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СИСТЕМА СБОРА МОРСКИХ ОТХОДОВ: ТЕХНОЛОГИИ, ЭФФЕКТИВНОСТЬ И НАПРАВЛЕНИЯ УСТОЙЧИВОГО РАЗВИТИЯ

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Аннотация. Морской мусор, в основном пластиковое загрязнение, представляет собой растущую глобальную экологическую проблему с серьезными экологическими, экономическими и социальными последствиями. В данном обзоре представлен всесторонний анализ существующих технологий сбора морских отходов, включая пассивные системы (например, Eco-booms), использующие природные силы, и активные системы (например, The Ocean Cleanup, Seabin, SeaClear, WasteShark), применяющие современные технологии. Рассматриваются их эффективность, преимущества и недостатки, подчеркивается необходимость интегрированных решений, объединяющих передовые технологии с вовлечением сообществ для комплексного подхода к проблеме загрязнения морей. Обзор подчеркивает важность устойчивых инноваций, международного сотрудничества и инвестиций в решения по сбору морских отходов для сохранения морских экосистем.

Ключевые слова: морской мусор, системы сбора морских отходов, пассивные и активные технологии, экологические последствия, устойчивое управление морскими отходами.

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REVIEW OF OCEAN WASTE COLLECTION SYSTEMS: TECHNOLOGIES, EFFECTIVENESS AND SUSTAINABLE DEVELOPMENT DIRECTIONS

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Abstract. Marine debris, mainly plastic pollution, represents a growing global environmental crisis with severe ecological, economic, and societal implications. While prevention strategies, such as reducing plastic consumption and enhancing waste management, are crucial, they alone cannot mitigate the substantial amounts of waste already present in marine ecosystems. This review offers a comprehensive evaluation of existing ocean waste collection technologies, emphasizing passive systems (e.g., Eco-booms) that leverage natural forces and active systems (e.g., The Ocean Cleanup, Seabin, SeaClear, WasteShark) that utilize advanced technologies for waste removal. The study assesses their effectiveness, advantages, and limitations, underscoring the need for integrated solutions combining advanced technology with community engagement to tackle marine pollution comprehensively. The review concludes by highlighting the importance of sustained innovation, collaboration, and investment in sustainable ocean waste collection solutions to preserve marine ecosystems.

Keywords: marine debris, ocean waste collection systems, passive and active technologies, environmental impacts, sustainable marine waste management.

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INTRODUCTION

Marine debris (Fig.1), commonly referred to as marine plastic pollution, has become an increasingly urgent global environmental issue, posing significant risks to marine ecosystems, coastal economies, and public health [1]. This term encompasses all human-made solid materials discarded into marine environments, including shorelines and estuaries [2]. While marine debris can consist of various materials, plastics dominate due to their durability and resistance to degradation, leading to prolonged accumulation in marine environments [3].

Fig. 1. Garbage washed up on the shore of Vung Tau, Vietnam
Рис. 1. Мусор, выброшенный на берег Вунгтау, Вьетнам

The scale of ocean litter is both immense and growing. Approximately 8 million tons of plastic are dumped into the ocean annually [4]. If this trend continues, it is projected that by 2050, the ocean could contain more plastic than fish by weight [5]. A prominent example of this accumulation is the Great Pacific Garbage Patch, a vast concentration of debris between California and Hawaii [6]. Moreover, in 2019 alone, 53.6 million tons of e-waste were generated globally, a portion of which likely entered the ocean [7].

The negative impacts of marine litter are multifaceted. Environmentally, plastic waste endangers marine life through entanglement, ingestion, and exposure to harmful substances [8]. Many marine species, from seabirds and sea turtles to marine mammals and fish, are directly affected by plastic pollution [9]. The degradation of plastics into microplastics, which are less than 5 mm in size, raises further concerns due to their potential to enter the food chain and impact human health [10]. Additionally, marine debris can damage fragile ecosystems such as coral reefs and mangroves [11].

Economically, marine litter impacts industries reliant on a clean marine environment, including tourism, fishing, and shipping [12]. Polluted beaches deter tourists, reducing revenue for coastal communities, while lost or damaged fishing gear due to litter results in financial losses for fishermen. Furthermore, the costs of beach clean-ups and waste management represent a significant financial burden for local governments [13].

Socially, the accumulation of marine debris diminishes the aesthetic value of coastal areas, limiting recreational activities and negatively affecting community well-being. In some cases, waste accumulation near residential areas has led to public health issues and sanitation concerns [14].

Given the severe consequences of marine debris and its ever-growing volume, the development and implementation of effective waste collection and removal systems is critical. In recent years, various systems and technologies for collecting marine debris have been proposed, ranging from fixed barriers to autonomous devices and community-driven initiatives [15]. However, due to the diversity of these approaches, a comprehensive evaluation is needed to assess their effectiveness, feasibility, and associated challenges.

Effective management of marine debris requires a comprehensive legal framework at both national and international levels. In Vietnam, the Law on Environmental Protection 2020 has introduced specific regulations on marine waste management, including control of pollution sources and marine pollution treatment [16]. The National Strategy on Integrated Solid Waste Management to 2025, with a vision to 2050 [17], outlines objectives and solutions to reduce marine plastic waste. Internationally, the International Convention for the Prevention of Pollution from Ships (MARPOL) sets stringent standards for ship-based pollution [18]. Concurrently, the United Nations Environment Programme (UNEP) has implemented numerous initiatives to address marine litter and microplastics on a global scale [19-23]. Despite these significant efforts, implementing and monitoring these regulations remain challenging, necessitating close coordination between nations and international organizations.

SEVERAL SYSTEMS DESIGNED FOR MARINE WASTE COLLECTION

Passive collection systems are designed to capture and control waste in water bodies without requiring active human or machine intervention (Fig.2). These systems rely on natural forces, such as water currents and tides, to direct debris towards collection points. Below is an example of a prominent passive system:

Eco-booms, floating trash barriers specially designed to contain and collect waste, oil spills, and other pollutants on water surfaces. They are commonly deployed in sensitive environments, such as rivers, lakes, canals, and coastal areas, to prevent waste from spreading further into marine ecosystems.

Fig. 2. Plastic waste collected[1]
Рис. 2. Собранные пластиковые отходы

Eco-booms are typically constructed from durable, water- and UV-resistant materials, such as high-density polyethylene (HDPE), polyvinyl chloride (PVC), or PVC-coated polyester fabric. The design features a floating section and a submerged skirt that extends below the water's surface. The floating section traps debris, while the skirt prevents pollutants from passing underneath.

Key Features of the Eco-boom System (Table 1):

- **Adaptability:** Can be customized in various sizes and shapes to suit different environments and waste types.
- **Versatility:** Suitable for deployment in diverse water conditions, from calm lakes to fast-flowing rivers.
- **Durability:** Built from materials resistant to water and UV rays, ensuring long operational life.
- **Easy to install and maintain:** Requires minimal technical expertise for setup and regular maintenance.

Table 1. Advantages and disadvantages of the Eco-boom system
Таблица 1. Преимущества и недостатки системы Eco-boom

Advantages	Disadvantages
Pollution Control: Effectively prevents waste, oil spills, and other pollutants from spreading, protecting sensitive ecosystems.	**Dependent on Environmental Conditions:** The efficiency of Eco-booms can be affected by factors such as strong water currents, waves, and the volume of waste.
Waste Collection: Helps improve the aesthetics of water bodies by capturing floating debris.	**Frequent maintenance:** Regular cleaning and repair are necessary to maintain effectiveness.
Biodiversity protection: Reduces the risk of entanglement and ingestion of waste by marine species.	**Challenges in waste retrieval:** Collecting large quantities of waste accumulated by Eco-booms can be difficult, especially in remote locations.
Cost-effective initial setup: Requires relatively low investment compared to more complex systems.	**Limited to floating waste:** Ineffective for submerged or seabed debris, limiting its scope in comprehensive cleanup efforts.

[1] The Ocean Cleanup successfully collects ocean plastic, aims to scale design [Электронный ресурс]. – URL: https://news.mongabay.com/2019/10/the-ocean-cleanup-successfully-collects-ocean-plastic-aims-to-scale-design (дата обращения: 06.02.2025)

Active collection systems play a significant role in addressing marine debris by directly removing waste from coastal and marine environments. These systems often employ advanced technologies, including autonomous devices and artificial intelligence (AI), to enhance the efficiency of waste collection efforts. Below are notable examples of active collection systems currently in use or development.

The Ocean Cleanup, a non-profit initiative founded by Dutch inventor Boyan Slat in 2013, focuses on large-scale plastic waste removal from the world's oceans (Fig.3, Table 2). The project has developed two main systems: a passive ocean cleanup system targeting garbage patches and an active interceptor system for river waste.

Fig. 3. The Ocean Cleanup Project[2]
Рис. 3. Проект The Ocean Cleanup

The ocean cleanup system features a U-shaped floating barrier, extending over a kilometer in length, that concentrates and captures floating debris. Two vessels tow the barrier slowly across the ocean surface, allowing accumulated waste to be periodically collected and transported for recycling. AI technology is employed to identify high-density waste areas and optimize operational routes.

The interceptor system, designed for river applications, is an autonomous device that prevents debris from reaching the ocean by collecting waste directly from rivers. It operates continuously, using a conveyor mechanism to lift waste from the water surface and store it in onboard containers.

Table 2. Advantages and disadvantages of The Ocean Cleanup
Таблица 2. Преимущества и недостатки The Ocean Cleanup

Advantages	Disadvantages
Large-scale capability: Effective at removing significant quantities of waste from both oceans and rivers.	**High operational cost:** Requires substantial financial resources for deployment and maintenance.
Advanced Technology: Incorporates AI and autonomous systems for efficient operation.	**Potential environmental impact:** Risks of interfering with marine life during waste collection.
Pollution reduction: Helps mitigate the impact of marine litter by removing large debris concentrations.	**Durability concerns:** System reliability in extreme ocean conditions remains uncertain.
Awareness-raising: Promotes global awareness of ocean plastic pollution.	**Limited microplastic collection:** Ineffective at capturing microplastics, which are a critical component of marine pollution.

[2] The Ocean Cleanup successfully collects ocean plastic, aims to scale design [Электронный ресурс]. – URL: https://news.mongabay.com/2019/10/the-ocean-cleanup-successfully-collects-ocean-plastic-aims-to-scale-design (дата обращения: 06.02.2025)

The Seabin Project, initiated by Australian surfers Andrew Turton and Pete Ceglinski, targets plastic pollution in calm coastal waters, such as marinas, harbors, and docks (Fig.4, Table 3). The Seabin acts as a "floating trash can," collecting surface debris through a submersible water pump that draws water into a mesh bag, where waste is trapped while clean water is returned to the environment.

Fig. 4. Seabin Project[3]
Рис. 4. Проект Seabin

The Seabin functions as a water filtration device designed to act as a floating trash bin. It is permanently installed in docks or other calm water environments, operating continuously to collect waste from the water surface. The device comprises a cylindrical container made from recycled HDPE plastic and stainless steel, housing a mesh bag that captures debris. A submersible water pump draws in water, trapping waste in the mesh bag while releasing filtered, clean water back into the environment. The Seabin is capable of collecting a wide range of waste materials, including large debris, microplastics, grease, and even microplastic fibers.

Table 3. Advantages and disadvantages of the Seabin project
Таблица 3. Преимущества и недостатки проекта Seabin

Advantages	Disadvantages
Continuous operation: Runs 24/7, collecting waste without requiring constant human intervention.	**Limited range:** Only effective in calm, enclosed waters; unsuitable for open seas or rough conditions.
Low operating cost: Requires minimal maintenance and operational expenses.	**Limited capacity:** Each Seabin can hold a limited amount of waste (approximately 20 kg).
Microplastic collection: Capable of capturing microplastics and small debris.	**Energy consumption:** Requires electricity to power the pump, contributing to carbon emissions.
Ease of use: Simple design allows for quick installation and maintenance.	**Potential impact on small marine life:** Risk of inadvertently trapping small marine organisms.

SeaClear, a project funded by the European Union's Horizon 2020 program, aims to tackle marine litter using a multi-robot platform that operates autonomously in coastal areas. Unlike other systems focused on surface debris, SeaClear targets waste on the seabed, where concentrations are higher and have a more direct impact on marine ecosystems (Fig.5, Table 4).

[3] SF on the Bay. Seabin Project Celebrates a New Seabin Installation! [Электронный ресурс]. – URL: https://www.sfonthebay.com/tag/seabin-project/ (дата обращения: 06.02.2025)

Fig. 5. SeaClear project robot[4]
Рис. 5. Робот проекта SeaClear

The system includes several robotic components:

- **Unmanned Aerial Vehicles (UAVs)**: Monitor the ocean surface and identify waste hotspots.
- **Underwater Observation Robot (ROV)**: Uses AI to distinguish waste from marine life and classify different types of debris.
- **Underwater Collection Robot (ROV)**: Equipped with a gripper and suction mechanism to collect waste from the seabed.
- **Autonomous Surface Vessel (USV)**: Serves as the control center, providing power and data processing for the other robotic units.

Table 4. Advantages and disadvantages of the Seaclear
Таблица 4. Преимущества и недостатки SeaClear

Advantages	Disadvantages
Comprehensive coverage: Can access and clean areas difficult for humans to reach, such as under docks or in deep waters.	**High initial investment:** Development and deployment of autonomous robots require substantial financial resources.
Environmental protection: Helps remove seabed waste, reducing its harmful effects on ecosystems.	**Limited capacity:** Current prototypes have limited ability to collect large or complex waste items.
Technological innovation: Promotes advancements in autonomous robotics and AI for environmental applications.	**Potential ecological impact:** Despite AI-based waste detection, there is a risk of inadvertently harming marine life.
Safety: Reduces the risks faced by human divers during cleanup operations.	—

WasteShark developed by RanMarine Technology, is an autonomous surface water robot designed to operate in coastal areas, ports, and inland waters (Fig.6, Table 5). Shaped like a whale shark, it features a wide open “mouth” to collect floating debris, including plastics, algae, and other pollutants. The robot is equipped with electric propulsion motors and LiDAR sensors for collision avoidance.

[4] SeaClear Project. Autonomous Robots for Marine Litter Collection [Электронный ресурс]. – URL: https://seaclear-project.eu/ (дата обращения: 06.02.2025)

Fig. 6. WasteShark project robot[5]
Рис. 6. Робот проекта WasteShark

WasteShark features a compact design inspired by the whale shark, with a wide, open "mouth" to collect floating debris. The robot navigates the water surface using two electric propulsion motors, safeguarded by RanMarine's proprietary protection technology. It can function autonomously or be operated remotely via a 4G connection. Equipped with LiDAR sensors for collision avoidance, WasteShark is also capable of monitoring water quality by measuring parameters such as pH, dissolved oxygen, turbidity, and other key indicators. The robot can operate continuously for up to six hours and has a capacity to collect up to 500 kg of waste per day.

Table 5. Advantages and disadvantages of the WasteShark
Таблица 5. Преимущества и недостатки WasteShark

Advantages	Disadvantages
Environmentally friendly: Powered by electric motors, it emits no greenhouse gases.	**Limited operating range:** Primarily effective in coastal and inland waters; not suitable for open seas.
High capacity: Can collect up to 500 kg of waste daily.	**The limited waste size:** Designed to collect only floating waste of certain sizes.
Flexibility: Operates in various environments, including canals, marinas, and harbors.	**Automation challenges:** May encounter difficulties in complex or crowded environments.
Data collection: Capable of monitoring water quality by measuring parameters such as pH, dissolved oxygen, and turbidity.	—

Comparative analysis of ocean waste collection systems. The following table provides a comparative analysis of ocean waste collection systems based on key criteria such as investment cost, collection efficiency, environmental impact, and scalability (Table 6).

Passive systems such as Eco-boom and Seabin require significantly lower initial investment compared to active systems like SeaClear and The Ocean Cleanup, which involve complex technology and substantial financial resources. WasteShark presents a moderate investment cost, benefiting from its relatively simple design and use of electric motors.

Regarding collection efficiency, The Ocean Cleanup and SeaClear demonstrate high efficiency in collecting large quantities of ocean and seabed waste, albeit at higher costs and with potential environmental risks. In contrast, Eco-boom and Seabin are effective in specific environments, primarily targeting floating debris in confined areas.

[5] Designboom. Drone WasteShark removes plastic waste and biomass from water bodies [Электронный ресурс]. – URL: https://www.designboom.com/technology/drone-wasteshark-ranmarine-technology-plastic-waste-biomass-07-04-2022/ (дата обращения: 06.02.2025)

Table 6. Comparative analysis of ocean waste collection systems
Таблица 6. Сравнительный анализ систем сбора океанских отходов

System	Investment Cost	Collection Efficiency	Environmental Impact	Scalability
Eco-boom	Low	Moderate (targets only floating waste)	Low (minimal impact on marine life)	High (easy to deploy in various locations)
The Ocean Cleanup	High	High (collects large amounts of waste)	Moderate (potential impact on marine life)	Moderate (dependent on environmental conditions)
Seabin Project	Low	Low (limited to small areas)	Low (minimal impact on small marine life)	Low (suitable only for calm, enclosed waters such as marinas)
SeaClear	Very High	High (targets seabed waste)	Moderate (potential risks to benthic organisms)	Low (still in the experimental stage)
WasteShark	Moderate	Moderate (collects floating waste and microplastics)	Low (environmentally friendly with electric propulsion)	High (easy to deploy in coastal and inland waters)

In terms of environmental impact, Eco-boom, Seabin, and WasteShark are assessed to have low environmental impact due to their passive or eco-friendly operational mechanisms. Conversely, SeaClear and The Ocean Cleanup pose potential risks to marine ecosystems, particularly due to their active collection mechanisms and possible interference with marine life.

When considering scalability, Eco-boom and WasteShark exhibit high scalability, being relatively simple to deploy across various locations. However, SeaClear remains in the experimental phase, limiting its current scalability for large-scale deployment.

FUTURE RESEARCH DIRECTIONS AND POLICY RECOMMENDATIONS

As ocean pollution continues to escalate, future research should focus on advancing both existing technologies and innovative approaches to waste collection. Potential research directions include:

1. Development of AI-driven autonomous systems: Enhancing the capabilities of autonomous robots by integrating advanced AI and machine learning algorithms to improve real-time decision-making, navigation, and waste classification.
2. Hybrid systems combining active and passive mechanisms: Designing systems that can leverage both passive collection and active removal strategies to increase overall efficiency and adaptability to different marine environments.
3. Biodegradable collection materials: Exploring the use of biodegradable and eco-friendly materials for building collection systems to further reduce their environmental footprint.
4. Microplastic filtration technologies: Developing efficient filtration systems capable of capturing microplastics, which are a significant and persistent threat to marine ecosystems.
5. Long-term impact studies: Conducting longitudinal studies to assess the ecological and economic impacts of various waste collection systems, ensuring sustainable deployment.

Based on the findings of this study, several policy recommendations can be made to promote the adoption of ocean waste collection systems, particularly in developing countries:

1. Incentivizing public-private partnerships: Governments should encourage collaboration between public agencies, private companies, and non-governmental organizations to fund and implement ocean cleanup initiatives.
2. Subsidies and tax incentives: Providing financial support, such as subsidies and tax incentives, for companies investing in ocean waste collection technologies can accelerate their development and deployment.
3. Capacity building and knowledge transfer: Establishing international cooperation programs to share best practices, technical expertise, and resources with developing nations.
4. Community-based initiatives: Promoting community-driven cleanup programs and citizen science initiatives to raise public awareness and foster local engagement in marine conservation efforts.

5. Legislation and regulation: Implementing stricter regulations on waste management, marine littering, and plastic production, combined with enforcement mechanisms, can significantly reduce the influx of waste into the ocean.

CONCLUSIONS

Marine debris, predominantly plastic waste, has emerged as a critical environmental issue with far-reaching ecological, economic, and social implications. Despite ongoing global efforts to curb pollution at its sources, the vast quantity of waste in marine ecosystems underscores the urgent need for effective remediation strategies. This review explores a variety of ocean waste collection systems, encompassing both passive and active technologies, and highlights their respective advantages and limitations.

While passive systems present a low-cost, energy-efficient approach, they primarily target surface debris and are often limited by environmental conditions. Conversely, active systems, driven by advanced technologies, offer higher efficiency and the capacity to address a broader spectrum of marine waste, yet they require significant financial investment and may pose risks to marine life.

The findings indicate that a multifaceted approach, integrating advanced technological solutions with preventive measures and public engagement, is essential for addressing marine debris comprehensively. Future research should prioritize innovation in collection systems, particularly in enhancing scalability, cost-effectiveness, and environmental compatibility. Additionally, sustained policy support and global collaboration are crucial to advancing the deployment of sustainable waste collection solutions. Through a concerted effort, it is possible to mitigate the impact of marine debris and safeguard the health of marine ecosystems for future generations.

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