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Impact of nano plastics on the physiological and metabolic integrity of mangrove ecosystems

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Abstract

Mangrove forests represent a critical ecological interface, providing indispensable services such as coastal stabilization, nutrient cycling, and massive carbon sequestration. However, the pervasive influx of plastic debris into these intertidal zones has introduced a significant environmental stressor: Nano plastics. These particles, typically defined as plastic fragments smaller than 1000 nanometers, exhibit unique physicochemical properties that allow them to bypass biological barriers and interact with plant physiology at the cellular and molecular levels. This research examines the effects of Nano plastics on mangrove physiology, examining the mechanisms of uptake, translocation, and subsequent systemic disruption. Evidence suggests that Nano plastics induce a cascade of physiological impairments, including the inhibition of photosynthesis through both light-shielding and genetic downregulation, the promotion of oxidative stress, and the alteration of ionic and hormonal homeostasis. Furthermore, the specialized morphological adaptations of mangroves, such as salt glands and complex aerial root systems, serve as hotspots for Nano plastic accumulation, fundamentally altering the plant's adaptive responses to salinity and nutrient acquisition. By synthesizing data from multiple species-specific studies, this report elucidates the profound threat Nano plastic pollution poses to the long-term survival and ecological function of mangrove forests.

Keywords: Nano plastic accumulation, mangrove forests, mangrove ecosystems

Introduction

Plastic pollution has emerged as one of the most critical global environmental challenges, threatening the sustainability of both aquatic and terrestrial ecosystems (Pulusu *et al.*, 2025) ^[12]. Mangrove forests are recognized as significant global sinks for plastic debris due to their complex geomorphology and the physical filtering capacity of their root structures (He *et al.*, 2025) ^[6]. Within these environments, larger plastic items undergo continuous degradation through a combination of physical, chemical, and biological processes (Wang *et al.*, 2026) ^[15]. This fragmentation leads to the formation of microplastics and, ultimately, Nano plastics, which are defined as particles smaller than 1000 nm (Wang *et al.*, 2026) ^[15]. Nano plastics are particularly concerning because their small size and high surface area-to-volume ratio increase their chemical reactivity and bioavailability (Arini *et al.*, 2023) ^[4]. These minute particles can easily penetrate biological barriers that usually exclude larger debris (Pulusu *et al.*, 2025) ^[12]. Once internalized, Nano plastics interfere with a wide range of metabolic, physiological, and biochemical processes (He *et al.*, 2025) ^[6]. The pervasive presence of Nano plastics in mangrove sediments poses a fundamental threat to the physiological integrity of these essential coastal forests (Aguirre-Sanchez *et al.*, 2024) ^[1]. Understanding the specific interactions between Nano plastics and mangrove plant systems is vital for predicting ecosystem health in the Anthropocene (Wang *et al.*, 2026) ^[15].

Research Methodology

This study employs a systematic review methodology to synthesize quantitative and qualitative data from multiple species-specific studies regarding the impact of Nano plastics on mangrove ecosystems. Rather than conducting primary experimental fieldwork, the authors aggregate existing research to trace the cascade of metabolic disruptions initiated by Nano plastic deposition, analyzing pathways from physical surface obstruction to deep

oxidative perturbations and hormonal imbalances. The methodology involves a comparative analysis of uptake mechanisms specifically distinguishing between root-mediated absorption and foliar capture in salt-secreting versus salt-excluding species and evaluates physiological consequences such as photosynthetic inhibition, iron dyshomeostasis, and "Trojan Horse" toxicity across varied mangrove habitat zones.

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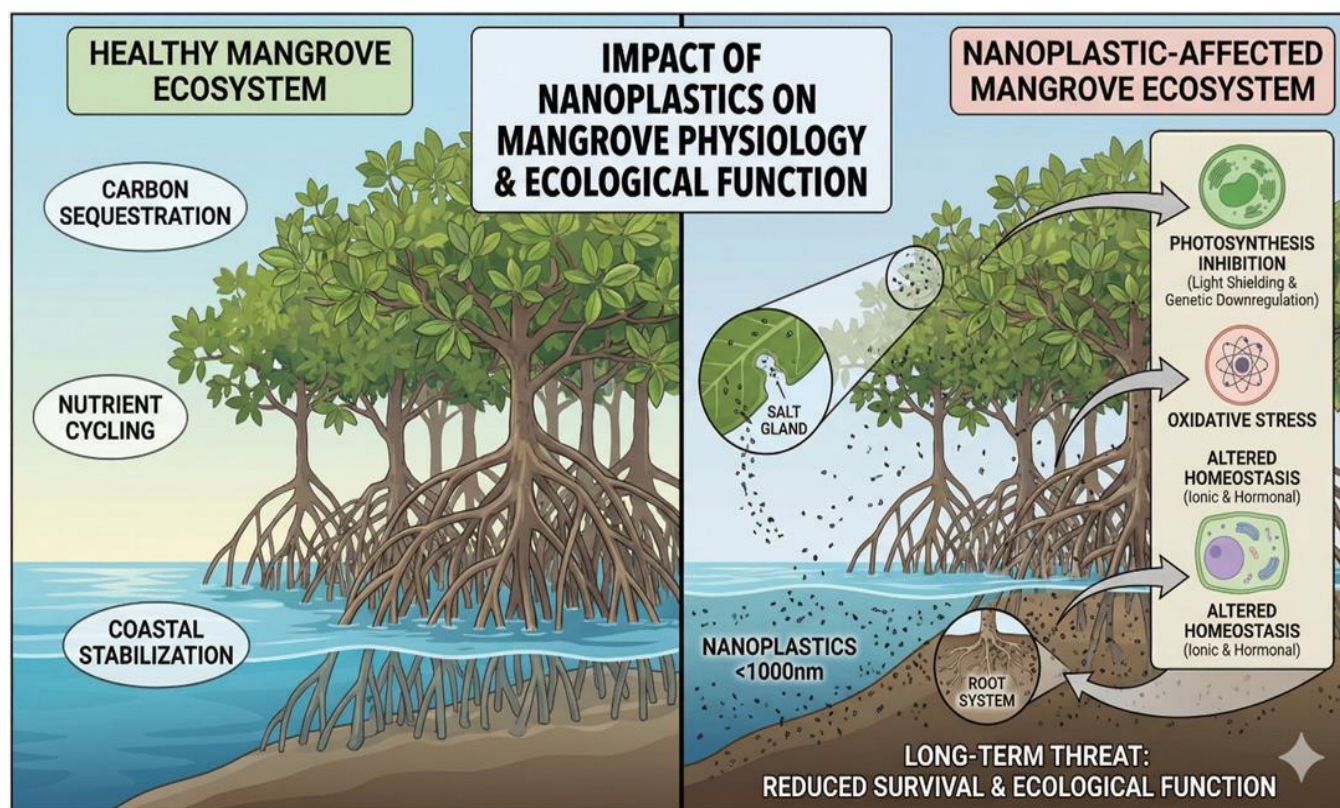


Fig 1: Overview of impact of Nano plastics on mangrove physiology & ecological function

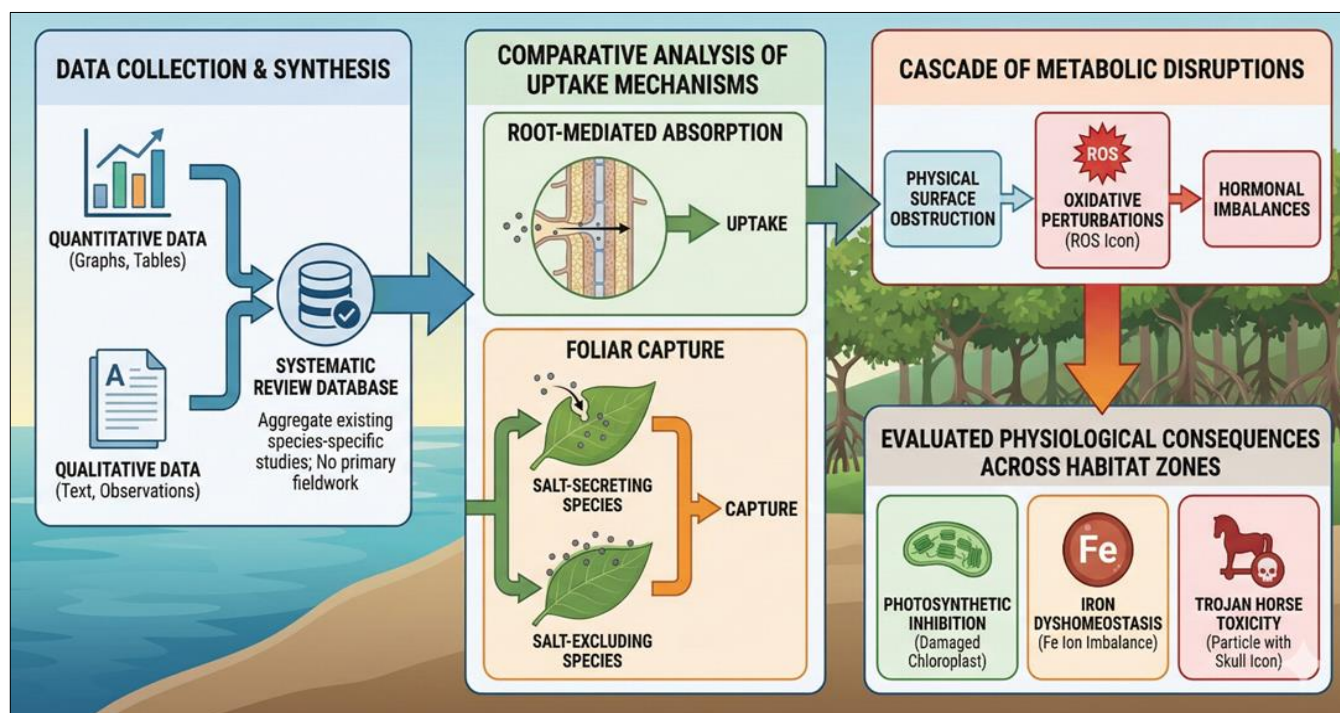


Fig 2: Overview of Research Methodology

Environmental fragmentation and distribution dynamics

The transition from Macro plastics to Nano plastics in mangrove swamps is accelerated by intense environmental exposure (Wang *et al.*, 2026) ^[15]. Ultraviolet radiation from sunlight, combined with high temperatures, causes the

photo-oxidation and weakening of polymer bonds (Lin & Yu, 2025) ^[8]. Mechanical stress from tidal reciprocating currents further facilitates the physical abrasion of plastics against sand and other debris (He *et al.*, 2025) ^[6]. Chemical weathering in the brackish environment degrades the

molecular weight of the plastics, making them brittle and prone to fragmentation (Arini *et al.*, 2023) ^[4]. Biological activity also contributes to this fragmentation, as microorganisms colonize plastic surfaces and utilize hydrocarbons as energy sources (Ma *et al.*, 2025) ^[9]. The resulting nanoplastics possess high mobility, allowing them to distribute throughout all layers of the sediment column (He *et al.*, 2025) ^[6]. In some coastal estuaries, the abundance

of these particles in mangrove sediments is three to five times higher than in adjacent bare mudflats (He *et al.*, 2025) ^[6]. Interior forest habitats often exhibit higher accumulation rates than edge zones due to reduced wave energy and complex root trapping (He *et al.*, 2025) ^[6]. Submerged leaves also act as dynamic sinks, showing diurnal fluctuations in particle abundance driven by hydrodynamic forces (Wang *et al.*, 2024) ^[16].

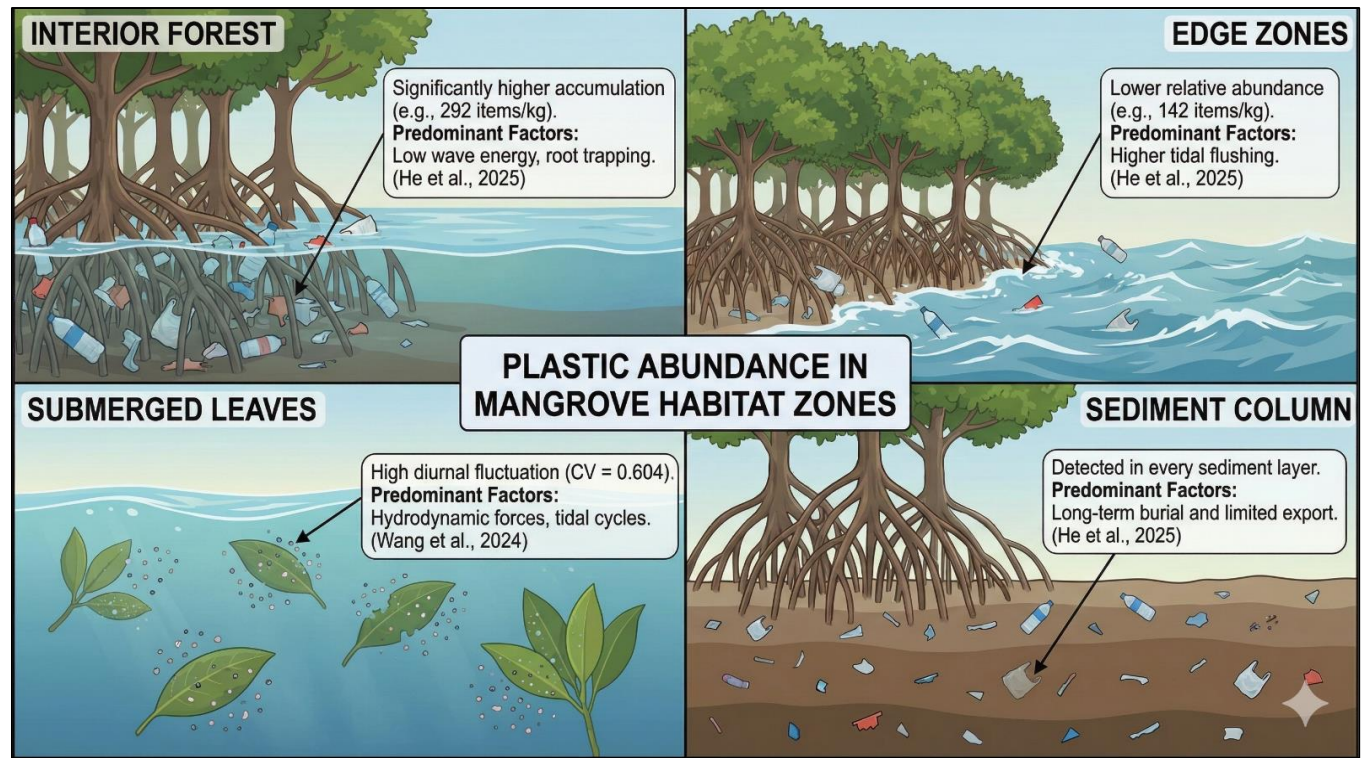


Fig 3: Overview of plastic abundance in mangrove habitat zones

Table 1: Plastic abundance in mangrove habitat zones

Habitat Zone	Plastic Abundance Characteristics	Predominant Factors	Reference
Interior Forest	Significantly higher accumulation (e.g., 292 items/kg)	Low wave energy, root trapping	(He <i>et al.</i> , 2025) ^[6]
Edge Zones	Lower relative abundance (e.g., 142 items/kg)	Higher tidal flushing	(He <i>et al.</i> , 2025) ^[6]
Submerged Leaves	High diurnal fluctuation (CV = 0.604)	Hydrodynamic forces, tidal cycles	(Wang <i>et al.</i> , 2024) ^[16]
Sediment Column	Detected in every sediment layer	Long-term burial and limited export	(He <i>et al.</i> , 2025) ^[6]

Mechanisms of Nano plastic Uptake and Internal Translocation

Mangrove plants have evolved specialized pathways for managing salt and water, which nanoplastics exploit to enter the plant system (Wang *et al.*, 2026) ^[15]. These pathways involve both root-mediated absorption from the soil and foliar-mediated capture from the atmosphere or water column (Wang *et al.*, 2026) ^[15].

Root Absorption and Movement

Mangrove roots are the primary site for the uptake of nanoplastics found in the rhizosphere (Chai *et al.*, 2023) ^[5]. Particles can be adsorbed onto root hairs, where they interact with the hydrophobic surfaces of the epidermis (He *et al.*, 2025) ^[6]. Internalization occurs via two main routes: the apoplastic and symplastic pathways (Zhao *et al.*, 2024) ^[21]. The apoplastic pathway involves passive transport

through the cell wall and intercellular spaces (Qin *et al.*, 2024) ^[13]. In contrast, the symplastic pathway requires particles to cross the plasma membrane, often through endocytosis or specialized transporter proteins (Zhao *et al.*, 2024) ^[21]. Nano plastics can also enter the vascular system through "crack-entry" modes, where mechanical damage or lateral root emergence creates temporary openings in the endodermis (Yin *et al.*, 2021) ^[18]. Once inside the root cortex, the particles move into the xylem and are translocated upward to the stems and leaves by transpirational pull (He *et al.*, 2025) ^[6]. The surface charge of the nanoparticles significantly influences these uptake rates (Zhao *et al.*, 2024) ^[21]. Positively charged particles show higher initial attraction to cuticles but may have restricted movement compared to negatively charged ones (Zhao *et al.*, 2024) ^[21].

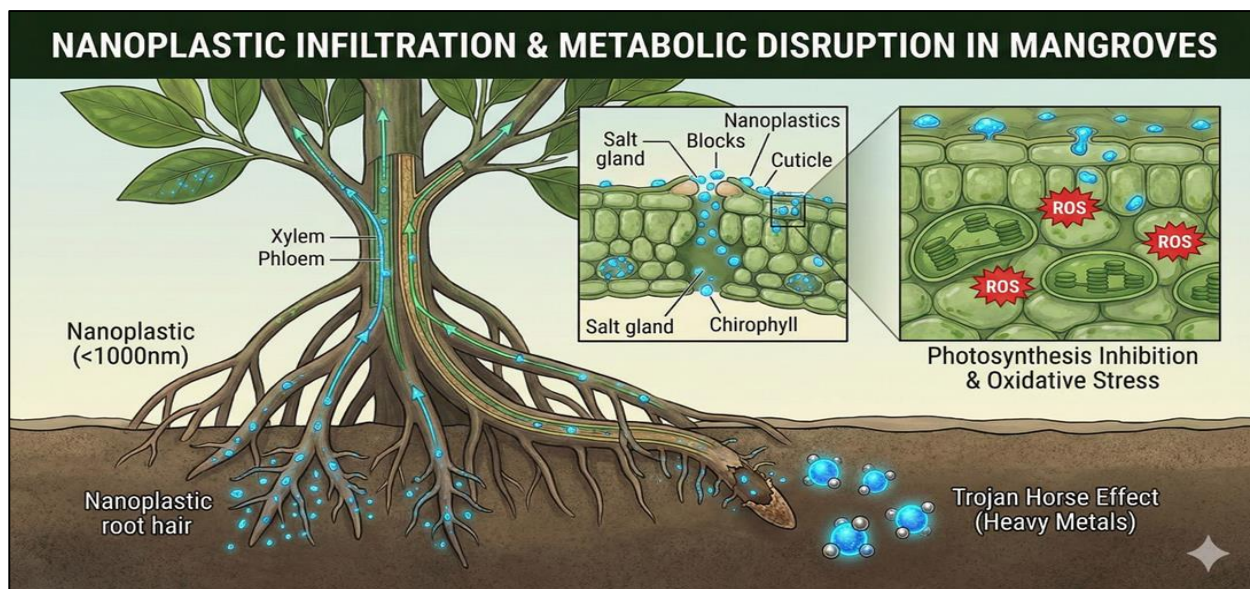


Fig 3: Overview of Nano infiltration & metabolic disruption in mangroves

Foliar Capture and Salt Gland Hotspots

Foliar uptake is a critical pathway for Nano plastics, particularly for species that utilize salt glands for ion regulation (Wang *et al.*, 2026) ^[15]. Atmospheric Nano plastics are deposited on leaf surfaces, where they adhere to the epidermal wax (Wang *et al.*, 2026) ^[15]. In salt-secreting species like *Aegiceras corniculatum*, the salt glands act as accumulation hotspots (Wang *et al.*, 2026) ^[15]. These glands exhibit particle densities over 50% higher than adjacent epidermal cells (Wang *et al.*, 2026) ^[15]. This preferential retention is driven by the glandular micromorphology and interfacial adhesion mediated by π - π stacking (Wang *et al.*, 2026) ^[15]. Importantly, these glands provide entry points for Nano plastic internalization, facilitating rootward translocation through the phloem (Wang *et al.*, 2026) ^[15]. In contrast, salt-excluding species such as *Kandelia candel* experience complete interception by the thick cuticular layer, restricting the particles to the leaf surface (Wang *et al.*, 2026) ^[15].

Physiological Disruption of Photosynthesis: Nano plastic

exposure leads to a significant decline in the photosynthetic capacity of mangroves (Chai *et al.*, 2023) ^[5]. This impairment is caused by a combination of physical interference with light harvesting and the metabolic disruption of enzymatic processes (Chai *et al.*, 2023) ^[5].

Chlorophyll Degradation

Nano plastics accumulated within tissues cause a decline in chlorophyll a and b concentrations, as well as carotenoid levels (Chai *et al.*, 2023) ^[5]. In *Kandelia obovata*, polyethylene and polypropylene Nano plastics have been shown to restrict chlorophyll synthesis and alter photochemical efficiency (Chai *et al.*, 2023) ^[5]. The reduction in chlorophyll content is often dose-dependent, leading to lower maximum photochemical efficiency (F_v / F_m) (Chai *et al.*, 2023) ^[5]. These changes disrupt the Electron Transport Chain (ETC) and limit the production of ATP and NADPH required for the Calvin cycle (Chai *et al.*, 2023) ^[5]. In some cases, Nano plastics cause more than a 30% decrease in plant biomass due to inhibited photosynthesis (Chai *et al.*, 2023) ^[5].

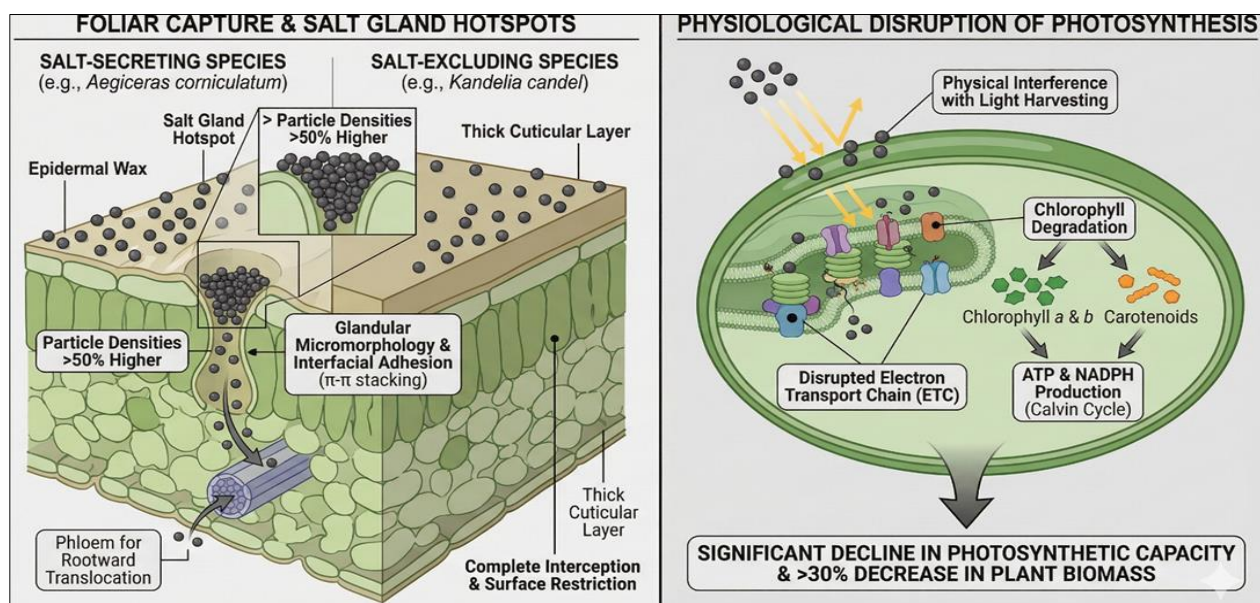


Fig 4: Overview of physiological disruption in mangrove transpirational and photosynthetic activity

Downregulation of carbon fixation genes

Beyond physical interference, Nano plastics cause deep-seated metabolic changes by altering the expression of genes involved in carbon fixation (Wang *et al.*, 2026) ^[15]. In salt-secreting mangroves, internalized Nano plastics trigger "dark reaction failure" (Wang *et al.*, 2026) ^[15]. This is characterized by the 35% to 68% downregulation of genes responsible for carbon fixation, such as OEE1, PQL2, and

FDX3 (Wang *et al.*, 2026) ^[15]. This molecular disruption prevents the plant from effectively converting atmospheric CO₂ into organic matter (Wang *et al.*, 2026) ^[15]. Furthermore, Nano plastics can alter leaf ionomers, particularly reducing magnesium and iron levels (Chai *et al.*, 2023) ^[5]. Magnesium is essential for chlorophyll synthesis, and its depletion directly hinders light absorption (Chai *et al.*, 2023) ^[5].

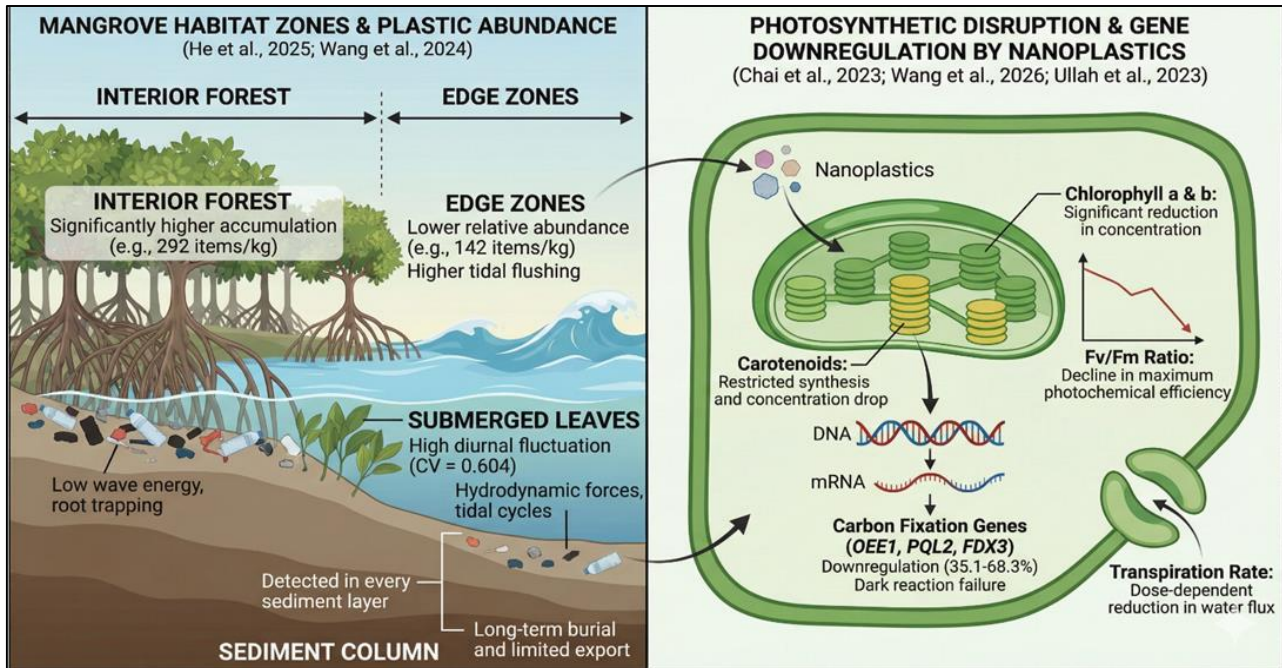


Fig 5: Disruption in carbon fixation gene and photosynthetic gene activity

Table 2: Role of Nano plastic in disruption in carbon fixation gene and photosynthetic gene activity

Photosynthetic Parameter	Effect of Nano plastic Exposure	Reference
Chlorophyll a & b	Significant reduction in concentration	(Chai <i>et al.</i> , 2023) ^[5]
Fv /Fm Ratio	Decline in maximum photochemical efficiency	(Chai <i>et al.</i> , 2023) ^[5]
Carbon Fixation Genes	Downregulation (35.1-68.3%)	(Wang <i>et al.</i> , 2026) ^[15]
Carotenoids	Restricted synthesis and concentration drop	(Chai <i>et al.</i> , 2023) ^[5]
Transpiration Rate	Dose-dependent reduction in water flux	(Ullah <i>et al.</i> , 2023) ^[14]

Induction of oxidative stress and antioxidant defense

The most common biochemical response to Nano plastic stress in mangroves is the excessive production of reactive oxygen species (ROS) (He *et al.*, 2025) ^[6]. This oxidative burst is a primary driver of Nano plastic-induced phytotoxicity (He *et al.*, 2025) ^[6].

ROS Generation and Lipid Peroxidation

Nano plastic particles stimulate the production of superoxide anions (O₂⁻), hydrogen peroxide (H₂O₂), and hydroxyl radicals within plant tissues (He *et al.*, 2025) ^[6]. These ROS molecules are highly reactive and cause the oxidation of lipids, proteins, and DNA (He *et al.*, 2025) ^[6]. Lipid peroxidation, measured by levels of malondialdehyde (MDA), is a hallmark of membrane damage (He *et al.*, 2025) ^[6]. Studies have shown that both root and leaf tissues of mangrove-like model systems exhibit significantly increased MDA levels upon exposure (He *et al.*, 2025) ^[6]. This oxidative damage can compromise organelle function, particularly in mitochondria and chloroplasts, leading to a decline in energy production (He *et al.*, 2025) ^[6]. In *Avicennia marina*, ROS accumulation in the roots is a primary symptom of polyethylene and polyamide stress (He

et al., 2025) ^[6].

Enzymatic Antioxidant Response

Mangroves attempt to neutralize ROS through an array of antioxidant defense mechanisms (Yildiztugay *et al.*, 2022) ^[17]. This involves the upregulation of enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) (Yildiztugay *et al.*, 2022) ^[17]. Non-enzymatic antioxidants like ascorbic acid (ASA) and glutathione (GSH) also play a vital role (Yildiztugay *et al.*, 2022) ^[17]. However, the response of these systems is often overwhelmed at high nanoplastic concentrations (Yildiztugay *et al.*, 2022) ^[17]. Chronic exposure eventually leads to a decrease in total antioxidant capacity and subsequent apoptosis or necrosis (Zhao *et al.*, 2024) ^[21].

Metabolic Reprogramming and Iron Dyshomeostasis

The internalization of Nano plastics has been shown to fundamentally rewire microbial and plant metabolic priorities (Zhao *et al.*, 2024) ^[21]. This is particularly evident in the disruption of iron and nitrogen cycles (Zhao *et al.*, 2024) ^[21].

Depletion of Intracellular Iron

Nano plastic internalization can deplete intracellular Fe^{2+} levels by approximately 25% (Zhao *et al.*, 2024) ^[21]. This triggers a compensatory 9.7-fold increase in siderophore synthesis to chelate extracellular iron (Zhao *et al.*, 2024) ^[21]. This iron starvation inactivates key regulators and diverts cellular energy away from nitrogen metabolism pathways (Zhao *et al.*, 2024) ^[21]. In mangroves, this disruption can lead to a decline in leaf and root ionomers (Chai *et al.*, 2023) ^[5]. Impaired synthesis of iron-dependent enzymes, such as nitrate reductase, further compromises plant health (Zhao *et al.*, 2024) ^[21]. This cascade establishes iron dyshomeostasis as a pivotal mechanism of Nano plastic

toxicity (Zhao *et al.*, 2024) ^[21].

Impact on nitrogen metabolism: Nitrogen limitation, resulting from nanoplastic-induced shifts, slows down plant growth (Chai *et al.*, 2023) ^[5]. Nanoplastics interfere with the abundance of nitrogen-metabolizing genes (Zhou *et al.*, 2024). This leads to a decreased efficiency in the assimilation of nitrogen from the soil (Zhao *et al.*, 2024) ^[21]. Such metabolic shifts compromise the overall ecosystem functionality and biomass production (Zhao *et al.*, 2024) ^[21]. In *Rhizophora mucronata*, propagules exposed to HDPE-MPs showed significantly higher protein carbonyl content (Alfara *et al.*, 2025) ^[3].

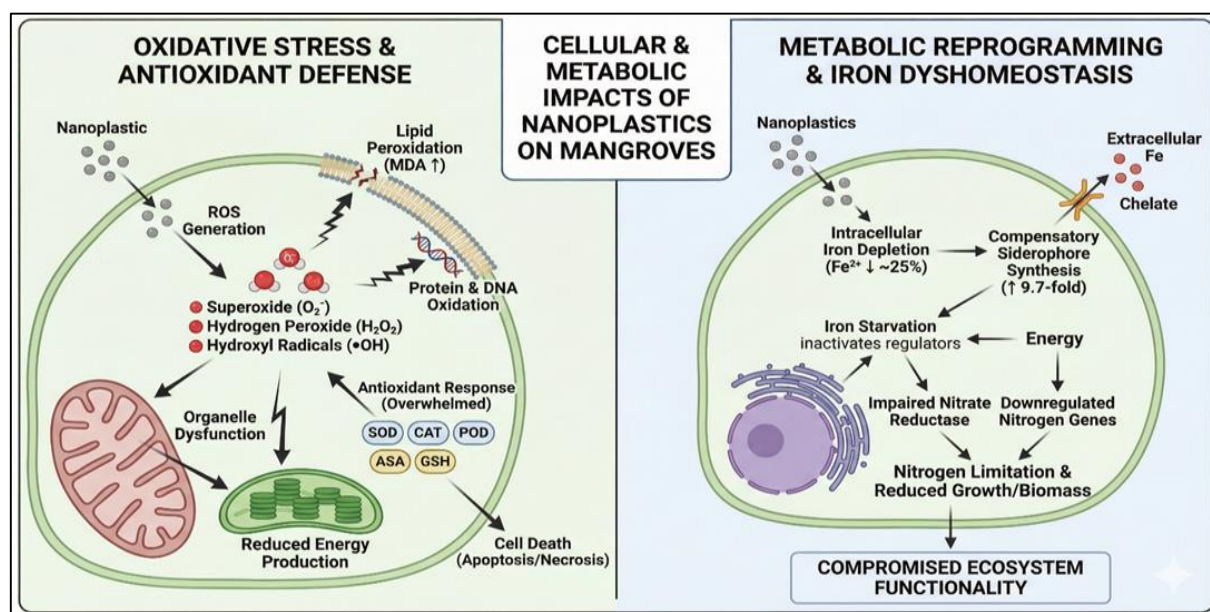


Fig 6: Overview of induction of oxidative stress and antioxidant defense in mangroves due to Nano plastic

Phytohormonal and Developmental Shifts

Phytohormones are the primary messengers controlling plant growth and stress responses (Ullah *et al.*, 2023) ^[14]. Their concentrations are frequently altered by Nano plastic exposure, affecting overall plant architecture (Ullah *et al.*, 2023) ^[14].

Auxin and Cytokinin Imbalance

Nano plastics interfere with the production and transport of auxin and cytokinin (Yin *et al.*, 2021) ^[18]. These hormones are essential for the regulation of root development (Yin *et al.*, 2021) ^[18]. Polystyrene Nano plastics have been reported to decrease the levels of these hormones, leading to a reduction in the formation of lateral roots and root hairs (Yin *et al.*, 2021) ^[18]. In mangroves, where specialized root structures are vital for stability in anoxic mud, this disruption can severely weaken the plant (Chai *et al.*, 2023) ^[5]. The inhibition of root elongation is a common morphological indicator of Nano plastic-induced stress (Chai *et al.*, 2023) ^[5].

Gibberellins and Lignin Synthesis

Other key hormones, such as gibberellins and salicylic acid, are also affected by Nano plastic exposure (Ullah *et al.*, 2023) ^[14]. Gibberellins, which regulate plant elongation, show reduced endogenous levels in the presence of Nano plastic stress (Ullah *et al.*, 2023) ^[14]. Salicylic acid is critical for maintaining cell permeability and nitrogen uptake, and

its reduction leads to impaired nutrient use efficiency (Ullah *et al.*, 2023) ^[14]. Additionally, Nano plastics can inhibit the synthesis of lignin, a crucial component of cell wall strength (Ullah *et al.*, 2023) ^[14]. Such changes in mangroves could lead to increased susceptibility to mechanical damage from waves and tides (Magdayo, 2024) ^[10].

Synergistic Toxicities and the "Trojan Horse" Effect

Nano plastics exhibit a high capacity to adsorb and transport other environmental pollutants (Arini *et al.*, 2023) ^[4]. This leads to synergistic toxic effects that are more severe than the impacts of the particles alone (Arini *et al.*, 2023) ^[4].

Heavy Metal Co-transport

The large surface area of Nano plastics allows them to serve as carriers for heavy metals such as cadmium, lead, and zinc (Arini *et al.*, 2023) ^[4]. In mangrove sediments, these contaminants are adsorbed onto the surface of Nano plastics and transported into plant tissues through the "Trojan Horse" effect (He *et al.*, 2025) ^[6]. This mechanism significantly increases the bioavailability of toxins (He *et al.*, 2025) ^[6]. For example, the combined exposure of mangrove seedlings to Nano plastics and cadmium resulted in aggravated root necrosis (He *et al.*, 2025) ^[6]. In *Avicennia marina*, trace metal accumulation is particularly high in reproductive tissues such as buds and embryos (He *et al.*, 2025) ^[6]. This may impair long-term population regeneration (He *et al.*, 2025) ^[6].

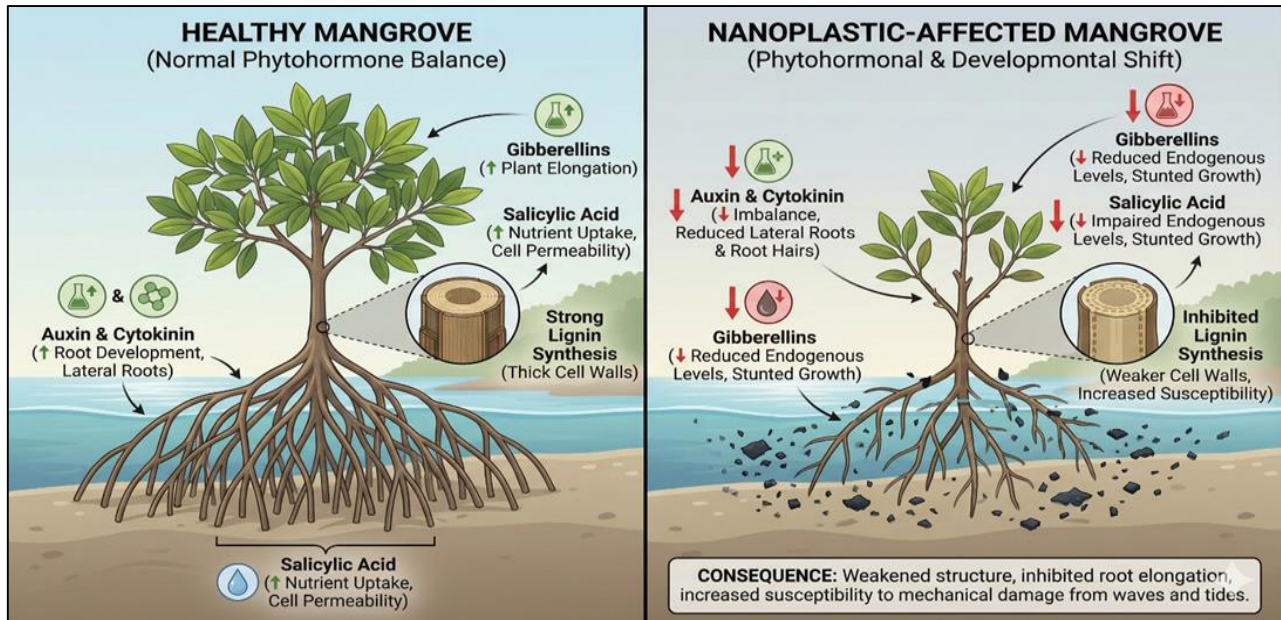


Fig 7: Overview of phytohormonal and developmental shifts in mangroves due to Nano plastic

Interaction with Climate Stressors

The physiological impact of Nano plastic pollution is compounded by climate-related stressors such as rising temperatures and fluctuating salinities (Perri *et al.*, 2025) ^[11]. Ocean warming has been shown to work synergistically with Nano plastic pollution to decrease photosynthetic

efficiency (Li *et al.*, 2024) ^[7]. Mangroves surviving in extreme environments are already near their physiological limits (Akram *et al.*, 2023) ^[2]. The added metabolic burden of Nano plastic-induced oxidative stress may compromise their overall resilience (Akram *et al.*, 2023) ^[2].

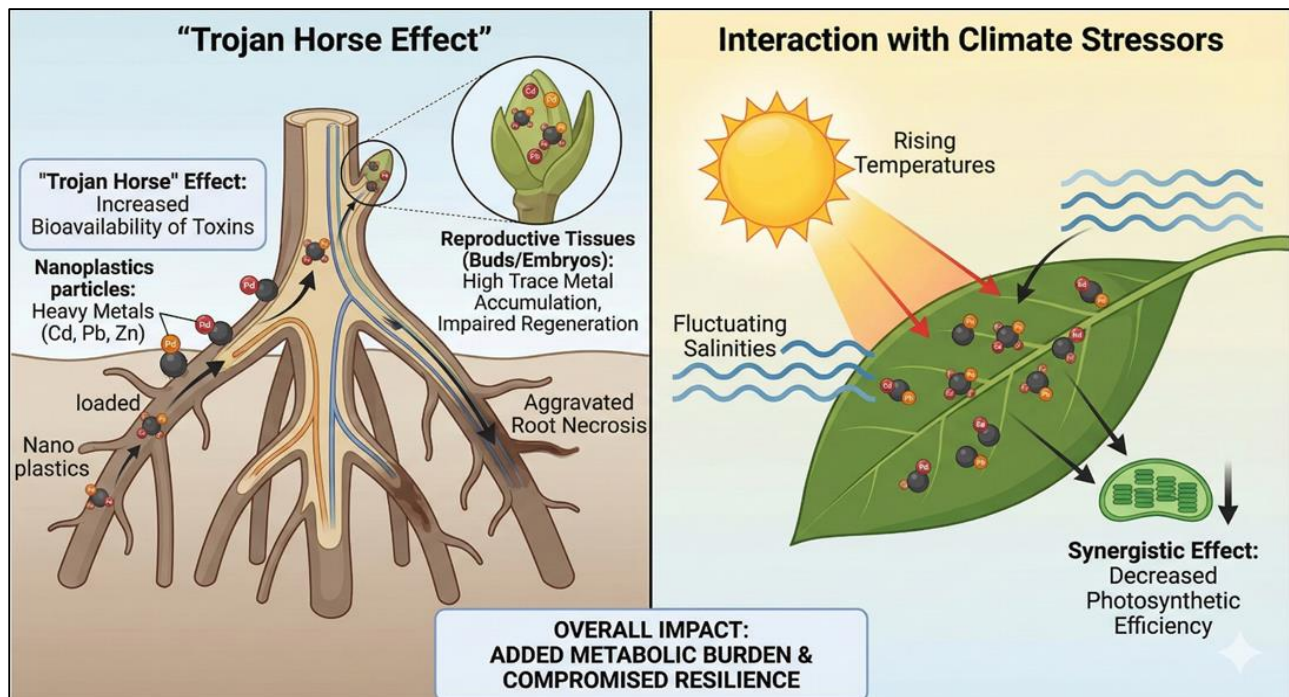


Fig 8: Overview of Synergistic Toxicities and the "Trojan Horse" Effect in Mangroves due to Nano plastic

Summary of species-specific physiological responses

Table 3: Summary of species-specific physiological responses

Species	Primary Absorption Route	Major Physiological Impairment	Reference
<i>Aegiceras corniculatum</i>	Leaf Salt Glands	35-68% downregulation of carbon fixation genes	(Wang <i>et al.</i> , 2026) ^[15]
<i>Kandelia candel</i>	Cuticular Adsorption	Light reaction failure due to photon shielding	(Wang <i>et al.</i> , 2026) ^[15]
<i>Avicennia marina</i>	Pneumatophores	High ROS accumulation and biomass stunting	(He <i>et al.</i> , 2025) ^[6]
<i>Rhizophora mucronata</i>	Prop Roots	78% decrease in survival rate under dual stress	(Alfajara <i>et al.</i> , 2025) ^[3]
<i>Kandelia obovata</i>	Root Epidermis	Energy charge deficit and restricted root growth	(Chai <i>et al.</i> , 2023) ^[5]

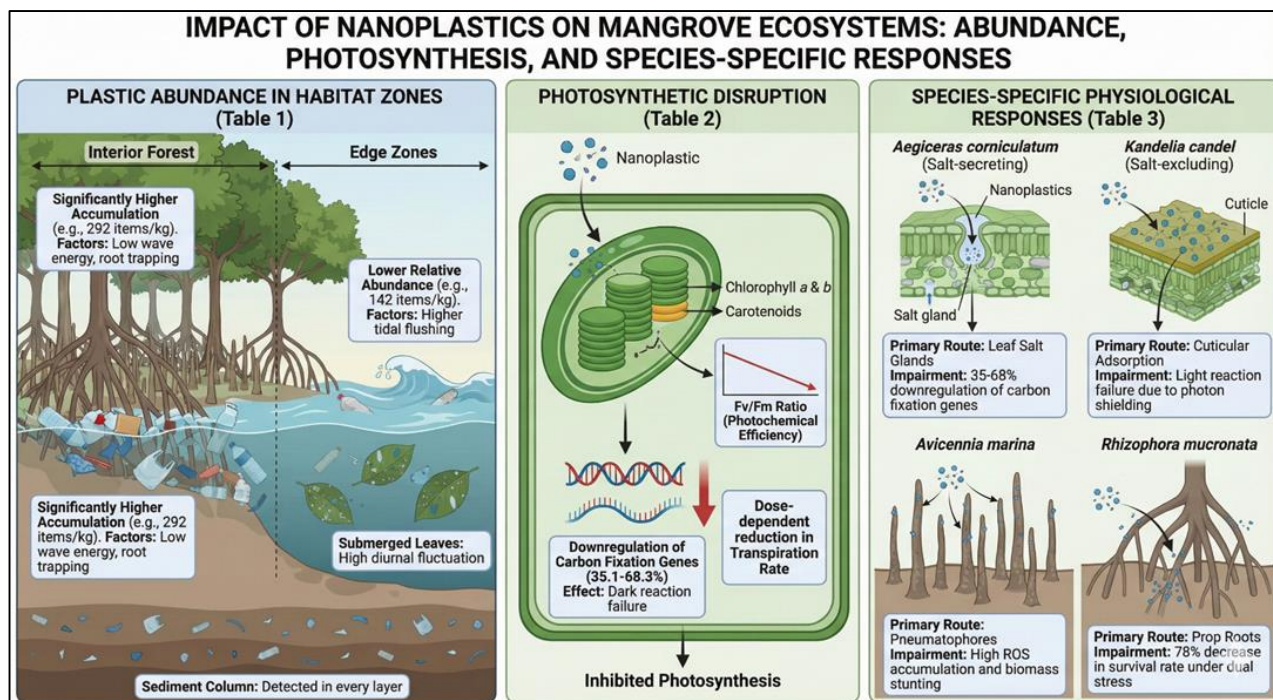


Fig 9: Summary of species-specific physiological responses

Conclusion

Nano plastic pollution represents a multifaceted threat to the physiological health and ecological integrity of mangrove forests. These particles infiltrate mangrove tissues through specialized root and foliar pathways, where they initiate a complex series of metabolic disruptions. The impairment of photosynthesis, characterized by both chlorophyll degradation and the genetic downregulation of carbon fixation pathways, directly threatens the carbon storage capacity of these vital ecosystems. Furthermore, Nano plastic-induced oxidative stress, hormonal imbalances, and the disruption of ionic homeostasis—particularly regarding iron and salt regulation—compromise the plants' ability to withstand the harsh conditions of the intertidal zone. The role of Nano plastics as vectors for heavy metals and their impact on sediment biogeochemistry further extend these risks to the broader ecosystem. As mangroves are critical nodes in global carbon cycles and coastal protection, the physiological degradation of these forests by Nano plastics could have far-reaching consequences for biodiversity and climate resilience. Addressing this challenge requires an integrated understanding of the microscopic interactions between plastics and plant biology to develop effective mitigation and preservation strategies for these essential coastal landscapes.

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