sea turtles, increasing temperatures pose a significant threat to their life cycle. The incubation temperature of their eggs plays a pivotal role in determining the sex of hatchlings. Elevated nest temperatures can lead to female-skewed populations, compromising genetic diversity and long-term population stability [15]. Furthermore, ocean warming disrupts prey distribution, altering the availability of key food sources such as jellyfish and crustaceans, while also degrading vital habitats like coral reefs, which serve as essential feeding and refuge areas for numerous marine species [13].

**3. SEA TURTLES AND THEIR HABITATS**

Sea turtles are long-lived migratory species with lifespans ranging from 50 to 100 years [16]. They play critical ecological roles in marine and coastal ecosystems, inhabiting tropical, subtropical, temperate, and subpolar waters. Throughout their life cycle, they rely on distinct habitats for feeding, mating, and nesting [16]. Juveniles primarily occupy oceanic and pelagic zones, which provide abundant food resources and refuge from predators, while adults frequent neritic and benthic areas, such as coastal waters and coral reefs, where they forage and reproduce. Nesting beaches are essential for species perpetuation, as females return to their natal sites to lay eggs [17,18].

Sea turtles strongly contribute to ecosystem stability by regulating marine biomass and maintaining coral reef health [19,20]. They also serve as bioindicators, reflecting environmental conditions through their population dynamics, health, and behavior. Declines in their numbers often signal habitat degradation, pollution, or shifts in food availability due to anthropogenic disturbances [19,20].

Trophic interactions further highlight their ecological importance. *Chelonia mydas*, for instance, controls algal growth on coral reefs, preventing overgrowth that could smother corals. Benthic feeders such as *Ca. caretta* redistribute nutrients by disturbing the substrate while foraging, facilitating organic matter recycling [21,22]. Additionally, nest excavation aerates beach sediments and enriches them with nutrients from unhatched eggs. However, sea turtles face escalating threats from human activities and environmental changes, compromising their survival [21,22].

Oceanic and pelagic zones are crucial for juvenile development, offering abundant plankton and protection from open-sea predators. Ocean currents, such as the Gulf Stream and the Brazil Current, further aid in nutrient transport, supporting their growth [7]. Coastal areas and coral reefs, in turn, provide key foraging and nesting sites, with abundant food sources, such as sponges and algae, and suitable substrates for egg incubation [23]. However, these habitats are increasingly threatened by pollution, habitat destruction, and human activities, including unregulated tourism and coastal development [24,25].

Sea turtles interact with a diverse range of marine organisms, further reinforcing their ecological significance. During their pelagic phase, they rely on phytoplankton and zooplankton, which sustain various predatory species, including fish and invertebrates that serve as prey [26]. By feeding jellyfish and sponges, they help regulate these populations, preventing imbalances in coral reef ecosystems [27]. In reef and coastal areas, they engage in symbiotic relationships with cleaner fish and crustaceans, which remove parasites from their skin, promoting overall health [28].

Additionally, sea turtles host epibiont communities-organisms that colonize their shells and skin. The diversity and composition of these epibionts provide insights into turtle migratory patterns, habitat use, diet, and overall health. Barnacles, for instance, serve as biological markers of their movement across different marine regions [28]. Table 2 summarizes the primary ecological roles, habitats, and threats faced by sea turtles.

**Table 2.** Ecological roles, main habitats, and threats of sea turtles.

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| **Aspect** | **Description** |
| Life expectancy | 50 to 100 years |
| Habitat | Tropical, subtropical, temperate and subpolar waters; juveniles in oceanic/pelagic zones, adults in coastal/benthic zones. |
| Ecological niche | Biomass control, preservation of coral reefs, bioindicators of environmental quality. |
| Trophic dynamics | They regulate jellyfish, algae and sponges, as well as algae on reefs. |
| Sedimentary dynamics | They distribute nutrients and recycle organic matter by feeding on benthic organisms. |
| Impact on soil fertility | Sediment aeration and soil fertilization with nutrients from unhatched eggs. |
| Environmental threats | Pollution, environmental degradation, uncontrolled tourism and inadequate coastal occupation. |
| Importance of oceanic/pelagic zones | High availability of plankton and refuge from predators; influenced by ocean currents. |
| Importance of coastal zones/reefs | Ample supply of food and substrates for incubating eggs; threatened by degradation and pollution. |
| Interspecific interactions | They depend on phytoplankton and zooplankton; they interact with cleaner fish and crustaceans on the reefs. |
| Epibionts | Epibionts such as barnacles indicate migratory movements, diet, behaviors and health of turtles. |

**4. IMPACTS OF GLOBAL WARMING ON SEA TURTLES**

The increase in global temperature and the resulting environmental changes directly affect sea turtles at various stages of their life cycle, disrupting reproduction, migration, and habitat availability, thereby posing significant challenges to their conservation [29]. Rising temperatures influence embryonic development, altering the sex ratio and potentially compromising population structure. In line with this, Laloë et al. [30] demonstrated that rising incubation temperatures at Cape Verde led to a sharp decline in hatchling survival, particularly when sand temperatures exceeded 32.7°C, highlighting the direct impact of temperature rise on sea turtle reproductive success. Furthermore, rising sea levels lead to beach erosion and the loss of suitable nesting sites, reducing reproductive success [31]. Furthermore, rising sea levels lead to beach erosion and the loss of suitable nesting sites, reducing reproductive success [32].

Climate change also impacts ocean currents by warming waters, reducing their density and salinity due to the influx of freshwater from melting ice, which weakens thermohaline circulation [31,32,33]. Alterations in the Atlantic Meridional Overturning Circulation (AMOC), which redistributes heat between the tropics and the North Atlantic, could result in harsher winters in Europe and rising sea levels along the U.S. East Coast. Additionally, shifts in wind patterns and an increase in extreme events, such as *El Niño* and *La Niña*, affect the distribution of heat and nutrients, thereby threatening marine ecosystems. These changes in ocean currents disrupt the migratory patterns of turtles, hindering their movement between feeding and breeding areas [32]. Ocean warming further threatens food availability, impacting the survival of both juveniles and adults. Given these challenges, the implementation of effective conservation strategies is essential for the long-term preservation of these species [32,33].

Recent studies have tested practical conservation strategies aimed at mitigating the thermal impacts of climate change on sea turtle nests. Hill et al. [34] evaluated the effectiveness of artificial shading and nest watering at Playa Grande, Costa Rica, in reducing sand temperature and enhancing nest conditions. Their results demonstrated that shading was the most effective method, decreasing incubation temperatures by up to 4°C, while watering showed shorter-term effects but improved sand moisture content, an important factor for embryonic development and hatching success. These findings support the use of combined mitigation approaches tailored to local environmental conditions and species-specific nesting depths, offering promising strategies to counteract the feminization of hatchlings and decline in reproductive success under future climate scenarios.

**4.1 CHANGE IN THE RATIO OF MALES AND FEMALES**

The sex determination of sea turtles is governed by the egg incubation temperature, a phenomenon known as temperature-dependent sex determination (TSD) [35]. Empirical studies demonstrate that incubation temperatures exceeding 29°C bias hatchling sex ratios toward females, whereas temperatures below this threshold favor male development. As global temperatures continue to rise due to anthropogenic greenhouse gas emissions, this thermal sensitivity is driving a progressive feminization of sea turtle populations, leading to a skewed sex ratio [35].

This imbalance arises from the pivotal role of temperature in gonadal differentiation during embryogenesis [36]. During the thermosensitive period, which occurs in the second third of incubation (ca. 30-45 days), temperature modulates the enzymatic pathways responsible for steroidogenesis and gonadal fate determination. Elevated temperatures upregulate estrogen synthesis, promoting ovarian differentiation, whereas cooler conditions favor testicular development [36]. Even minor thermal fluctuations within the nest microenvironment can therefore influence the resultant sex ratio of a clutch, with potential long-term consequences for population viability. This phenomenon has been empirically modeled in different nesting regions.

Laloë et al. [37] analyzed the impact of rising temperatures on *Ca. caretta* hatchling sex ratios in Cape Verde, where sand temperature varies between light (high albedo) and dark (low albedo) beaches. Using a 250-year dataset combining historical air temperatures (1854–2013) with IPCC projections (SRES A2), they found that current feminization reaches 70.1% on light beaches and 93.5% on dark ones, with projections of 97.8% and 99.5%, respectively, by 2100. Embryonic metabolic heat raised nest temperatures by 0.5°C, intensifying skewed ratios. Despite this, operational sex ratios remained balanced (42.9% female historically) due to higher male breeding frequency and delayed maturity, although models predict 96.1% feminization by 2150. Short-term population growth may benefit from increased female recruitment, but long-term fertility risks emerge if male scarcity persists. The study emphasizes the value of light-colored beaches as male-producing refugia and advocates for mitigation strategies such as nest shading and translocation, alongside integrated monitoring of sex ratios and population dynamics under climate change.

Nesting site characteristics are key determinants of nest temperature, influenced by sediment composition and grain size, nest depth, and vegetation cover [34]. Darker, coarser sediments retain more heat, elevating incubation temperatures and favoring female-biased hatchling production [38]. Shallower nests are more thermally variable and generally warmer than deeper ones [36]. Vegetation provides shade, mitigating excessive heating and increasing the proportion of male hatchlings [39].

Sex ratio imbalances threaten population viability by limiting genetic diversity and reducing fertilization rates [39]. A predominantly female population may struggle to maintain reproductive pairings, while low genetic variability undermines resilience to diseases and environmental changes. Anthropogenic pressures including habitat destruction, pollution, and bycatches exacerbate these risks. In extreme cases, local populations may face functional extinction, disrupting marine ecosystems where sea turtles play essential roles in benthic regulation and coral reef health [40].

Addressing these challenges requires the implementation of targeted mitigation strategies, including the protection of nesting habitats, artificial regulation of nest temperatures, and public awareness initiatives to curb greenhouse gas emissions. Without effective interventions, the progressive loss of viable populations may push sea turtles toward extinction [36,40].

Lamont et al. [41] examined the incubation environment of loggerhead sea turtle (*Ca. caretta*) nests in Northwest Florida, a genetically distinct and threatened subpopulation. The study measured internal and external nest temperatures across multiple beaches, revealing variations influenced by geographic location, depth, and proximity to the Apalachicola River. Mean monthly sand temperatures remained below 29°C, suggesting a higher proportion of male hatchlings compared to Florida’s Atlantic coast, where warmer temperatures predominantly yield females. Incubation duration correlated with sand temperature, with notable differences observed along the vertical beach profile. These findings underscore the ecological importance of this subpopulation in maintaining sex ratio diversity, particularly under climate change scenarios that may exacerbate female-biased sex ratios. To mitigate these threats, adaptive strategies such as nest relocation, beach shading, and habitat restoration could help stabilize sex ratios, while long-term monitoring should guide dynamic conservation efforts [42].

**4.2 REDUCTION OF SPAWNING AREAS**

The main sea turtle nesting areas in Brazil encompass the northern coastline of Bahia, Sergipe, Espírito Santo, and oceanic islands such as Trindade and Fernando de Noronha [23]. Species such as *C. mydas*, *C. caretta*, and *E. imbricata* rely heavily on these regions for reproduction, yet face significant threats, including pollution, bycatch, and environmental changes that hinder hatching success [43]. According to the Tamar Project [23], the number of nests per season varies by species, with approximately 10,500 for *L. olivacea*, 4,000 for *C. mydas*, and about 9,000 for *Ca. caretta*. Moreover, global temperature rise is driving sea level rise and increasing the frequency of extreme weather events, such as storms and hurricanes, which compromise nesting beaches through erosion and nest destruction.

Rising sea levels significantly reduce the availability of suitable nesting sites, with projections indicating that up to half of the currently available nesting areas may disappear as sea levels continue to rise [43,44,45]. This effect is particularly severe on islands, where relocation to higher ground is not possible, and in regions with artificial barriers, such as seawalls, roads, and urban infrastructure, that prevent natural beach migration, a phenomenon known as "coastal squeeze." Coastal squeeze occurs when the advancing sea forces the coastline inward, but human-made structures restrict this natural movement, leading to the progressive loss of nesting habitats [45]. In southeastern Brazil, Costa et al. [44] demonstrated that severe erosion, defined as shoreline retreat exceeding 3 meters per year, and urbanization significantly reduce nesting activity of *Ca. caretta*. Their study found that only 6% of recorded nests occurred in heavily eroded areas, while nest-free sectors were more likely to exhibit such conditions, indicating active avoidance. Additionally, nesting was concentrated in low-urbanized zones, and false crawls were more frequent in developed areas, evidence of anthropogenic disruption. The authors advocate for nature-based restoration and strategic nest relocation as urgent conservation measures.

In the coming decades, this impact is expected to intensify due to population growth and the significantly higher population densities along coastal areas compared to the global average [45]. This habitat loss has severe consequences for the reproductive success of nesting females, further threatening the long-term viability of sea turtle populations. Although still located within available nesting regions, sea turtle nests are increasingly vulnerable to rising sea levels, particularly when rising groundwater levels cause flooding from below. Some species are more vulnerable than others, such as *C. mydas*, *Dermochelys coriacea*, and *C. caretta*, which nest closer to the high tide line compared to other populations on the same beaches [46]. This phenomenon is not limited to Brazil. Studies from different regions of the world have shown that sea level rise poses a widespread and escalating threat to nesting habitats.

Fish et al. [47] employed GIS modeling to predict the impacts of sea level rise on sea turtle nesting beaches in Bonaire, estimating losses of up to 50% of total beach area and 52% of optimal nesting habitat under high sea level rise scenarios. Low-lying, narrow beaches, particularly those adjacent to hotels and salt lakes, were identified as the most vulnerable due to their limited capacity for inland retreat, underscoring the urgent need for integrated coastal planning and setback policies. Similarly, Fuentes et al. [48] utilized 3D elevation models to assess the potential impacts on green turtle (*Chelonia mydas*) nesting sites in the northern Great Barrier Reef. Their projections indicated habitat losses of up to 38%, with additional threats from storm-induced wave run-up exacerbating egg mortality rates.

On Bioko Island, Equatorial Guinea, Veelenturf et al. [49] projected nesting habitat losses of up to 62% between 2046 and 2065, and up to 87% by 2100 due to rising sea levels. Green turtles, which prefer narrow, steep beaches, were found to be more vulnerable than leatherbacks, which nest on broader, flatter beaches. Alarmingly, the least vulnerable site (Beach D) is currently under threat from human development. The study also documented shifts in nesting behavior, such as increased nesting closer to the high tide line, elevating the risk of egg inundation and emphasizing the need for immediate conservation interventions.

Wiggins et al. [39] investigated artificial shading as a climate adaptation strategy for green turtles on Ascension Island. The intervention lowered incubation temperatures by up to 1.2°C, increased hatching success by approximately 23% on warmer beaches, and enhanced male hatchling output by up to 12% on cooler beaches. While promising, the large-scale implementation of this technique poses logistical challenges and may be more feasible for smaller rookeries. Mitigation strategies proposed by Fuentes et al. [48] include the construction of seawalls, beach nourishment, dune restoration, and the enforcement of zoning regulations.

**4.3 CHANGES IN OCEAN CURRENTS AND MIGRATION PATTERNS**

Climate change is profoundly altering oceanic systems, disrupting marine current dynamics and, consequently, affecting the habitat and life cycle of sea turtles. The rise in global temperatures, driven by excessive greenhouse gas emissions [11], has led to ocean warming and shifts in current patterns, factors that play a critical role in the distribution and migratory behavior of these species [43].

Sea turtles, such as *Ca. caretta*, depend on ocean currents for dispersal and migration between feeding and breeding grounds [50]. However, as global warming intensifies or modifies these currents, species movement, resource availability, and population connectivity may be severely compromised. Additionally, fluctuations in water temperature directly influence epibiont communities associated with sea turtles, potentially increasing epibiotic loads. This, in turn, elevates locomotion costs and reduces survival rates [50].

The green turtle (*C. mydas*) has a prolonged life cycle, characterized by late sexual maturation and extensive migrations exceeding 1,500 km between feeding and nesting areas [50,51]. However, climate change-induced shifts in oceanic circulation may disrupt food supply chains and hinder migratory routes, jeopardizing population viability. Furthermore, the philopatric behavior of nesting females, which return to specific beaches to lay eggs, may be affected by altered ocean currents, making adaptation to environmental changes increasingly challenging [51].

Water temperature and salinity are key determinants of sea turtle migration. Rising ocean temperatures and shifts in salinity gradients can force turtles to seek alternative feeding and breeding sites, often resulting in interspecies competition and resource scarcity [52]. Moreover, food availability is directly linked to nutrient and plankton transport, both of which may be redistributed unevenly due to ocean current alterations, with cascading effects on sea turtle populations and associated marine ecosystems [53].

Juvenile turtles rely on pelagic environments before transitioning to coastal habitats, and disruptions in marine currents can significantly impact their development and growth [54]. Furthermore, changes in the larval transport of marine organisms, which constitute a critical component of juvenile turtle diets, may reduce food availability and compromise survival rates [54]. In this context, the stability of sea turtle populations is increasingly at risk, as reduced genetic variability heightens the likelihood of local extinctions [55].

Given these challenges, conservation strategies must integrate climate change mitigation efforts to safeguard sea turtle populations. Protective measures such as nesting site preservation, sand temperature monitoring, and bycatch reduction are essential to minimizing the impacts of global warming and ensuring the long-term survival of these highly migratory species [56].

Shillinger et al. [57] conducted a multi-year satellite tracking study of 46 female leatherback turtles (Dermochelys coriacea) nesting at Playa Grande, Costa Rica, the largest remaining rookery in the eastern Pacific. The study revealed a consistent southbound migratory corridor extending from the nesting beach to the South Pacific Gyre, documented over 12,095 tracking days (2004–2007). Post-nesting migrations were highly directed, with turtles crossing dynamic equatorial currents at rapid speeds (c.a. 42.9 km/day) before dispersing into the oligotrophic waters of the gyre (c.a. 23.8 km/day). Migration routes were strongly shaped by ocean currents, and turtles displayed compensatory movements to maintain a southward trajectory, suggesting precise navigation potentially guided by geomagnetic cues. Unlike other populations that follow more variable routes, this eastern Pacific group relies on predictable pathways, making it particularly vulnerable to spatially concentrated threats. The study identified two critical areas of high use: a migratory corridor between 12°N and 5°S, where seasonal aggregations occur from February to April, and low-productivity foraging grounds in the South Pacific Gyre. The authors highlight the need for transboundary conservation strategies, including dynamic time-area fishery closures, improved bycatch monitoring, and international collaboration through initiatives such as the Eastern Tropical Pacific Seascape, to mitigate fisheries interactions and support the recovery of this critically endangered population.

**4.4 ADDITIONAL CLIMATE-INTENSIFIED THREATS**

Anthropogenic activities represent one of the primary threats to sea turtle conservation in Brazil and globally. In addition to environmental degradation, ocean pollution, incidental capture, and unregulated coastal development, artificial light pollution significantly disrupts sea turtle population dynamics [58]. The situation is exacerbated during the summer months when sea turtles are actively reproducing, and human presence on beaches increases. The expansion of urban areas and the development of tourism infrastructure along the coast further intensify these pressures, severely impacting turtle populations [59].

A particularly critical factor in this context is artificial coastal lighting, which disrupts the natural migration of hatchlings to the ocean. Light pollution interferes with the visual cues that guide neonates, heightening their vulnerability to predation and reducing their chances of survival [58]. Ongoing nest monitoring during the hatching season is crucial to mitigate the adverse effects of light pollution and other environmental factors that may hinder hatchlings' migration. Additionally, Tapavicsky et al. [60] emphasize that waste accumulation in nesting areas along the Ipojuca coastline poses a significant threat to sea turtle survival, compromising nest integrity and hatchling health. Discarded materials such as plastics, bottles, and fishing nets can obstruct the path to the ocean, exacerbating the challenges faced by the turtles [60].

In addition to light pollution and waste accumulation, the expansion and intensification of fishing activities over recent decades have placed immense pressure on marine ecosystems, leading to high rates of incidental sea turtle capture [59]. This is especially problematic with the use of gillnets, pelagic longlines, and trawl nets targeting fish and shrimp. Many turtles, unable to surface for air, become unconscious and perish by drowning. Moreover, artisanal fishing, a traditional practice in some regions of Brazil, also contributes to incidental turtle captures [59]. To address these mounting challenges, the implementation of effective public policies, the strengthening and establishment of conservation units, and the development of integrated environmental management and educational strategies are essential for raising public awareness about the critical need to preserve sea turtle populations [58].

Further compounding these threats is the increase in greenhouse gas emissions, which contributes to ocean acidification [61]. As atmospheric carbon dioxide (CO₂) is absorbed by the oceans, it forms carbonic acid, which dissociates into hydrogen ions (H⁺) and bicarbonate ions (HCO₃⁻), lowering the pH of ocean water. This reduction in pH, in turn, diminishes the availability of carbonate ions (CO₃²⁻), which are essential for the calcification of marine organisms, thereby jeopardizing biodiversity and the health of coastal ecosystems. Ocean acidification also disrupts vital physiological processes, such as internal pH regulation and reproduction, impacting species survival and the stability of marine food webs. Over time, the continued decrease in ocean pH levels may lead to the degradation of coral reefs and reduce the availability of calcium carbonate, leading to significant ecological and socioeconomic consequences [61].

**5. conclution**

This review underscores the significant threats climate change poses to sea turtle populations, particularly through rising temperatures, habitat loss, and disrupted oceanic currents. The findings support the hypothesis that increased greenhouse gas emissions drive global warming, leading to female-biased sex ratios, reduced nesting sites, and altered migration patterns that compromise population viability.

Mitigation strategies, including nesting site protection, sand temperature monitoring, and bycatch reduction, are essential to minimizing these impacts. Strengthening conservation policies and reducing greenhouse gas emissions are critical for ensuring long-term species resilience. Future research should explore adaptive strategies to enhance sea turtle survival amid accelerating environmental changes.

Disclaimer (Artificial intelligence)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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