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The Threat of Aquatic Invasive Species: Understanding and Addressing Biological Pollution

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ABSTRAK

Spesies invasif akuatik telah muncul sebagai polutan biologis yang signifikan, yang semakin mengganggu ekosistem laut dan air tawar di seluruh dunia, termasuk di Indonesia. Spesies ini sering kali memiliki keunggulan adaptif seperti cepatnya pertumbuhan dan tingginya kapasitas reproduksi yang jika dikombinasikan dengan aktivitas antropogenik dan kondisi lingkungan yang mendukung, akan mempercepat penyebarannya. Perkembangbiakannya mengubah dinamika ekosistem, mengancam keanekaragaman hayati asli, dan mempersulit pengelolaan sumber daya akuatik. Artikel reviu ini bertujuan untuk mengkaji dampak ekologis spesies invasif akuatik, menilai pendekatan regulasi dan remediasi saat ini, dan mengidentifikasi tantangan dalam mengendalikan penyebarannya. Metode tinjauan kualitatif digunakan, dengan mengacu pada artikel jurnal bereputasi, laporan ilmiah, dan dokumen kebijakan yang diterbitkan antara tahun 2000 dan 2024. Literatur bersumber dari basis data seperti ScienceDirect, Scopus, SpringerLink, dan Google Scholar, dengan menggunakan kata kunci seperti "spesies invasif akuatik", "polusi biologis", dan "strategi remediasi". Temuan menunjukkan bahwa berbagai langkah regulasi internasional dan nasional telah ditetapkan, termasuk daftar hitam spesies invasif Uni Eropa dan kerangka hukum Indonesia untuk pengendalian spesies. Strategi bioremediasi seperti zooremediasi—misalnya, menggunakan bivalvia pemakan filter—telah menunjukkan hasil yang menjanjikan dalam mengurangi polusi biologis. Selain itu, pendekatan pemodelan seperti strategi ekologi Top-Down dan Bottom-Up menawarkan alat yang berharga untuk pengelolaan tingkat ekosistem. Sebagai kesimpulan, pengelolaan spesies invasif akuatik yang efektif memerlukan penilaian ekosistem yang komprehensif, kebijakan regulasi yang terpadu, dan metode remediasi yang adaptif. Memperkuat pemahaman kita tentang dampak ekologis spesies ini sangat penting untuk melindungi lingkungan akuatik dan memastikan keberlanjutan ekosistem jangka panjang.

***Kata kunci*:** Disrupsi ekosistem, Pencemar biologi, Pengelolaan spesies invasif, Remediasi lingkungan, Spesies invasif perairan

ABSTRACT

Aquatic invasive species have emerged as significant biological pollutants, increasingly disrupting marine and freshwater ecosystems worldwide, including in Indonesia. These species often possess adaptive advantages such as rapid growth and high reproductive capacity, which, when combined with anthropogenic activities and favorable environmental conditions, accelerate their spread. Their proliferation alters ecosystem dynamics, threatens native biodiversity, and complicates aquatic resource management. This review aims to examine the ecological impact of aquatic invasive species, assess current regulatory and remediation approaches, and identify challenges in controlling their spread. A qualitative review method was employed, drawing on peer-reviewed journal articles, scientific reports, and policy documents published between 2000 and 2024. Literature was sourced from databases such as ScienceDirect, Scopus, SpringerLink, and Google Scholar, using keywords like “aquatic invasive species,” “biological pollution,” and “remediation strategies.” Findings indicate that various international and national regulatory measures have been established, including the European Union’s blacklist of invasive species and Indonesia’s legal framework for species control. Bioremediation strategies such as zooremediation—e.g., using filter-feeding bivalves—have shown promise in mitigating biological pollution. Additionally, modeling approaches such as Top-Down and Bottom-Up ecological strategies offer valuable tools for ecosystem-level management. In conclusion, effective management of aquatic invasive species requires comprehensive ecosystem assessments, integrated regulatory policies, and adaptive remediation methods. Strengthening our understanding of these species' ecological impacts is essential for protecting aquatic environments and ensuring long-term ecosystem sustainability.

***Keywords*:** Aquatic invasive species, biological pollutants, Ecosystem disruption, Environmental remediation, Invasive species management

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1. INTRODUCTION

The global human population continues to rise, with projections suggesting it will reach 10 billion by 2050 (Ribeiro *et al*., 2024). This growth is accompanied by an increasing demand for essential resources, particularly water, which is vital for sustaining human life. Water, the most abundant resource on Earth, is crucial for fulfilling these needs. The term "waters" refers to collections of water bodies located in specific regions around the world.

However, human activities and socio-economic development have led to a decline in water quality and, in many cases, pollution (Zhou *et al*., 2024). A significant contributor to environmental pollution is population growth and industrial development, which involve excessive water usage and waste discharge (Dobaradaran *et al*., 2018a). Water is considered polluted when its physical, chemical, or biological properties change due to the introduction of contaminants (Anyaene *et al*., 2023; Iber *et al*., 2023). Water pollution has become a major concern in recent years, as it threatens one of the most essential resources for human life (Suwito *et al*., 2014)

Water pollution can also result from invasive species, which are organisms introduced outside their natural habitats. These species can become invasive when they face no natural predators, posing risks to native ecosystems (Karfakis *et al*., 2023). According to the United Nations Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES), at least 58% of ecosystem changes are linked to invasive species (Meiners *et al*., 2012; Krigas *et al*., 2023). Therefore, this review aims to explore various invasive species contaminating water bodies and the application of bioremediation as a method to mitigate their impact.

Ensuring a sustainable environment requires comprehensive strategies to address biological pollution caused by invasive species, as their unchecked spread can significantly disrupt ecosystem services and biodiversity (Simberloff *et al*., 2013). Invasive species contribute to habitat degradation, alter food webs, and diminish water quality, which can have cascading effects on fisheries, agriculture, and public health (Vilà *et al*., 2010). Sustainable management approaches must integrate early detection, rapid response, and long-term control strategies, incorporating scientific research, policy enforcement, and community engagement to mitigate their impacts effectively (Pyšek *et al*., 2020). By prioritizing sustainable solutions such as ecosystem-based management and bioremediation, we can safeguard aquatic resources while maintaining ecological balance and resilience against future environmental threats (Mazza *et al*., 2014).

2. METHODS

This article employs a narrative literature review approach (Sukhera, 2022) to synthesize existing knowledge regarding aquatic invasive species (AIS) and their role as biological pollutants in global and Indonesian water ecosystems. The primary aim is to examine different invasive species affecting water environments and to evaluate bioremediation strategies as potential solutions for reducing their adverse effects.

Relevant peer-reviewed articles (both journal and proceeding), books, and credible organizational reports were gathered from several electronic databases, including ScienceDirect, SpringerLink, PubMed, Google Scholar, and Scopus, using search terms such as "aquatic invasive species", "biological pollution", "water quality degradation", "invasive species remediation", and "sustainable aquatic ecosystems". Articles published between 2000 and 2024 were prioritized to ensure up-to-date insights, although one seminal earlier work was included due to its high relevance.

Selection criteria included studies that: (1) directly addressed aquatic invasive species and their ecological or environmental impacts, (2) presented case studies or documented remediation strategies, (3) offered theoretical models (e.g., top-down/bottom-up approaches) relevant to invasive species management, or (4) explained policies aimed at mitigating biological pollution in aquatic ecosystems.

The extracted information was organized according to the subheadings in the Results and Discussion section, including a dedicated section outlining the study's limitations

3. RESULTS AND DISCUSSION

3.1. Invasive species in Aquatic Ecosystems

Pollution has been a prominent topic of discussion over the last three decades, with water pollution receiving particular attention due to the critical role water plays in meeting human needs. Water covers two-thirds of the Earth's surface, making it more abundant than land. Water pollution can be categorized into three types: biological, chemical, and physical pollution. Among these, biological pollution is one of the most dangerous (Fotoohi *et al*., 2024), yet it is often overlooked, as biological agents are mistakenly perceived as non-threatening. In reality, biological pollutants, particularly invasive species, have significant environmental and human impacts (Gherardi, 2007).

Invasive species are organisms introduced outside their natural habitats. In the absence of natural predators, they proliferate and disrupt native ecosystems (Karfakis *et al*., 2023). A classic example is the ballast water incident in 1991, which caused a cholera outbreak in South America, killing approximately 10,000 people (McCarthy and Khambaty, 1994; Duan *et al*., 2023). Table 1 provides examples of invasive species that have polluted aquatic environments around the world.

One prominent species is *Eichhornia crassipes*, a macrophyte that poses a serious threat to freshwater ecosystems in southern Africa (Strange *et al*., 2019). First recorded as naturalized in KwaZulu-Natal in

1910 (Hill *et al*., 2020), *E. crassipes* has been joined by other invasive species in the region, such as Pontederiaceae and *Pistia stratiotes* L. (Strange *et al*., 2019).

In India, *Pterygoplichtys* sp. has become an invasive species with its large size, high fecundity, and ability to migrate short distances on land. Its hard pectoral fins and capacity to survive in low-oxygen environments help it evade predators, enabling rapid population growth that destabilizes aquatic ecosystems (Bijukumar et al., 2015). This species also poses economic risks, damaging infrastructure and affecting the fishing industry (Raj *et al*., 2021; Seshagiri *et al*., 2021).

A similar case is seen with *Pterois volitans*, an invasive species in the Bahamas. Protected by venomous spines, this fish faces no natural predators in its new environment, leading to rapid expansion throughout the Gulf of Mexico. Its presence has caused a reduction of up to 94% in native fish populations (Albins *et al*., 2015).

In Spain, *Procambarus virginalis* is the only shrimp species with obligatory apomictic parthenogenesis, allowing reproduction without fertilization (Vogt *et al*., 2008). This reproductive advantage, coupled with a short egg incubation period, has enabled it to spread quickly (Kouba *et al*., 2021; Sánchez *et al*., 2024).

Another invasive species, *Gambusia holbrooki*, originally found in Turkey, has now spread to at least 84 countries (Kurtul *et al*., 2024). Other notable invasive species include *Egeria densa*, *Undaria pinnatifida*, *Asterias*, *Mytilus amurensis*, and various seaweeds, all of which have invaded ecosystems in Japan (Clark, 2015; Asaeda *et al*., 2020).

3.2. Invasive Species Cases in Indonesia

The spread of invasive species has become a global issue, affecting nearly every country worldwide (Sohrabi, 2023). Over the past few decades, invasive species have caused widespread negative impacts. Southeast Asia, including Indonesia, has also experienced biological invasions, but research gaps have limited understanding of the issue in the region (Chan, 2021). As a maritime nation with vast water areas, Indonesia is particularly vulnerable to biological pollution, including the spread of invasive species.

Table 2 highlights various invasive species found across Indonesia, with the phylum Mollusca being the most commonly encountered (Zalzabil *et al*., 2023). One of the most studied species in this phylum is *Pomacea canaliculata*, a fast-reproducing predator of other snails originating from South America (Maldonado, 2019). This species has invaded numerous lakes across Indonesia, including Rawa Pening Lake in Central Java (Marwoto *et al*., 2020). Another invasive species, *Melanoides tuberculata*, native to South Asia, has spread extensively in freshwater environments throughout Southeast Sulawesi (Purnama *et al*., 2022).

In addition to the Mollusca, species from the phylum Chordata such as *Oreochromis niloticus* and *Amphilophus citrinellus* are among the most well-

known invasive species in Indonesia. *Oreochromis niloticus*, commonly known as tilapia, has been introduced to over 90 countries worldwide. Its tolerance to salinity and rapid reproduction explain its widespread presence across Indonesia, particularly in lakes on Sumatra and Java (Hafidz *et al*., 2024). *Amphilophus citrinellus*, commonly referred to as the red devil fish, is a predatory species (Kartamiharja, 2006) that thrives in tropical waters with temperatures between 21-26°C and a pH of 6-8 (Umar *et al*., 2015). Morphological variations have been observed in different regions, such as the pale orange coloration in Jati Luhur Reservoir and the brighter coloration with a white belly in Lake Sentani (Dadiono *et al*., 2023).

Table 1. Documented Invasive Species Contributing to Aquatic Ecosystem Pollution

Name of Invasive Species	Habitat Origin	New Habitat	The Main Cause	Reference
Eichhornia crassipes	location not specifically identified	South Africa	- Holticultural trade and aquarium - Transfer of propagules via boat passengers and anglers	Strange *et al*., 2019
Procambarus virginalis	location not specifically identified	Northern Iberian Peninsula (Spain)	Deliberate release or escape of captive animals	Sánchez *et al*., 2024
Pterygoplichtys sp.	South America	India	Cultivation and ornamental fish trade	Ganguly *et al*., 2024
Species not specifically identified	location not specifically identified	Port of Koper and Slovenian sea	Balast water	David *et al*., 2007
Gambusia holbrooki	South America	Turkey	Malaria biocontrol	Kurtul *et al*., 2024
Egeria densa	South America	Japan	Not specifically stated	Asaeda *et al*., 2020
Pterois volitans	Indo-Pacific (location not specifically identified)	Bahama	Not specifically stated	Albins *et al*., 2015
- *Undaria pinnatifida* - *Asterias* - *Mytilus amurensis* - seaweed (species not specifically identified)	location not specifically identified	Japan	Natural disaster (Tsunami)	Clark, 2015

Table 2. Invasive Species Contributing to Aquatic Pollution in Indonesia

Name of Invasive Species	Habitat Origin	New Habitat	The Main Cause	Reference
Pomacea canaliculata	South America	Danau Rawa Pening, Central Jawa	- Holticultural trade and aquarium - Aquaculture (as duck or fish feed)	Marwoto *et al*., 2020
Melanoides tuberculate	South Asia	Southeast Sulawei	Not specifically explained	Purnama *et al*., 2022
Oreochromis niloticus	North and East Africa	Kepulauan Belitung	Accidental release into natural waters	Hafidz *et al*., 2024
Amphilophus citrinellus	Central America	Sanguling Reservoir, West Bandung Regency, West Jawa	Ornamental fish trade	Dadiono *et al*., 2023
- Araceae - Pontederiaceae - Salviniaceae	Not specifically stated	Jatiluhur Reservoir, Purwakarta Regency, West Jawa	Not specifically explained	Ismail *et al*., 2019
Cherax quadricarinatus	Not specifically stated	Spread almost throughout Indonesia	Released into the wild on purpose	Akmal *et al*., 2024
- Mollusca - Echinodermata - Chlorophyte - Chordata - Porifera - Arthropoda - Rhodophyta	Not specifically stated	Spread almost throughout Indonesia	Not specifically explained	Zalzabil *et al*., 2023

Another invasive species in Indonesia is *Cherax quadricarinatus* from the phylum Arthropoda, commonly known as crayfish. This species is widely distributed across Indonesia and is frequently found in cricket farms, agricultural lands, reservoirs, rivers, and fish markets. Despite its prevalence and use, many Indonesians are unfamiliar with its name, recognizing it more for its utility than as an invasive species (Akmal *et al*., 2024).

In addition to animals, several invasive aquatic plant species have been identified in Indonesia. Notable examples include *Spirodela polyrrhiza*, *Lemna minor*, *and Pistia stratiotes* from the Araceae family; *Eichornia crassipes* and *Salvinia molesta* from the Pontederiaceae family; and *Azolla pinnata* from the Salviniaceae family. These plants have been documented in locations such as the Jatiluhur Reservoir in West Java (Ismail *et al*., 2019).

The numerous cases presented indicate that invasive species have significantly impacted Indonesia's waters, with Mollusca being the most frequently observed invader, followed by Echinodermata and Chlorophyta (Zalzabil *et al*., 2023). Despite the identification of many invasive species, research remains insufficient across much of Indonesia. Between 2003 and 2008, studies on invasive species were conducted in only 22 provinces, with the most publications in Aceh and Maluku, while many other regions still have little to no research (Zalzabil *et al*., 2023).

3.3. Major Causes of Invasive Species Spread

The growth of invasive species in southern Africa is believed to be driven by the region's topography and climate, which do not favor the accelerated evolution of native flora, allowing introduced species to adapt more easily (Strange *et al*., 2018a). However, the primary cause of species spread in southern Africa is attributed to the horticultural and aquarium trades (Hill *et al*., 2020). This pattern mirrors the introduction of *Pterygoplichthys* sp. in India, where the species threatens native organisms and ecosystems by altering nutrient dynamics and competing with indigenous species (Wei *et al*., 2017; Quintana *et al*., 2023; Ganguly *et al*., 2024).

Similarly, *Procambarus virginalis* Lyko, an invasive species introduced through human activity, became widespread due to the release—either deliberate or accidental—by hobbyists (Sánchez *et al*., 2024). This species poses significant environmental risks, earning it a spot among the top ten most dangerous invasive species (Sánchez *et al*., 2024). Another example is *Gambusia holbrook*i, initially introduced in 1960 in the Çukurova basin as a biocontrol measure for malaria (Kurtul *et al*., 2024).

In contrast, the spread of other invasive species, such as *Undaria pinnatifida*, *Asterias*, and *Mytilus amurensis*, was largely due to natural disasters like the 2012 tsunami in Japan, which highlighted the impact of ballast water on species introduction (Clark, 2015). This issue has become increasingly relevant, akin to the ballast water phenomenon, where ships discharge water containing various microorganisms and small organisms, often classified as Invasive Alien Species (IAS), which disrupt marine ecosystems worldwide (David *et al*., 2007).

Ballast water, used by ships for stability, is released into different environments and has been identified as a major vector for the global spread of invasive species (Karfakis *et al*., 2023). Maritime transport, which handles over 90% of global cargo, transfers around 10 billion tons of ballast water annually (IMO, 2012; Wan *et al*., 2016). Due to the significant environmental risks, legal frameworks have been implemented to regulate ballast water discharge (David *et al*., 2007; Karfakis *et al*., 2023; Duan *et al*., 2023).

In Indonesia, the spread of invasive species follows similar patterns. Human activities, such as aquaculture and trade, are the primary drivers. For example, *Pomacea canaliculata*, originating from South America, spread to Asia via the aquarium trade. In Indonesia, this species is even cultivated for food or used as feed

for ducks and fish (Marwoto *et al*., 2020). Likewise, the spread of *Amphilophus citrinellus* and *Oreochromis niloticus* is also linked to the aquarium trade, which remains largely unregulated (Dadiono *et al*., 2023; Hafidz *et al*., 2024). A similar situation applies to *Cherax quadricarinatus*, which was introduced by Indonesian hobbyists for fishing and bait, leading to its uncontrolled spread (Akmal *et al.,* 2024).

3.4. Policies for Mitigating Biological Pollution in Aquatic Ecosystems

The primary concern with this organism is its potential to rapidly spread as an invasive species. Once invasive species are introduced into the aquatic environment, they are nearly impossible to completely eradicate (Karfakis *et al*., 2023). In response, several regulations have been enacted to minimize pollution and contamination linked to the spread of invasive species. One such measure is the establishment of a blacklist in Europe for species that pose a significant threat if imported or traded (Vilà *et al*., 2010), as well as the European Union Regulation No. 1143/2014, which focuses on the prevention and management of invasive alien species (IAS) (Dobrzycka-Krahel, 2023).

Similarly, Indonesia has implemented numerous government policies aimed at curbing the spread of invasive species. These include "Undang-undang No. 5 tahun 1990" on the Conservation of Biological Natural Resources and Their Ecosystems, "Undang-undang No. 41 tahun 1999" on Forestry, "Undang-undang No. 16 tahun 1992" on Animal, Fish, and Plant Quarantine, "Undang-undang No. 5 tahun 1994" on the Ratification of the United Nations Convention on Biological Diversity, "Undang-undang No. 31 tahun 2004" (amended by "Undang-undang No. 45 tahun 2009") on Fisheries, "Undang-undang No. 32 tahun 2009" on Environmental Protection and Management, and Regulation of the Minister of Environment and Forestry Number P.94/MENLHK/SETJEN/KUM.1/12/2016 concerning invasive species (Triadi, 2024).

Internationally, regulations have also been established to manage the spread of invasive species through ballast water. The International Maritime Organization (IMO) developed the International Convention for the Control and Management of Ships' Ballast Water and Sediments in 2004. This led to the creation of the Ballast Water Management (BWM) Convention, which aims to protect marine environments from harmful aquatic organisms transported in ballast water. The BWM Convention came into force on September 8, 2017, and includes regulations that prohibit the discharge of ballast water unless it meets the D-2 standard, which classifies organisms into three size groups: those ≥ 50 µm, those 10–50 µm, and indicator microbes (IMO, 2004; Chen *et al*., 2023; Outinen *et al*., 2024). Indonesia has also ratified the BWM Convention through Presidential Regulation Number 132 of 2015.

3.5. Challenges and Solutions for Managing Aquatic Biological Pollutants

In response to various instances of pollution caused by invasive species, governments worldwide have undertaken efforts to minimize the impacts of biological pollution. Despite these initiatives, the risk of biological pollution persists, prompting collaboration among governments, researchers, and society to identify effective strategies for mitigating existing pollution. One potential solution is bioremediation, which, although not universally applicable to all types of biological pollution, includes several techniques that can address specific issues. Notably, zooremediation has been identified as an effective method for managing biological pollutants in aquatic environments, particularly invasive species (Ismail *et al*., 2015; Durand *et al*., 2020).

One effective zooremediation technique involves the use of bivalves. For instance, the bivalve *Anodonta californiensis* has been utilized to eliminate *E. coli* in lakes (Ismail *et al*., 2015). Similarly, *Geukensia demissa*, commonly known as the ribbed mussel, has been employed in New York to remediate waters contaminated with bacteria (Durand et al., 2020). While zooremediation is not exclusively aimed at controlling invasive species, it has demonstrated efficacy in addressing biological contamination by microbes.

Invasive species control can also be approached through simple methods like Top-Down and Bottom-Up modeling. Top-Down control involves using predators or natural enemies to manage invasive populations (Strange *et al*., 2018b). Alternatively, a positive approach to utilizing invasive species can present new opportunities. For example, employing *Sinanodonta woodiana* as a bioindicator and monitoring tool offers a novel strategy for managing invasive shellfish (Elia *et al*., 2024).

Managing aquatic biological pollutants, particularly invasive species, presents a range of complex challenges that require a multidimensional approach. A comprehensive understanding of how these species impact ecosystems is essential for developing effective control measures. Invasive species often alter food webs, outcompete native species, and disrupt ecosystem services, making their control difficult and costly (Simberloff *et al*., 2013). Addressing these issues involves more than just scientific knowledge—it also requires collaboration between policymakers, scientists, and local communities to implement practical solutions that balance ecological, economic, and social concerns (Strayer *et al*., 2012; Vilà *et al*., 2011).

Key considerations for effective management include recognizing the urgency of the crisis. Early detection and rapid response are crucial, as invasive species become increasingly difficult to manage once established (Lodge *et al*., 2006). Valuing expert opinions is vital, as specialists in ecology, biology, and environmental management can provide critical insights into the life cycles, behaviors, and

vulnerabilities of invasive species (Hulme *et al*., 2008). However, it is equally important to avoid unnecessary inquiries or redundant research that does not directly contribute to solving the problem. This requires a focused research agenda that targets the most pressing questions and employs predictive models to forecast potential spread or impact (Simberloff *et al*., 2013; Strayer *et al*., 2012).

Additionally, managing aquatic biological pollutants demands a clear understanding of the prediction domain—geographic, temporal, and ecological factors that influence invasion success (Keller *et al*., 2011). Effective management must consider how specific environmental conditions, such as water temperature, nutrient levels, and habitat availability, contribute to the success or failure of control efforts (Ricciardi *et al*., 2011). Contextualizing invasions within the broader ecosystem is also crucial; efforts to manage invasive species must account for how native species and other ecological processes may respond to interventions, as management actions can have unintended consequences (Hulme *et al*., 2008; Strayer *et al*., 2012).

Planning for potential inaccuracies is essential. Invasion dynamics are inherently unpredictable, and management strategies must be adaptable to new information and evolving environmental conditions (Lodge *et al*., 2006). Policymakers and managers should incorporate flexibility into their plans, allowing for mid-course corrections based on real-time monitoring data. In the face of these challenges, innovative solutions, such as integrating biocontrol methods with habitat restoration or the development of new bioremediation techniques, may provide a more holistic approach to mitigating the impact of invasive species in aquatic ecosystems (Simberloff *et al*., 2013; Strayer *et al*., 2012).

A comprehensive understanding of how invasive species impact ecosystems is essential for developing effective control measures. Key considerations for this approach include recognizing the crisis, valuing expert opinions, avoiding unnecessary inquiries, focusing on the relevant prediction domain, contextualizing invasions within the ecosystem, and planning for potential inaccuracies (Strayer, 2012).

Expanding this understanding is crucial because invasive species can rapidly alter ecosystem dynamics, outcompete native species, and disrupt ecological balance, leading to biodiversity loss and long-term environmental degradation. Without a well-informed and strategic approach, management efforts may be ineffective, allowing invasive species to spread further and cause irreversible damage. Additionally, integrating scientific research, policy-making, and public awareness can enhance early detection and rapid response strategies, minimizing economic and ecological consequences. By addressing these challenges with a structured and knowledge-based approach, conservation efforts can be more targeted, ensuring the sustainability of aquatic ecosystems and the preservation of their ecological functions (Simberloff *et al*., 2013; Strayer *et al*., 2012).

3.6. Potential Future Research

Despite growing recognition of aquatic invasive species (AIS) as significant contributors to biological pollution, considerable knowledge gaps persist, underscoring the need for further investigation. Current research is disproportionately concentrated in the Northern Hemisphere, leading to a lack of comprehensive data from tropical freshwater and marine ecosystems, particularly in biodiversity-rich but underrepresented regions such as Southeast Asia (Seebens et al., 2017). This geographical bias limits our understanding of AIS behavior, impact, and control in tropical environments. For countries like Indonesia, which face logistical and geographical challenges due to their archipelagic nature, early detection and rapid response mechanisms are especially critical.

To address this, improved detection technologies are urgently needed. Molecular tools such as environmental DNA (eDNA) offer promising solutions by enabling early, species-specific identification of invasive species before they become firmly established (Borrell et al., 2020). These tools are highly sensitive and can detect low-abundance organisms that traditional methods might miss, making them essential for proactive monitoring efforts.

Complementary approaches, such as camera trap systems, can further enhance surveillance by capturing visual data on species presence and activity, especially in inaccessible or complex aquatic habitats. Additionally, engaging local communities through citizen science initiatives and social media platforms can expand monitoring coverage and support data collection in real time (Fricke & Olden, 2023). Together, these integrated strategies can significantly improve early warning systems and contribute to more effective AIS management in diverse aquatic ecosystems. Future research should focus on improving the accuracy of early detection methods and species-specific monitoring tools, especially in biodiverse but understudied regions like Southeast Asia.

Further comparative research is essential to evaluate the long-term effectiveness and limitations of various remediation strategies, particularly bioremediation approaches such as zooremediation. Although several case studies have reported localized success, these methods often face challenges related to scalability and ecological sustainability when applied across diverse aquatic systems. Moreover, predictive modeling frameworks, including Top-Down and Bottom-Up ecological approaches, should be further developed and integrated into invasive species management to better anticipate invasion dynamics and inform targeted interventions in both freshwater and marine environments (Strayer et al., 2012). Enhancing these models by accounting for

complex environmental stressors—such as pollution, eutrophication, and climate change—can significantly improve their robustness and applicability across different ecological contexts.

Finally, a more integrative and interdisciplinary approach is needed to address the socio-economic dimensions of AIS invasions. Research that connects ecological impact with economic cost, community livelihoods, and public health risks is still limited (Cuthbert *et al*., 2022). There is also a pressing need to evaluate the effectiveness of current policies and governance structures in controlling invasive species, particularly under shifting climate and trade patterns. Adaptive policy-making, coupled with community-based management and transboundary cooperation, can be crucial in mitigating the global spread of AIS and ensuring sustainable aquatic ecosystems.

3.7. Limitation of the Study

Despite offering an overview of various aquatic invasive species and remediation strategies, this review is limited by the availability and accessibility of published data. Many studies on aquatic invasive species are region-specific and not widely available in global databases, which may result in a lack of representation from certain countries or ecosystems (Liu *et al*., 2020). This could potentially overlook unique cases or local strategies that may be effective in managing biological pollutants, especially in underrepresented tropical and developing regions such as parts of Southeast Asia and Africa (Pyšek *et al*., 2020; Seebens *et al*., 2018).

Another limitation is the lack of standardized methodologies across the studies reviewed, which complicates efforts to compare findings or draw robust generalizations. Differences in experimental designs, environmental conditions, and species-specific responses to remediation efforts reduce the ability to identify consistent patterns or determine the most universally effective solutions (Simberloff *et al*., 2013). Furthermore, limited long-term studies hinder the ability to assess the sustained effectiveness of invasive species control strategies, particularly those involving biological or zooremediation agents (Kočovský *et al*., 2018).

Lastly, while the review highlights several successful cases of bioremediation and ecosystem-based management approaches, it does not delve deeply into socioeconomic, cultural, or political factors that influence their implementation. Effective management of aquatic invasive species requires interdisciplinary approaches that combine ecological knowledge with governance structures, community participation, and public awareness (Epanchin-Niell & Hastings, 2010; Shackleton *et al*., 2019). These dimensions, though essential for real-world applications, were beyond the scope of this article and should be addressed in future research to ensure more holistic and practical outcomes.

4. CONCLUSION

This review highlights the significant impact of various aquatic invasive species, which act as biological pollutants and disrupt ecosystem balance in numerous countries, including Indonesia. The rapid proliferation of these species can be attributed to their unique body structures and reproductive strategies, which give them a competitive advantage. Human activities and favorable environmental conditions further facilitate their spread.

To address the challenges posed by invasive species, multiple policies have been implemented to curb their dissemination. Additionally, several remediation strategies have been developed, ranging from comprehensive approaches to straightforward techniques like Top-Down and Bottom-Up modeling, all of which have proven effective in managing certain invasive species. These efforts are crucial for protecting ecosystems worldwide from the detrimental effects of biological pollution.

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