



# Mangroves as Living Classrooms: Environmental Education and Sustainability in Urban Coastal Ecosystems

## Manguezais como Salas de Aula Vivas: Educação Ambiental e Sustentabilidade em Ecossistemas Costeiros Urbanos

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### ABSTRACT

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Mangrove ecosystems provide excellent opportunities for interdisciplinary environmental education by integrating biodiversity, conservation, sustainability, scientific culture, and the One Health approach. This narrative review examines the educational potential of the Guaratiba mangrove, located in Rio de Janeiro, Brazil, highlighting its role as a living educational territory where ecological, microbiological, climatic, health-related, and sociocultural dimensions intersect. Drawing upon the literature on Environmental Education, Ecology, Environmental Microbiology, Sustainability, and Environmental Health, and how educational experiences in mangrove ecosystems can strengthen scientific literacy, environmental citizenship, climate awareness, and participatory governance. The review further demonstrates how these ecosystems provide valuable opportunities to understand the relationships among environmental quality, public health, biodiversity conservation, and socioecological resilience, while simultaneously addressing challenges associated with urbanization, pollution, environmental injustice, and the degradation of coastal ecosystems. Mangroves should be recognized not only as priority ecosystems for conservation but also as strategic environments for promoting transformative education aimed at sustainability, social participation, and the development of environmentally responsible citizens.

**Keywords:** Blue carbon; Climate change; Mangroves; Environmental Education; Guaratiba; Scientific Culture; Sustainability; One Health; Environmental Citizenship.

### RESUMO

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Os ecossistemas de manguezais oferecem oportunidades excelentes para a educação ambiental interdisciplinar ao integrarem biodiversidade, conservação, sustentabilidade, cultura científica e a abordagem Uma Só Saúde (One Health). Esta revisão narrativa examina o potencial educacional do manguezal de Guaratiba, no Rio de Janeiro, Brasil, destacando seu papel como território educativo vivo, onde dimensões ecológicas, microbiológicas, climáticas,

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sanitárias e socioculturais se interconectam. A partir da literatura sobre Educação Ambiental, Ecologia, Microbiologia Ambiental, Sustentabilidade e Saúde Ambiental, discutimos como experiências educativas em manguezais podem fortalecer a alfabetização científica, a cidadania ambiental, a conscientização climática e a governança participativa. A revisão também evidencia como esses ecossistemas permitem compreender as relações entre qualidade ambiental, saúde pública, conservação da biodiversidade e resiliência socioecológica, ao mesmo tempo em que abordam desafios associados à urbanização, poluição, injustiça ambiental e degradação dos ecossistemas costeiros. Os manguezais devem ser reconhecidos não apenas como ecossistemas prioritários para conservação, mas também como ambientes estratégicos para promover uma educação transformadora voltada à sustentabilidade, à participação social e à formação de cidadãos ambientalmente responsáveis..

**Palavras-chave:** Carbono azul; Mudanças climáticas; Manguezais; Educação Ambiental; Guaratiba; Cultura Científica; Sustentabilidade; Uma Só Saúde; Cidadania Ambiental.

## 1. INTRODUCTION

Mangrove ecosystems are among the most productive and ecologically complex coastal environments on Earth, occupying tropical and subtropical intertidal regions where terrestrial and marine systems converge (Wang et al., 2021). These ecosystems provide essential ecological services, including shoreline stabilization, nutrient cycling, fisheries support, water filtration, biodiversity conservation, and long-term carbon sequestration (Bimrah et al., 2022; Lee et al., 2025). In recent decades, mangroves have also gained increasing global attention because of their role in climate change mitigation through blue carbon storage and their capacity to enhance coastal resilience against sea-level rise and extreme climatic events (Macreadie et al., 2021; Das et al., 2026).

Despite their ecological and socioeconomic importance, mangroves remain highly threatened by anthropogenic pressures, including urbanization, industrialization, aquaculture expansion, pollution, land reclamation, and inadequate sanitation infrastructure (Akram et al., 2023). The accelerated degradation of coastal wetlands reflects broader environmental challenges associated with the Anthropocene, in which human activities increasingly alter ecological processes at local and planetary scales (Sreelekshmi et al., 2025). In highly urbanized coastal regions, mangrove degradation is frequently accompanied by biodiversity loss, contamination by persistent pollutants, habitat fragmentation, and increasing social vulnerability (Sharma et al., 2022).

Simultaneously, environmental education has undergone substantial conceptual

transformation over recent decades. Traditional conservation-oriented educational approaches focused primarily on nature protection have progressively evolved toward broader frameworks emphasizing sustainability, environmental justice, participatory governance, climate adaptation, and socioecological resilience (Ardoin et al, 2019; Acosta Castellanos et al., 2022). Contemporary environmental education increasingly seeks to integrate scientific literacy, ethical reflection, civic engagement, and experiential learning while fostering critical understanding of the interdependence between ecological integrity and human well-being (Trott et al, 2023).

Within this context, mangrove ecosystems possess exceptional educational potential. Their ecological complexity, sensory richness, and direct exposure to anthropogenic pressures make them particularly suitable environments for interdisciplinary and place-based learning (Smith et al., 2002; Gunawan et al, 2025). Mangroves allow students and communities to observe ecological interactions, sediment dynamics, biodiversity patterns, pollution processes, climate-related phenomena, and socioenvironmental conflicts within a single ecosystem. Consequently, these environments may function not only as ecological habitats but also as living classrooms capable of promoting ecological literacy, sustainability awareness, and environmental citizenship (Müller et al., 2026).

The pedagogical relevance of mangroves is further reinforced by emerging educational frameworks such as Education for Sustainable Development, One Health, and civic ecology education (Arfan et al., 2024). Mangrove ecosystems illustrate, in a highly tangible manner, the interconnectedness between environmental quality, public health, biodiversity conservation, climate resilience, and social sustainability. The presence of contaminated sediments, sewage-associated microorganisms, antibiotic-resistant bacteria, and plastic pollution in urban mangroves demonstrates how environmental degradation directly affects ecosystem functioning and human populations (Bouchez et al., 2013; Abou Seedo et al., 2017; Kannankai et al., 2022). At the same time, mangroves support ecological restoration initiatives, citizen science projects, and participatory conservation programs that may strengthen community engagement and scientific culture (Amaral et al., 2025).

In Brazil, the mangroves of the Guaratiba region, located in the metropolitan area of Rio de Janeiro, represent one of the largest and best-preserved mangrove remnants in the state (dos Santos et al., 2022). Protected in part by the Guaratiba State Biological Reserve, the ecosystem simultaneously experiences intense anthropogenic pressure associated with irregular urban occupation, pollution, and infrastructure expansion. These characteristics make Guaratiba an especially relevant case study for examining

the educational potential of mangroves within densely urbanized coastal landscapes.

Although the ecological functions of mangrove ecosystems have been extensively investigated, comparatively less attention has been devoted to their role as strategic environments for environmental education and sustainability learning. Existing studies frequently address mangrove conservation, biodiversity, or climate regulation independently, while interdisciplinary educational perspectives remain fragmented across the literature (Gunawan et al., 2025). Moreover, few narrative reviews have integrated ecological, microbiological, sociocultural, pedagogical, and policy-oriented dimensions of mangrove-centered environmental education.

Therefore, the objective of this narrative review is to examine mangrove ecosystems as strategic spaces for environmental education, scientific literacy, and sustainability-oriented learning, with particular emphasis on the Guaratiba mangrove as a representative urban coastal ecosystem. Specifically, this review aims to: (i) discuss the interdisciplinary educational potential of mangroves; (ii) analyze the relationship between mangrove ecosystems, environmental citizenship, and scientific culture; (iii) explore the integration of mangrove education into sustainability and One Health frameworks; and (iv) identify future directions and policy implications for mangrove-centered

environmental education. By synthesizing ecological, educational, microbiological, and socioenvironmental perspectives, this review argues that mangroves should be understood not merely as ecosystems requiring protection, but as dynamic pedagogical landscapes capable of fostering ecological awareness, participatory conservation, and sustainability.

## 2. MATERIAL AND METHODS

This study was conducted as a narrative review focused on the educational, ecological, sociocultural, and sustainability-related dimensions of mangrove ecosystems. Unlike systematic reviews, narrative reviews allow broader conceptual integration across interdisciplinary themes, particularly in emerging research areas where empirical studies remain fragmented across multiple disciplines. The review sought to synthesize literature from environmental education, coastal ecology, sustainability science, microbiology, climate adaptation, and environmental governance to examine mangroves as strategic spaces for environmental learning and public engagement.

The literature survey was conducted using the databases Scopus, Web of Science, PubMed, and Google Scholar. Searches included publications in English and Portuguese published primarily between 2000 and 2026, although earlier landmark studies were also incorporated when considered conceptually relevant. The main

keywords and combinations included: “mangrove ecosystems”; “environmental education”; “sustainability education”; “Education for Sustainable Development”; “One Health”; “scientific literacy”; “environmental citizenship”; “place-based education”; “blue carbon”; “citizen science”; “coastal conservation”; “ecological restoration”; “mangrove microbiology”; “environmental justice”; “climate adaptation education”.

Additional references were identified through backward citation tracking from key review papers and foundational theoretical works in environmental education and sustainability studies. The inclusion criteria prioritized peer-reviewed articles, books, institutional reports, and theoretical frameworks directly related to environmental education in coastal ecosystems, mangrove ecology, sustainability learning, public engagement, and socioecological resilience. Studies exclusively focused on highly technical aspects of mangrove biogeochemistry or experimental microbiology without educational or socioenvironmental relevance were not prioritized in the present synthesis, as these themes will be explored separately in future experimental publications.

The Guaratiba mangrove in Rio de Janeiro, Brazil, was selected as a focal case study because it represents one of the largest remaining urban mangrove systems in southeastern Brazil and simultaneously exhibits high ecological relevance and intense anthropogenic pressure. Its

environmental complexity, biodiversity, microbiological richness, conservation status, and proximity to densely populated urban areas make it particularly suitable for discussing the educational potential of mangrove ecosystems within contemporary sustainability and environmental governance frameworks.

### **3. RESULTS AND DISCUSSION**

#### **3.1. Mangrove Ecosystems: Ecological Importance and Environmental Complexity**

Mangroves are highly specialized coastal wetlands distributed along tropical and subtropical shorelines, estuaries, lagoons, and river deltas. These ecosystems occupy intertidal zones characterized by fluctuating salinity, periodic flooding, anoxic sediments, and intense biogeochemical activity (Worthington et al., 2020). Despite the challenging environmental conditions associated with tidal oscillation and sediment instability, mangroves sustain exceptionally productive ecological systems that support diverse communities of plants, microorganisms, invertebrates, fish, birds, and mammals (Carugati et al., 2018).

Globally, mangroves provide essential ecosystem services with direct ecological, climatic, and socioeconomic importance. Their dense root systems stabilize sediments, reduce shoreline erosion, and attenuate wave energy during storms and extreme climatic events (Jayson-Quashigah et al., 2025). Mangrove forests additionally function as nursery habitats

for numerous marine species, supporting fisheries productivity and coastal food security (Ermgassen et al., 2025). In many tropical regions, local communities depend directly on mangrove-associated fisheries and extractive activities for subsistence and income generation (Alberto et al., 2024).

One of the most significant ecological functions of mangroves involves carbon sequestration and long-term carbon storage. Mangrove sediments accumulate large quantities of organic matter under anaerobic conditions, resulting in highly efficient blue carbon reservoirs capable of storing carbon over millennial timescales (Choudharyj et al., 2024). Consequently, mangrove conservation has become increasingly relevant within global climate mitigation strategies and ecosystem-based adaptation frameworks (Sunkur et al., 2023).

Beyond their climatic importance, mangrove ecosystems are characterized by remarkable microbiological diversity and intense biogeochemical cycling. Mangrove sediments harbor highly specialized microbial communities involved in sulfur reduction, nitrogen fixation, methane metabolism, organic matter decomposition, and pollutant degradation (Li et al., 2025). These microorganisms play essential roles in nutrient recycling and ecosystem functioning while also contributing to natural bioremediation processes (Meng et al., 2022).

The microbiological complexity of mangroves has attracted growing scientific interest in recent years, particularly regarding the discovery of novel microbial taxa, bioactive compounds, and biodegradation pathways (Zhang et al., 2023). Mangrove-associated microorganisms exhibit substantial metabolic diversity due to the physicochemical heterogeneity of estuarine environments. Such microbial communities may degrade hydrocarbons, pesticides, plastics, and other environmental contaminants, highlighting the ecological resilience and biotechnological potential of mangrove ecosystems (Siddique et al., 2024).

However, despite their ecological importance, mangroves are among the most threatened ecosystems globally. Urbanization, industrial contamination, shrimp farming, tourism expansion, port construction, deforestation, and land reclamation have contributed to accelerated mangrove degradation across multiple coastal regions (Goldberg et al., 2020). Pollution derived from untreated sewage, heavy metals, persistent organic pollutants (POPs), hydrocarbons, pharmaceutical residues, and microplastics further compromises ecosystem integrity and biodiversity (Landrigan et al., 2020).

In urbanized coastal regions, mangrove degradation frequently reflects broader patterns of environmental inequality and unsustainable territorial occupation. Vulnerable human

populations often inhabit areas adjacent to degraded mangrove ecosystems where exposure to flooding, contaminated sediments, and inadequate sanitation infrastructure is intensified (Moschetto et al., 2020). Consequently, mangroves are not only ecological systems but also socioenvironmental territories where biodiversity conservation intersects with public health, urban governance, and social justice.

The mangroves of the Guaratiba region, located in the western zone of Rio de Janeiro, exemplify this socioecological complexity. The area includes important remnants of mangrove vegetation associated primarily with *Rhizophora mangle*, *Avicennia schaueriana*, and *Laguncularia racemosa* (dos Santos et al., 2022). Protected sectors of the ecosystem are incorporated into the Guaratiba State Biological Reserve, one of the most important conservation units for mangrove preservation in southeastern Brazil. Nevertheless, despite its protected status, the Guaratiba mangrove remains under significant anthropogenic pressure. Urban expansion, irregular land occupation, sewage discharge, plastic pollution, and infrastructure development continue to threaten ecosystem integrity (Moschetto et al., 2020). Such pressures create visible environmental transformations, including habitat fragmentation, contamination, sediment alteration, and biodiversity decline. These characteristics make the Guaratiba mangrove particularly relevant not only for ecological research but also for environmental

education initiatives aimed at connecting local environmental realities with broader sustainability challenges.

Importantly, mangrove ecosystems possess distinctive characteristics that make them especially valuable for educational purposes. Their visible tidal dynamics, complex vegetation structures, sedimentary processes, biodiversity interactions, and pollution gradients provide highly accessible opportunities for experiential and interdisciplinary learning. Unlike more abstract environmental themes discussed exclusively in classrooms, mangroves allow students and communities to directly observe ecological processes and anthropogenic impacts in real-world contexts. Moreover, the coexistence of ecological richness and environmental degradation frequently observed in urban mangroves creates powerful conditions for critical environmental reflection. The simultaneous presence of biodiversity, pollution, conservation efforts, and social vulnerability enables educational discussions involving ecology, climate change, environmental justice, microbiology, sustainability, and public health within a single integrated landscape.

Thus, understanding mangroves as socioecological systems is fundamental for recognizing their broader educational potential. These ecosystems are not merely biological habitats; they are dynamic environments where ecological processes, human activities, cultural practices, and environmental conflicts converge.

This complexity positions mangrove as strategic territory for the development of interdisciplinary environmental education capable of fostering scientific literacy, sustainability awareness, and environmental citizenship.

### 3.1 Mangroves for Environmental Education

Environmental education has progressively evolved from predominantly conservation-oriented approaches toward broader pedagogical frameworks emphasizing sustainability, socioecological resilience, scientific literacy, and participatory citizenship (Ribó, 2024). Within this transition, interdisciplinary learning has become increasingly important because contemporary environmental problems rarely occur within isolated disciplinary boundaries. Climate change, biodiversity loss, pollution, environmental injustice, and public health crises are intrinsically interconnected phenomena requiring integrated educational approaches (Müller et al., 2026).

Mangrove ecosystems are particularly suitable for interdisciplinary environmental education because they naturally integrate biological, chemical, geological, climatic, microbiological, social, and cultural processes within a single landscape. Their ecological complexity allows educators and researchers to explore multiple dimensions of sustainability simultaneously while connecting theoretical scientific concepts with direct environmental observation (Gunawan et al., 2025).

### 3.2 Ecological Knowledge and Experiential Learning

Mangroves provide exceptionally effective environments for developing ecological literacy because ecological interactions are highly visible and spatially concentrated. Field-based educational activities conducted in mangroves allow students to directly observe tidal fluctuations, sediment deposition, salinity gradients, species interactions, and vegetation adaptations to extreme environmental conditions. The characteristic aerial roots of *Rhizophora mangle*, pneumatophores of *Avicennia schaueriana*, and salt-regulation mechanisms present in mangrove vegetation provide concrete examples of ecological adaptation and evolutionary resilience (Marfiana et al., 2025).

Experiential learning approaches are particularly relevant in mangrove ecosystems because direct sensory interaction with the environment often produces deeper educational engagement than exclusively classroom-based instruction (Unesco, 2026). The textures of mangrove sediments, tidal rhythms, odors associated with organic decomposition, and direct observation of biodiversity stimulate multisensory learning experiences capable of strengthening environmental memory and ecological identity. Educational research consistently demonstrates that contact with natural environments contributes positively to environmental awareness, emotional

engagement, and pro-environmental behavior (Datta et al., 2023). Mangroves may therefore function not only as scientific learning environments but also as spaces for emotional reconnection with ecological systems, particularly in urbanized societies characterized by increasing disconnection from nature.

### **3.3 Mangroves and Place-Based Education**

Place-based education represents another important theoretical framework applicable to mangrove-centered environmental learning. This pedagogical perspective emphasizes learning rooted in local ecological, social, and cultural realities rather than exclusively abstract or generalized environmental concepts (Freitas et al., 2026). According to Paulo Freire, meaningful education emerges through the critical interpretation of lived realities and social contexts (Almeida et al., 2024). Mangrove ecosystems strongly align with this perspective because they visibly reflect the consequences of urbanization, pollution, conservation policies, and climate vulnerability within local territories. In the case of the Guaratiba mangrove, environmental education activities may encourage students and communities to investigate how urban expansion, irregular occupation, sewage discharge, and plastic pollution directly influence ecosystem functioning and biodiversity. Such approaches help transform global sustainability debates into concrete local experiences capable of stimulating

critical environmental reflection (Muller et al., 2026).

Place-based environmental education additionally strengthens territorial identity and community engagement. Coastal communities frequently possess historical, cultural, and economic relationships with mangrove ecosystems through fishing, shellfish harvesting, artisanal practices, and traditional ecological knowledge. Integrating local knowledge systems into educational activities may contribute to culturally inclusive pedagogies while reinforcing community participation in conservation initiatives (Sen et al., 2025).

### **3.4 Mangroves as Living Laboratories for Scientific Literacy**

Mangrove ecosystems also possess substantial potential for promoting scientific literacy and inquiry-based learning. Scientific literacy involves not only the acquisition of scientific information but also the development of evidence-based reasoning, critical thinking, and understanding of scientific processes (Suparmi et al., 2025). Because mangroves integrate multiple ecological and biogeochemical processes, they can function as natural laboratories for investigating environmental dynamics in real time. Educational activities involving water quality monitoring, biodiversity surveys, sediment analysis, microbial cultivation, and pollution assessment allow students to participate actively in scientific investigation rather than

merely receiving passive information (Muller et al., 2026).

This participatory dimension is particularly important in environmental education because active involvement in scientific practices may strengthen both learning outcomes and environmental engagement. Citizen science initiatives developed in mangrove ecosystems further amplify this potential by integrating schools, universities, conservation agencies, and local communities into collaborative environmental monitoring networks (Sofue et al., 2025). Technological innovations increasingly expand the possibilities for scientific education in mangroves. Remote sensing, drone-based mapping, environmental DNA (eDNA) analyses, geospatial technologies, and digital ecological monitoring tools can be incorporated into educational programs to strengthen interdisciplinary learning and scientific curiosity. Nevertheless, technological approaches should complement rather than replace direct environmental immersion, which remains essential for fostering emotional connection and ecological perception (Sun et al., 2026).

### **3.5 Microbiology, One Health, and Environmental Education**

One of the most underexplored educational dimensions of mangrove ecosystems involves environmental microbiology. Microorganisms are fundamental to ecosystem functioning yet remain largely invisible in

traditional environmental education approaches (Armstrong, 2025). Mangrove sediments harbor highly diverse microbial communities associated with sulfur cycling, nitrogen metabolism, hydrocarbon degradation, methane production, and organic matter decomposition (Birnbaum et al., 2025).

The integration of microbiology into mangrove education offers important opportunities for interdisciplinary teaching involving ecology, biotechnology, public health, and sustainability science. Educational activities focused on microbial diversity may help students understand that biodiversity extends beyond visible fauna and flora while simultaneously highlighting the ecological importance of microbial processes. Field-based activities conducted within the Guaratiba mangrove ecosystem provided important opportunities for integrating environmental education with practical scientific investigation. During sampling campaigns, students and researchers can perform sediment collection and microbiological analyses aimed at exploring the cultivable microbial diversity associated with mangrove sediments (Figure 1).



**Figure 1.** Field sampling and cultivation of microorganisms associated with the Guaratiba mangrove ecosystem, Rio de Janeiro, Brazil. The left panel illustrates in situ sediment sampling within the mangrove environment, highlighting the experiential and field-based educational activities developed in the ecosystem. The right panel shows representative culture plates containing cultivable microbial colonies isolated from mangrove sediment samples.

The isolation of morphologically distinct microbial colonies demonstrates the rich microbiological complexity of these ecosystems and highlights their relevance as natural laboratories for teaching environmental microbiology, biodiversity, and ecological interactions. In addition to strengthening scientific literacy through experiential learning, such activities also promote greater understanding of the relationships between ecosystem health, environmental contamination, and sustainability within urban coastal environments. Moreover, mangroves provide highly relevant contexts for applying the One Health approach, which recognizes the

interconnectedness between environmental, plant, animal, and human health (Berbert et al., 2025).

Urban mangroves frequently accumulate sewage-associated microorganisms, antibiotic-resistant bacteria, pharmaceutical residues, microplastics, and persistent organic pollutants. These environmental contaminants may affect aquatic organisms, fisheries resources, and human populations dependent on coastal ecosystems (Lie et al., 2025). Educational programs based on One Health perspective can therefore demonstrate how ecosystem degradation directly influences public health, food safety, and environmental resilience. Such approach is particularly relevant in contemporary environmental education because they integrate ecological conservation with broader discussions regarding sanitation, disease prevention, antimicrobial resistance, and social sustainability (Ioannou et al., 2025).

### 3.6 Climate Change, Blue Carbon, and Sustainability Education

Climate change education represents another major interdisciplinary opportunity associated with mangrove ecosystems. Coastal regions worldwide are increasingly vulnerable to sea-level rise, saline intrusion, erosion, and extreme weather events. Mangroves function simultaneously as ecosystems threatened by climate change and as important natural

infrastructures capable of enhancing coastal resilience (Nandhini et al., 2026).

One of the most significant climate-related functions of mangroves involves blue carbon sequestration. Mangrove sediments store substantial quantities of organic carbon under anaerobic conditions, making these ecosystems among the most efficient natural carbon sinks globally. Educational activities addressing blue carbon dynamics can help students understand the relationship between ecosystem conservation and climate mitigation strategies (de Silva et al., 2025).

Importantly, climate education conducted in mangrove ecosystems allows abstract global climate discussions to become localized and tangible. Rather than perceiving climate change as a distant phenomenon, students can directly observe erosion patterns, vegetation changes, flooding dynamics, and anthropogenic pressures affecting coastal resilience. Such place-based climate education may strengthen environmental engagement and sustainability awareness more effectively than generalized climate narratives disconnected from local realities (Muller et al., 2026).

### 3.7 Environmental Ethics and Citizenship

Mangrove-centered environmental education additionally contributes to the

development of environmental ethics and citizenship. Environmental citizenship involves recognizing that ecological sustainability depends not only on governmental regulation but also on collective social responsibility and democratic participation (Hodriani et al., 2025).

Urban mangroves frequently expose students and communities to visible contradictions between biodiversity conservation and environmental degradation. The coexistence of ecological richness, pollution, socioeconomic inequality, and conservation conflicts may stimulate critical reflection regarding consumption patterns, environmental injustice, and public policy (Muller et al., 2026).

Educational projects involving ecological restoration, waste monitoring, participatory mapping, biodiversity inventories, and citizen science may empower communities to engage actively in conservation processes (Hodriani et al., 2025). Such participatory approaches align closely with transformative environmental education models that seek not merely to transmit ecological knowledge but also to encourage social action and sustainability-oriented behavior. Thus, mangrove ecosystems represent far more than ecological habitats. Their interdisciplinary complexity positions them as strategic educational environments capable of integrating ecological literacy, scientific culture, climate education, environmental ethics, and participatory citizenship within contemporary

sustainability frameworks (Gunawan et al., 2025).

### **3.8. Mangrove Ecosystems, Environmental Justice, and Public Health**

Environmental education in mangrove ecosystems cannot be restricted exclusively to biodiversity conservation or ecological processes. In highly urbanized coastal regions, mangroves are deeply intertwined with social inequality, inadequate sanitation infrastructure, environmental contamination, food insecurity, and public health vulnerability. Consequently, mangrove-centered environmental education must incorporate broader socioenvironmental perspectives capable of connecting ecological degradation with issues of environmental justice and human well-being (Santoso et al., 2026).

The concept of environmental justice emerged from the recognition that environmental risks and pollution are disproportionately distributed among socially vulnerable populations (Quiroga Manrique et al., 2026). Coastal communities located near degraded mangrove systems frequently experience greater exposure to contaminated water, flooding, waste accumulation, and deficient public infrastructure. In many developing countries, rapid urbanization has intensified the occupation of environmentally sensitive coastal zones where mangrove

degradation overlaps with socioeconomic marginalization (Christopher et al., 2025).

The Guaratiba region exemplifies this socioenvironmental complexity. Although portions of the ecosystem remain legally protected through the Guaratiba State Biological Reserve, surrounding areas continue to experience urban expansion, sewage discharge, irregular occupation, and increasing anthropogenic pressure (Rosa et al., 2026). These dynamics generate environmental conflicts involving conservation policies, territorial occupation, sanitation deficiencies, and ecosystem degradation. Importantly, environmental education initiatives developed in mangrove regions may help students and communities critically analyze the unequal distribution of environmental risks and ecological benefits. Rather than presenting environmental degradation merely as a technical or ecological issue, critical environmental education seeks to expose the political, economic, and social structures underlying environmental crises (Sund and Öhman, 2026).

Mangrove ecosystems provide particularly powerful educational contexts for discussing environmental injustice because the consequences of environmental degradation are frequently visible and measurable. Sewage contamination, plastic accumulation, sediment pollution, biodiversity decline, and flooding vulnerability can often be directly observed

during field activities (Kannankai et al., 2022). These characteristics transform mangroves into concrete pedagogical spaces where students may connect scientific concepts with lived environmental realities.

### **3.9 Pollution, Contamination, and Ecotoxicological Education**

One of the most significant environmental challenges affecting mangrove ecosystems involves contamination by chemical and biological pollutants. Mangrove sediments function as depositional environments with low hydrodynamic energy, favoring the accumulation of heavy metals, hydrocarbons, pesticides, pharmaceutical residues, persistent organic pollutants (POPs), and microplastics (Koka et al., 2025).

Educational activities centered on sediment contamination provide important opportunities for interdisciplinary teaching involving chemistry, microbiology, toxicology, and environmental sciences. Students can investigate how contaminants accumulate in sediments, move through trophic chains, and affect ecosystem functioning. Such approaches help transform abstract concepts related to pollution and ecotoxicology into tangible environmental observations (Muller et al., 2026).

Particularly relevant are discussions involving persistent organic pollutants such as polychlorinated biphenyls (PCBs), dioxins, furans, organochlorine pesticides, and polycyclic aromatic hydrocarbons (PAHs), which may remain in sediments for extended periods while exhibiting high bioaccumulative potential (Sun et al., 2025). Educational programs addressing these contaminants can strengthen public understanding of long-term environmental pollution and ecosystem vulnerability.

Plastic pollution represents another critical educational theme in mangrove ecosystems. Mangrove root systems frequently trap large quantities of plastic debris transported by rivers and tidal currents (Cerri et al., 2025). Microplastics and plastic-associated compounds such as phthalates increasingly contaminate sediments and aquatic organisms, generating ecological and toxicological concerns. Because plastic waste is directly associated with everyday consumption practices, educational discussions involving mangrove plastic pollution may help students connect personal behavior with global environmental challenges (Sun et al., 2025).

### **3.10 Mangroves, Microbial Contamination, and One Health Perspective**

Microbial contamination is particularly relevant in urban mangrove systems exposed to untreated sewage discharge. Mangrove sediments

and estuarine waters may harbor fecal indicator bacteria, pathogenic microorganisms, antibiotic-resistant bacteria, and antimicrobial resistance genes associated with anthropogenic pollution (Li et al., 2019; Palacios et al., 2021).

The growing global concern regarding antimicrobial resistance reinforces the importance of integrating microbiological themes into environmental education (Berbert et al., 2025). Mangrove ecosystems affected by sewage contamination may function as environmental reservoirs for resistant microorganisms capable of circulating among environmental, plant, animal, and human systems (Lertcanawanichakul et al., 2025).

Educational activities involving microbiological analyses may significantly enrich mangrove-centered environmental education. Water quality assessments, microbial cultivation, molecular biodiversity analyses, and discussions regarding antimicrobial resistance can help students understand how environmental degradation influences disease transmission and public health risks (Berbert et al., 2025). One Health approach may also help overcome disciplinary fragmentation frequently present in environmental education. Rather than treating ecology, microbiology, medicine, and sustainability as isolated fields, mangrove ecosystems enable these dimensions to be addressed simultaneously within integrated educational frameworks, while also incorporating

immersive environments as mediators in the teaching and learning process (Cardoso et al., 2025).

### **3.11 Food Security and Traditional Coastal Communities**

Mangroves additionally possess substantial importance for food security and subsistence economies. Coastal communities frequently depend on fish, crabs, oysters, mollusks, and other estuarine resources associated with mangrove ecosystems. Consequently, environmental degradation directly affects not only biodiversity but also nutrition, income generation, and cultural practices (Owuor et al., 2024).

Educational programs involving traditional fishers and shellfish gatherers may contribute significantly to culturally inclusive environmental education. Traditional ecological knowledge accumulated through generations often includes detailed understanding of tides, species seasonality, reproductive cycles, sediment behavior, and environmental change. Integrating such knowledge into formal educational activities may strengthen cultural recognition while enriching scientific learning (Ravaoarinosihoarana et al., 2023).

Moreover, discussions regarding contaminated seafood, bioaccumulation, and ecosystem health allow environmental education to connect ecological conservation with food

safety and public health. Such interdisciplinary perspectives are particularly important in urban coastal regions where local populations frequently consume seafood harvested from contaminated environments (Mahato et al., 2025).

### 3.12 Environmental Education

Environmental education research increasingly recognizes the importance of emotional engagement in shaping pro-environmental behavior and ecological identity. Mangrove ecosystems possess distinctive sensory characteristics capable of stimulating emotional responses associated with fascination, discomfort, curiosity, empathy, and environmental reflection (Nair and Chithra, 2025).

The coexistence of ecological beauty and visible environmental degradation often observed in urban mangroves may produce especially powerful educational experiences. Students exposed simultaneously to biodiversity richness and pollution impacts may develop a deeper understanding of environmental vulnerability and human responsibility (Putri et al., 2025).

Importantly, emotional engagement should not be interpreted as incompatible with scientific rigor. On the contrary, contemporary sustainability education increasingly emphasizes that environmental learning involves cognitive,

ethical, emotional, and social dimensions simultaneously (Lahteenkorva et al., 2025). Mangroves therefore provide educational environments where scientific literacy and emotional connection to nature may be developed together.

### 3.13 Mangroves and Transformative Environmental Education

The integration of ecology, microbiology, public health, environmental justice, and emotional engagement positions mangrove ecosystems as particularly suitable environments for transformative environmental education. Transformative educational approaches seek not merely to transmit information but to stimulate critical reflection, participatory citizenship, and sustainability-oriented social action (Sund and Ohman, 2026).

Sustainability education should encourage learners to navigate complexity, uncertainty, and socioecological interdependence rather than simply memorize environmental facts (Baierl et al., 2025). Mangroves embody these complexities because they simultaneously reveal ecological resilience, environmental vulnerability, social inequality, and conservation potential (Muller et al., 2026).

Educational projects involving ecological restoration, participatory monitoring, citizen

science, biodiversity inventories, and public science communication may therefore contribute to both scientific literacy and democratic environmental participation (Marfiana et al., 2025). In this sense, mangroves function not only as ecological systems but also as pedagogical territories capable of fostering ecological awareness, ethical responsibility, and environmental citizenship in the Anthropocene.

### **3.14 Challenges and Limitations**

Despite the growing recognition of mangrove ecosystems as strategic environments for sustainability education, significant structural, institutional, and sociopolitical barriers continue to limit the expansion and long-term effectiveness of mangrove-centered educational initiatives (Ding et al., 2025). Understanding these limitations is essential for developing realistic and scientifically grounded educational strategies capable of producing meaningful socioecological transformation.

Environmental education is frequently presented in normative or idealized terms, emphasizing its transformative potential while underestimating the institutional, economic, and political constraints that shape educational practice. In the context of mangrove ecosystems, these challenges are especially pronounced because conservation efforts frequently occur within regions characterized by urban pressure,

social inequality, governance fragmentation, and environmental conflict (Gunawan et al., 2025).

### **3.15 Institutional Fragility and Educational Discontinuity**

One of the most significant limitations affecting mangrove-based educational initiatives involves institutional discontinuity. Many existing projects depend heavily on temporary funding, isolated academic extension activities, or short-term institutional partnerships (Ramalho et al., 2025). As a result, educational programs are often interrupted after funding cycles end, reducing long-term community engagement and limiting broader social impact.

This problem is particularly evident in developing countries, where environmental education programs frequently receive insufficient financial and political support compared with infrastructure, industrial, or urban development priorities (Ramalho et al., 2025). In many cases, schools located near mangrove ecosystems lack transportation, field equipment, laboratory infrastructure, or adequately trained personnel capable of conducting interdisciplinary environmental activities.

Universities and research institutions frequently play central roles in sustaining mangrove education programs. However, excessive dependence on academic initiatives

may create vulnerability because projects become strongly associated with individual researchers or temporary grant availability (Basheer et al., 2025). Long-term sustainability therefore requires stronger integration between environmental education and formal public policy frameworks.

### 3.16 Fragmentation Between Science, Policy, and Society

Another major challenge concerns the persistent fragmentation between scientific research, environmental governance, and public participation. Mangrove ecosystems are widely studied within ecology, microbiology, climatology, and conservation biology; however, scientific knowledge often remains poorly translated into accessible educational materials or public policy (Kelly-Fair et al., 2026).

This disconnect contributes to situations in which local communities are directly affected by environmental degradation yet remain excluded from scientific debates and environmental decision-making processes. In many coastal regions, technical environmental information is concentrated within academic or governmental institutions while public participation remains limited (Rasquinha et al., 2026).

Mangrove-centered environmental education may help reduce this gap, but such integration requires institutional willingness to promote participatory governance and knowledge democratization. Without effective communication between researchers, educators, policymakers, and local communities, educational initiatives risk becoming socially disconnected or excessively technocratic.

### 3.17 Urbanization and Territorial Conflict

Urban expansion represents one of the greatest threats to mangrove ecosystems worldwide [176]. Coastal regions increasingly experience pressure associated with real estate speculation, infrastructure construction, industrial activity, tourism development, and irregular occupation. Such dynamics frequently generate territorial conflicts involving conservation units, local communities, and economic interests.

The Guaratiba mangrove reflects many of these tensions. Although portions of the ecosystem remain legally protected, surrounding areas continue to experience anthropogenic pressure associated with urban growth and inadequate sanitation infrastructure (Reid and Wood, 2026). These processes complicate environmental education because conservation discourse may sometimes conflict with immediate socioeconomic demands faced by

vulnerable populations. Importantly, environmental education programs that ignore such social realities risk reproducing simplistic conservation narratives disconnected from territorial complexity. Educational approaches focused exclusively on ecosystem preservation without addressing housing inequality, sanitation deficiencies, or economic vulnerability may inadvertently reinforce social exclusion (Castro et al., 2025).

Consequently, mangrove-centered education must incorporate critical socioenvironmental perspectives capable of recognizing environmental conflicts as political and structural phenomena rather than merely ecological problems.

### **3.18 Challenges in Teacher Training and Interdisciplinarity**

Although interdisciplinary education is widely advocated within sustainability discourse, practical implementation remains difficult in formal educational systems (Arntzen et al., 2025). Schools and universities are frequently organized around rigid disciplinary structures that hinder integration between ecology, microbiology, geography, chemistry, sociology, and environmental policy. Teacher training therefore represents a persistent limitation. Many educators receive limited preparation in field-based methodologies, environmental sciences, or

interdisciplinary pedagogy. Environmental education topics are often treated superficially within curricula, restricted to commemorative activities or isolated awareness campaigns rather than integrated sustainability learning (Arntzen et al., 2025; Muller et al., 2025).

Mangrove ecosystems demand especially complex educational approaches because they involve ecological, climatic, microbiological, cultural, and political dimensions simultaneously. Effective teaching in these contexts requires not only technical ecological knowledge but also pedagogical competencies related to participatory learning, science communication, and critical environmental reflection (Gunawan et al., 2025).

Expanding continuing education opportunities for teachers is therefore essential for strengthening mangrove-centered environmental education. Universities and conservation institutions may play particularly important roles in this process through collaborative extension activities and educator training programs (Kaewnoparat and Ounvichit et al., 2025).

### **3.19 Risk of Superficial Environmental Narratives**

Another important limitation concerns the risk of superficial or romanticized representations of mangrove ecosystems within environmental

education discourse (Muller et al., 2026). Educational programs sometimes portray mangroves exclusively as pristine ecological sanctuaries while neglecting social inequalities, pollution processes, governance conflicts, and historical exploitation associated with coastal environments.

Such narratives may unintentionally depoliticize environmental problems by emphasizing individual behavioral change while minimizing structural drivers of environmental degradation. Contemporary sustainability education increasingly recognizes that ecological crises are deeply linked to economic systems, urban planning models, social inequality, and political decision-making (Dewi et al., 2025). Mangrove education therefore requires careful balance between ecological appreciation and critical socioenvironmental analysis. Educational experiences should encourage emotional connection with ecosystems while simultaneously fostering critical understanding of environmental governance, public policy, and sustainability conflicts.

### **3.20 Accessibility and Social Inclusion**

Accessibility remains another major challenge in mangrove-centered environmental education. Field-based educational activities frequently depend on transportation, safety conditions, trained guides, and institutional

support that may not be equally available to all schools and communities (Novianti et al., 2025).

Marginalized populations living near mangrove ecosystems are often paradoxically excluded from educational and scientific initiatives involving those same environments. Financial limitations, institutional barriers, and historical exclusion may restrict participation in conservation and environmental governance processes. Future educational strategies should therefore prioritize inclusivity and accessibility by developing low-cost participatory methodologies, community partnerships, multilingual educational materials, and locally grounded pedagogical approaches (Helmi et al., 2025). Citizen science and community-based environmental monitoring may be especially valuable in this regard because they strengthen both participation and scientific engagement.

### **3.21 Educational Responsibility**

The intensification of climate change, biodiversity decline, pollution, and environmental crises has contributed to increasing levels of environmental anxiety, particularly among younger generations (Niedzwiedz et al., 2025). Environmental education faces the difficult challenge of communicating ecological risks without generating hopelessness or emotional paralysis. Mangrove ecosystems occupy an important

position in this discussion because they simultaneously reveal environmental vulnerability and ecological resilience. Pollution, habitat degradation, and climate impacts are often clearly visible in urban mangroves; however, these ecosystems also demonstrate remarkable regenerative capacity and restoration potential (Wirabuana et al., 2025).

### **3.22 Toward More Critical and Transformative Educational Models**

The future effectiveness of mangrove-centered environmental education will depend on the capacity to move beyond fragmented and awareness-oriented approaches toward more critical, participatory, and transformative educational models (Arfan et al., 2024). Mangrove ecosystems should not be reduced to scenic educational settings or symbolic conservation icons. They are complex socioecological territories where biodiversity, microbiology, climate dynamics, public health, urban inequality, cultural identity, and political conflict intersect continuously. Recognizing this complexity is fundamental for developing environmental education capable not only of transmitting ecological information but also of fostering scientific literacy, democratic participation, ethical reflection, and socioecological resilience.

## **4. Conclusions**

Beyond their well-established roles in biodiversity conservation, shoreline protection, and blue carbon storage, mangroves also possess excellent potential as spaces for environmental education, scientific culture, and sustainability learning. This narrative review explored the Guaratiba mangrove in Rio de Janeiro, Brazil, as a living educational territory where ecological, climatic, microbiological, and social dimensions converge. Mangrove-centered education allows students and communities to directly observe biodiversity dynamics, pollution, sewage contamination, urbanization pressures, and ecological restoration processes, transforming global environmental challenges into tangible local realities. In this context, the Guaratiba mangrove represents an important example of how urban coastal ecosystems can support interdisciplinary and experiential learning while simultaneously revealing the connections between environmental degradation, public health, climate resilience, and social well-being. This review also highlights the importance of integrating One Health perspective, environmental microbiology, citizen science, climate adaptation, and restoration-based learning into environmental education initiatives. Despite this potential, mangrove ecosystems remain underrepresented in environmental policies and formal educational frameworks. Expanding mangrove-centered sustainability education will require stronger collaboration

among schools, universities, conservation agencies, policymakers, and local communities, as well as greater investment in interdisciplinary educational strategies and public engagement. Mangroves should not be viewed solely as threatened coastal wetlands, but as dynamic educational landscapes where biodiversity, sustainability, scientific inquiry, and environmental citizenship intersect. Their ecological complexity and socioenvironmental relevance make them uniquely capable of fostering ecological awareness and promoting more sustainable and environmentally responsible societies.

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