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Article

Development and Field Testing of a Cavitation-Based Robotic Platform for Sustainable In-Water Hull Cleaning

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Abstract

Biofouling on ship hulls significantly increases hydrodynamic drag, fuel consumption, and greenhouse gas emissions, while also facilitating the spread of invasive species in regional and global waters, thereby threatening marine biodiversity. To address these environmental and economic issues, we developed an innovative robotic platform for in-water hull cleaning. The platform utilizes a cavitation-based cleaning module that removes biofouling while minimizing hull surface damage and preventing the spread of detached particles into the marine environment. This paper describes the design, operation, and testing of a developed robotic cleaning system prototype. Emphasis is placed on integrating components and sensors for continuous monitoring of key seawater parameters (temperature, salinity, turbidity, dissolved oxygen, chlorophyll-a, etc.) before, during, and after underwater cleaning. Results from real-sea trials show the platform's effectiveness in removing biofouling and its minimal environmental impact, confirming its potential as a sustainable solution for in-water hull cleaning.

Keywords: biofouling; underwater robot; cavitation; closed-loop in-water hull cleaning system; environmental monitoring; wastewater treatment; field testing; sensor integration

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1. Introduction

Biofouling—the accumulation of microorganisms, plants, algae, and animals on submerged ship surfaces—represents a major environmental and economic challenge for the maritime industry [1]. The presence of biofouling increases hydrodynamic drag, resulting in higher fuel consumption, increased greenhouse gas emissions, and higher operational costs. In addition to the hull, biofouling accumulation on propellers further reduces propulsion efficiency and increases total shaft power demand, thereby directly affecting a vessel's energy performance [2]. Recent studies have shown that ship resistance due to marine biofouling is not solely determined by the height of attached microorganisms or macroorganisms but also by their shape, hardness, and density, which collectively influence the hull surface roughness. Numerical simulations and experimental data indicate that biofouling can increase tangential surface shear stresses and account for up to 80% of total resistance under heavy fouling conditions, highlighting the urgent need for sustainable hull maintenance technologies [3].

Moreover, biofouling facilitates the spread of invasive alien species—a subset of non-indigenous species (NIS) with the most adverse environmental impact—across regional and global waters, posing a serious threat to marine biodiversity and ecosystem balance [4,5]. Through the attachment and release of organisms and gametes, ship hulls are among the most important vectors for the introduction of NIS worldwide [3]. These impacts are particularly critical in semi-enclosed seas such as the Northern Adriatic, where heavy maritime traffic and sensitive marine habitats coexist in proximity [6,7]. The ecological consequences of NIS introductions, combined with the chemical pollution caused by traditional antifouling coatings, highlight the complexity of biofouling management as both an environmental and operational challenge [8].

Traditional antifouling strategies have relied heavily on biocidal coatings that release toxic substances, such as copper (Cu) and zinc (Zn) compounds, into the marine environment [9,10]. Although effective at delaying fouling, these coatings contribute to chemical pollution and require regular reapplication. Recent analyses have shown that a passenger vessel using conventional biocidal coatings may release more than 100 kg of copper per year, posing a significant ecotoxicological risk to coastal waters [8]. Hull cleaning in dry docks remains the standard method for restoring surface performance, yet it is time-consuming, costly, and often logistically challenging. On the other hand, uncontrolled in-water cleaning, which is prohibited in a vast majority of countries, can release significant quantities of biofouling residues and harmful substances directly into the sea, degrading water quality and spreading non-indigenous organisms. Recent studies have demonstrated that wastewater generated during in-water hull cleaning contains both antifouling paint particles and biofouling residues, which can inhibit phytoplankton growth in the water column by eluting dissolved heavy metals such as copper and zinc [11,12]. In one experimental study, researchers evaluated the effects of increasing concentrations of these contaminants on coastal marine planktonic ecosystems, including phytoplankton, zooplankton, and periphyton [13]. Periphyton, a community of microalgae and microorganisms that grow attached to underwater surfaces, responded differently to exposure to higher concentrations of zinc and copper than free-floating plankton. Instead of collapsing under higher concentrations of contaminants, small amounts of metal-tolerant microalgae attached to the surface dominated the periphyton community. Their "tolerance" therefore reflects a transition from a diverse community to one composed primarily of stress-resistant species that displace more sensitive taxonomic groups. Moreover, these discharges can create localized "hotspots" of chemical contamination in ports and semi-enclosed bays, where sedimented paint particles continue to release metals over time. This evidence underscores the importance of developing closed-loop in-water cleaning systems capable of capturing, filtering, and treating effluents before discharge to minimize ecological risks [14,15].

To minimize these risks, sustainable management strategies—such as the use of biocide-free coatings [16,17] combined with in-water cleaning systems equipped with debris capture [14] are increasingly recognized as the lowest-risk option. In recent years, research has increasingly emphasized the importance of continuous hull monitoring to prevent heavy biofouling accumulation before it develops into a complex fouling community. Monitoring and evaluating the biofouling status of ship hulls—using tools such as underwater cameras and periodic inspections—has proven effective in reducing both fuel consumption and emissions [18]. Combining underwater photography technology with timely cleaning interventions enables operators to detect the onset of biofilm formation early, thereby preventing severe fouling and unnecessary dry-docking operations.

To address these challenges, there is an urgent need for eco-friendly and sustainable in-water cleaning technologies that can efficiently remove biofouling without causing secondary environmental impacts. Such technologies should enable real-time environmental monitoring, the safe collection and treatment of removed materials, and compliance with cross-border environmental regulations. In this context, the GreenHull project (Green technologies for ecological cleaning of biological incrustation on hulls in the Northern Adriatic Sea), funded by the Interreg V-A Italy–Slovenia Cooperation Programme, developed a closed-loop hull-cleaning system that combines advanced sensors on a remotely operated vehicle (ROV) platform with water-treatment technologies. The project focused on improving ship performance and preventing the spread of NIS while ensuring effective cross-border management of marine waters and waste generated during hull-cleaning operations. A key outcome of the project was the development of an innovative underwater robotic platform for in-water hull cleaning, featuring a cavitation-based cleaning mechanism. The platform can operate underwater and remove biological fouling efficiently while minimizing surface damage and preventing the dispersion of detached material into the surrounding environment. The cleaning process is integrated with a land-based filtration and purification unit, which treats the water and biofouling residues in three stages—mechanical, chemical, and ultraviolet (UV) disinfection—before discharging it back into the sea.

This paper presents the design, operation, and experimental validation of the GreenHull robotic cleaning ROV platform. Emphasis is placed on the cavitation-based cleaning mechanism, the integration of sensor components, and field-test results in real marine conditions. The findings demonstrate the platform's potential as a sustainable and efficient solution for in-water hull cleaning, contributing to cleaner seas and greener maritime operations in the Adriatic and beyond. The developed technology currently operates at technology readiness levels (TRL) 5–6, and more systematic and controlled experiments, including standardized measurements of cleaning efficiency, environmental impact, and comparisons with alternative methods (e.g., rotating brushes, laser cleaning), are ongoing. Detailed economic analyses, extended performance assessments, and standardized inspection protocols will be conducted in future work, as part of the continued optimization of the platform. These planned activities ensure that the technology meets industrial requirements, complies with low-energy and low-emission standards, and provides a robust and environmentally responsible solution for maritime applications.

2. System Overview

In recent years, international regulatory pressure has accelerated the transition to closed-loop hull-cleaning technologies, which capture wastewater along with all biological material and debris. The collected material is then transported to shore and treated as contaminated industrial waste, while the wastewater is remediated before being released back into the marine environment. That is why it is called a closed-loop system, since the water used for cleaning operations is not consumed. Early innovators, such as the Norwegian company ECOsubsea, anticipated this shift as early as 2008, when emerging biofouling regulations in New Zealand, California, and Australia began to restrict traditional diver-based cleaning and mandate full capture of residues [19]. Their pioneering work in robotic in-water cleaning systems demonstrated the feasibility of automated ROV-based operations combined with complete residue collection, setting a new industry standard for environmental compliance.

The GreenHull system described in this work represents an integrated eco-innovative solution for the sustainable removal of biofouling from ship hulls. It has been conceived as a comprehensive closed-loop approach that combines advanced underwater robotics, real-time environmental monitoring, and controlled waste management. The main goal of the system is to enable in-water hull cleaning without releasing pollutants or biological material into the surrounding environment. To achieve this, the GreenHull system connects an ROV platform, responsible for in-water cleaning operations, with an onshore (or onboard a large vessel) filtration and purification unit that processes and treats the removed material and seawater. The system has been designed to operate effectively in ports or marinas with minimal environmental impact, aligning with European strategies for greener, more sustainable maritime transport.

Today, closed-loop systems like ECOsubsea's and GreenHull's represent the state-of-the-art in sustainable hull maintenance. They comply with the latest environmental guidelines, which increasingly require that biofouling organisms and antifouling paint particles be captured and treated before discharge. This alignment with global regulatory trends enhances the replicability and scalability of such an approach across European ports. The overall configuration and working principles of the GreenHull closed-loop hull cleaning system are described in the following section (Section 2.1). After that, detailed descriptions of the robotic platform design and sensor integration are presented in Sections 2.2 and 2.3, respectively.

2.1. Closed-Loop Hull Cleaning System

The closed-loop hull-cleaning system was designed to enable environmentally safe, efficient, and controlled in-water hull cleaning. The system shown in Figure 1 integrates the following main functional components:

1. An ROV equipped with a cavitation-based cleaning module. The core of this system is a series of rotating jet nozzles powered by a high-pressure water pump, installed either on a vessel or onshore. These jet nozzles rotate within a bowl-shaped container mounted on the ROV, which leans against the vessel's hull. The nozzles are designed to cause a sudden change in water pressure, resulting in the formation and collapse of vapor-filled bubbles in the surrounding seawater. This phenomenon, called cavitation, is the primary mechanism for removing biofouling in the described system.
2. A high-voltage, neutrally buoyant tether operating at 800 V, combined with fiber optic communication and an additional high-pressure hose, all mounted on a spool with a slip-ring.
3. A flexible suction and transport hose used for conveying wastewater and fouling material.
4. A container-based modular wastewater treatment plant located on a nearby shore or vessel, large enough to hold a small container and supply electric power for the entire cleaning system.

During closed-loop hull cleaning, an ROV equipped with a cleaning module removes biological fouling from the ship's hull, and the captured material is immediately conveyed to the surface through a suction hose into a storage container, where it is temporarily held before entering the modular wastewater treatment plant. The purification system consists of three sequential modules:

- Module 1—Mechanical filtering: Removes large particles and suspended solids; the collected sediment is classified as hazardous waste and directed to a sludge tank for dewatering and disposal.
- Module 2—Biological and chemical treatment: Treats residual organic and chemical contaminants through combined biological and chemical processes.

- Module 3—Disinfection (UV lamp): Final treatment step that inactivates microorganisms, ensuring that purified seawater meets environmental safety standards before being discharged back into the sea.

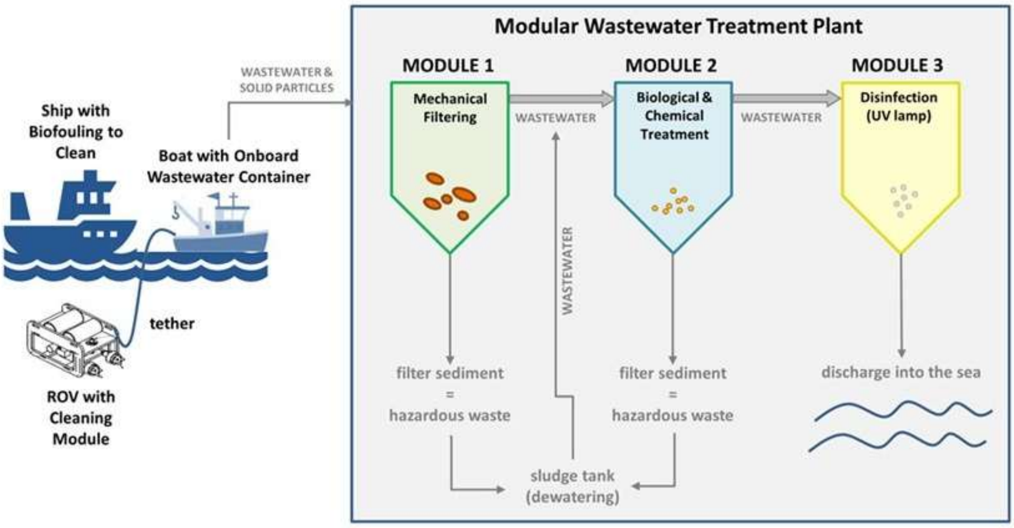

Figure 1. Schematic representation of the closed-loop hull cleaning system developed within the GreenHull project. The system features an ROV with a cleaning module and an onshore modular wastewater treatment plant that includes three stages: mechanical filtration, biological and chemical treatment, and UV disinfection.

A schematic representation of the entire system is shown in Figure 1, illustrating the interactions among the underwater robot, the connecting pipeline, and the onshore wastewater treatment facility. This closed-loop configuration eliminates the uncontrolled release of biofouling residues, heavy metals, or biocides during hull cleaning, significantly reducing the risk of cross-border pollution and the spread of invasive species. The system therefore provides a sustainable, regulatory-compliant solution for in-water hull maintenance in ecologically sensitive marine areas, such as the Northern Adriatic.

The development of the GreenHull system aligns with emerging global regulations and industry initiatives discussed at the annual In Port Inspection & Cleaning Conference (PortPIC), where regulators, coating manufacturers, and ship operators jointly emphasized the transition to standardized, science-based, and fully contained hull cleaning systems [20]. Recent International Maritime Organization (IMO) biofouling guidelines [21], together with the new ISO standards (ISO 20679:2025 and ISO 6319) [22,23], underline the requirement that in-water cleaning technologies ensure both coating compatibility and effective capture of residues. Ports such as Bergen and Oslo already permit only those systems that include complete debris recovery, reflecting a growing international consensus that hull cleaning without residue containment is no longer acceptable.

2.2. Robotic Platform Design

2.2.1. Alignment of System Design with Regulatory Requirements

A new prototype ROV was developed for eco-friendly biofouling removal from ship hulls in the challenging marine environment of the Northern Adriatic Sea. The system was designed in compliance with various national and transnational regulations, as there is currently no unified legal framework governing underwater hull cleaning. In Slovenia, although no specific national legislation yet exists for this activity, the development procedure ensured that each operational phase complies with relevant environmental and maritime regulations. In Italy, similar provisions apply, and operational compliance must align with national environmental standards and port regulations. At the EU level, the activity is guided by overarching directives on marine environmental protection, waste management, and water quality, such as the Marine Strategy Framework Directive (2008/56/EC), Water Framework Directive (2000/60/EC), and revised Urban Wastewater Treatment Directive (EU) 2024/3019. Globally, the project followed the recommendations and best practices of the IMO and the BIMCO guidelines for environmentally sustainable hull maintenance, ensuring that the GreenHull system adheres to internationally recognized standards for safe, eco-friendly operations.

2.2.2. ROV System Description

The developed ROV serves as the core of the underwater cleaning system. It is specially designed for efficient navigation, inspection, and cleaning of ship hulls in real marine environments. The ROV has a compact, durable, marine-grade aluminum-alloy frame that enables stable maneuvering in dynamic underwater conditions. It is equipped with 10 sensors, 10 low-light cameras, and 14 lighting units, supporting navigation, communication, and operation in complex underwater conditions. Its vector propulsion system, comprising 12 thrusters, provides precise multidirectional movement and station-keeping during cleaning tasks. For navigation and awareness, the ROV features inertial measurement units (IMUs), ultrasound sensors, and 10 high-resolution, low-light cameras that provide a full 360° view, supplemented by 14 LED lights for better visibility in turbid water. An onboard artificial intelligence (AI) system processes sensor data and video streams to assist the operator with navigation and control. Electric power is supplied through a 300 m neutrally buoyant tether that also transmits communication signals to the surface control unit. This tether, along with a high-pressure hose, is wound onto a spool with a slip ring. The overall system allows real-time monitoring and operation in shallow and semi-deep waters, providing versatility for port-based cleaning. The main technical specifications of the ROV and the integrated cleaning module are summarized in Table 1.

Table 1. Technical specifications of the ROV and cleaning module.

Parameter	Specification
ROV dimensions	60 cm (W) × 60 cm (L) × 20 cm (H)
Complete system with ship-hull cleaning module	86 cm (W) × 104 cm (L) × 53 cm (H)
Cleaning principle	Mechanical + Cavitation
Total weight in air (ROV + cleaning module)	~180 kg
Maximum biofouling thickness	7 cm
Electric power	Up to 10 kW, 800 V DC
Cleaning rate	1–7 m^2/min (ship hulls)/1–8 m^2/min (submerged structures)
Power and communication tether length	300 m
Propulsion system	12 vector thrusters (12 × 700 W/69 N)
Imaging system	10 high-resolution cameras with a 360° view
Lighting	14 LED lights
Environmental monitoring	7 seawater parameters (WiMo probe)

The ROV also integrates a WiMo multiparametric environmental probe that continuously measures seven key seawater parameters (temperature, salinity, pH, dissolved oxygen, turbidity, conductivity, and chlorophyll-a) before, during, and after the in-water cleaning process. This ensures that cleaning operations are both safe and environmentally sustainable.

2.2.3. Cleaning Module for Underwater Ship Biofouling Removal

Recent studies recommend combining the cavitation cleaning principle with rotating brush units or integrating ultrasonic and laser cleaning technologies to increase efficiency further while keeping the system compact. Moreover, implementing local heating, UV irradiation, or sterilization methods can directly treat the biofouling removed from the hull, reducing the complexity and cost of waste handling. The use of bio-inspired adhesion technologies and AI-assisted autonomous navigation can further enhance the ROV's stability, cleaning coverage, and overall performance [24]. The GreenHull cleaning module removes biofouling by employing cavitation, generated by high-pressure water-jet nozzles that create a sudden pressure drop in the surrounding water, resulting in the formation of cavitation bubbles. Cavitation-based cleaning has proven to be one of the more effective methods for underwater applications [24,25], as it removes fouling particles without damaging the antifouling coatings on the hull surface. This significantly reduces the risk of releasing harmful substances or micro-particles into the marine environment.

Two jet nozzle systems are mounted on the GreenHull cleaning module, each with a 40 cm diameter. They are housed within a bowl-shaped container to prevent the escape of the fouling material produced during cleaning. The jet nozzles are mounted at a slight angle parallel to the cleaning surface and rotate around their perpendicular axis attached to the ROV. The high-water pressure of 220 bar at 40 L/min induces rotation of the axis and the formation of cavitation bubbles. This process effectively removes fouling within the module's working area without damaging the antifouling paint. Similarly to advanced cavitation intensification strategies in Venturi-type reactors, where optimizing pressure pulsation frequency and cavitation number suppresses ineffective cavitation while enhancing collapse energy density for process intensification [26], the rotating nozzle configuration in the GreenHull system modulates local pressure transients to promote vigorous, targeted bubble collapse. This design maximizes cleaning efficacy against biofouling while minimizing energy waste from non-productive cavitation regimes. The waste material produced is then pumped to the wastewater treatment plant through an attached discharge hose. The cleaning module can process fouling up to a few centimeters in height, owing to its soft-bottom attachment design. The ROV's forward movement, driven by two rear-mounted wheels and aided by the thrusters, guarantees a consistent cleaning path. The ROV with the cleaning module attached is shown in Figure 2.

Figure 2. Schematic representation of the ROV equipped with the cavitation-based cleaning module prototype for biofouling removal from ship hulls (**left**) and the final render of the assembled system with two bowl-like housings (blue) of rotating nozzles (**right**).

Our test showed that the cleaning rate of the entire system depends on various operational conditions, mainly influenced by fouling density and type, operator skill, hull curvature, and more. We achieved cleaning speeds of up to 7 m^2/min in light fouling, but about 1 m^2/min for heavy fouling. Although cavitation cleaning is gentle and causes minimal coating damage, it has certain limitations. Its effectiveness drops against very hard calcareous fouling (>5–10 cm thick), which may require mechanical pre-treatment or the use of specialized cavitation nozzles or hybrid cleaning approaches, as also reported in recent reviews of contactless underwater cleaning technologies [24]. The energy use is higher than that of simple brush-based systems (~15–25 kWh per 100 m^2, mainly due to the high-pressure pump in the developed prototype), and periodic nozzle maintenance is required due to wear. These trade-offs are acceptable for proactive, frequent cleaning of light-to-moderate fouling typical in regulated fleets. A direct and quantitative comparison of energy consumption and cleaning performance with alternative technologies (e.g., rotating brushes or laser-based cleaning) [24,27] requires additional measurements and analyses conducted under strictly controlled and comparable conditions, including identical fouling characteristics, surface areas, and operational parameters. Such benchmarking activities are planned as part of the continued development and optimization of the proposed cavitation-based system, with the aim of improving energy efficiency and ensuring compliance with industrial requirements and emerging low-energy and low-emission standards for underwater hull cleaning.

2.2.4. Cleaning Module for Submerged Structures

Since biofouling also accumulates on other artificial underwater structures, such as piers, barriers, and submerged walls, an additional cleaning module was developed for the ROV. This module combines mechanical and cavitation-based cleaning methods and is currently undergoing laboratory testing. It has potential for broader use in maintaining submerged infrastructure in ports and coastal structures. The main advantage of this module is its ability to remove thicker layers of biofouling from submerged objects. Since these structures are cleaned less frequently, they tend to accumulate significant biofouling.

The module for submerged structures relies on the same cavitation phenomena used in the hull cleaning module. However, in this case, high-pressure jet nozzles are integrated into a razor-shaped blade that moves side to side while producing cavitation bubbles. This movement enables the mechanical removal of biofouling material when cavitation alone is insufficient. The enclosed module system connects to a water pump with a macerator blade, which grinds up larger remains of biofouling material and facilitates its suction into the wastewater treatment plant on the ground. The developed prototype module is pending field testing and is shown in Figure 3.

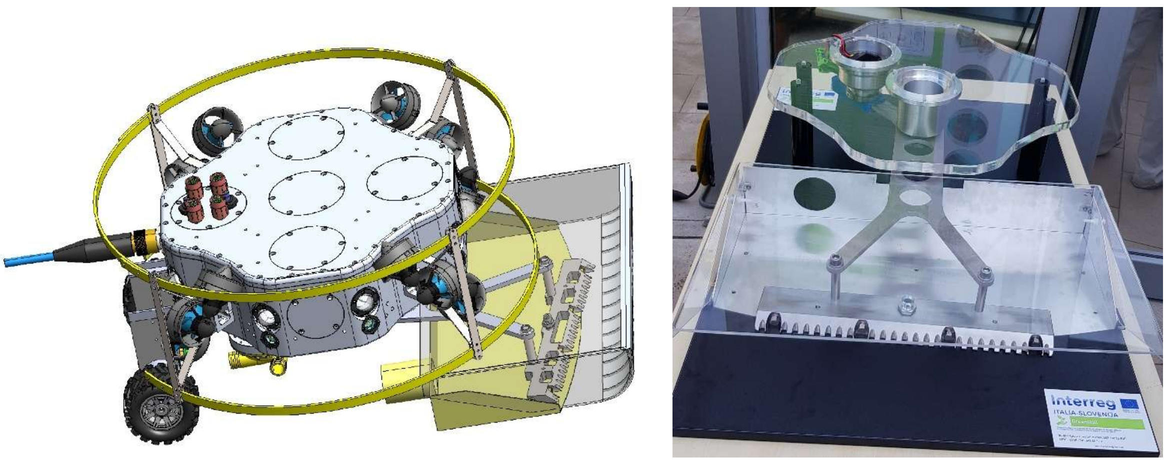

Figure 3. Schematic representation of the ROV with the cleaning module intended for submerged marine structures (**left**) and the first prototype of this cleaning module (**right**).

2.3. Sensor Integration for Environmental Monitoring

To monitor the cleaning process and ensure that the surrounding water is not contaminated, we use several environmental sensors. Among the multiparametric probes available on the market and suitable for the GreenHull project, a comparison of their main features is presented in Table 2. This table lists the parameters measured, communication modes, and additional options available for each system (CTD = conductivity/salinity, temperature, depth; Tu = turbidity; Chl-a = chlorophyll-a; DO = dissolved oxygen; PAR = photosynthetically active radiation).

Table 2. Comparison of selected multiparameter probe models.

Manufacturer	**Probe Model**	**Weight in Air/Water (kg)**	**Communication/ Connectivity**	**Basic Set of Required Parameters**	**Optical Sensors, Except CTD**	**Easy Calibration**
Sea-Bird Sci., Bellevue, WA, USA	SBE 52-MP Moored Profiler CTD & (optional) DO Sensor	5.3/3.7	RS232	CTD, DO	No	No
Teledyne Valeport Ltd., Totnes, UK	SWiFT CTD plus turb.	2.7/1.65	USB serial, Bluetooth	CTD, Tu	No	No
Idronaut S.r.l., Brugherio (MB), Italy	Ocean Seven 308	1.1/0.65	RS232C/RS485; WiFi/Bluetooth	CTD	No	No
OTT Hydromet, Kempten, Germany	Hydrolab HL7	4.5/NA	USB, SDI-12, RS232/485 Modbus	CTD, Tu, Chl-a, DO	Yes	No
AML Oceanographic Ltd., Victoria, BC, Canada	AML-6 RT CTD	4.0/2.1	WiFi, USB-C/MCBH, RS232	CTD, Tu, Chl-a, DO	Yes	No
Sea & Sun, Technology, Trappenkamp, Germany	CTD 90M	6.0/NA	USB; RS 232	CTD, Tu, Chl-a, DO, PAR	No	No
nke Instrumentation, Hennebont, France	WiMo Plus 7	3.05/NA	WiFi, ModBus RTU	CTD, Tu, Chl-a, DO	Yes	Yes

A general overview of the data shows that the Sea & Sun CTD 90M probe is the heaviest but includes the broadest range of sensors, being the only model equipped with a PAR sensor. In contrast, the Idronaut Ocean Seven 308 is the lightest but is limited to basic CTD measurements. The Valeport SWiFT CTD plus turbidity is slightly more advanced, as it includes a turbidity sensor in addition to CTD parameters.

The WiMo Plus 7 probe (Figure 4), produced by NKE Instrumentation, was ultimately selected as the most suitable option for the project. It combines robustness, modularity, and versatility while maintaining a relatively low weight and volume. The probe allows simultaneous installation of up to seven sensors. It supports a broad range of environmental measurements, including temperature, salinity, turbidity, DO, Chl-a (in situ fluorometric detection), PAR, and pressure. Additional modules can measure nitrates, pH, phycocyanin, and colored dissolved organic matter (CDOM).

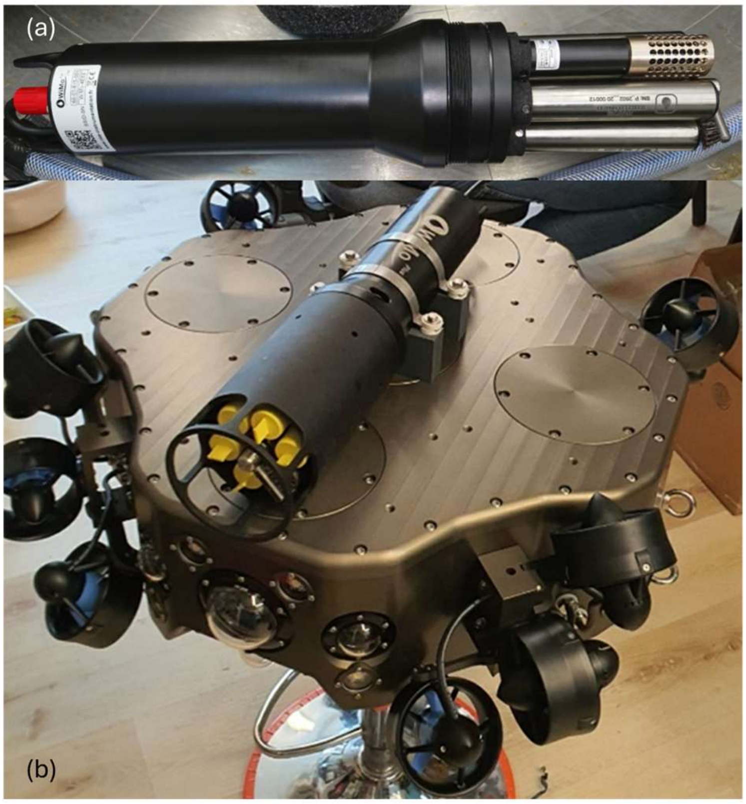

Figure 4. (**a**) WiMo Plus 7 multiparametric probe used for environmental monitoring during hull cleaning operations. (**b**) ROV equipped with the WiMo Plus 7 probe for in situ measurement of marine environmental parameters before, during, and after the cleaning process.

Each sensor on the WiMo Plus 7 can be easily mounted or replaced in the field without specialized tools. The probe supports both wired and wireless communication (WiFi or Bluetooth), enabling real-time data access via a laptop or mobile device. A key advantage of the WiMo system is its simple calibration procedure: using a dedicated calibration kit, individual sensors can be immersed in reference solutions of known concentration (e.g., oxygen or Chl-a standards), and calibration can be finalized with laboratory verification—without sending the sensors back to the manufacturer. The WiMo probe, mounted on the ROV, was purchased on 9 October 2020, along with the calibration certificate. It was used for less than 15 h before the field experiment on 18 August 2022. Therefore, recalibration was not necessary. The sampling frequency is configurable, with an interval of a few seconds being sufficient for the intended application, as the environmental conditions during cleaning change relatively slowly. High precision is not critical for this purpose; instead, stability and robustness of measurements are essential, both in terms of sensor structure and data consistency.

3. Experimental Setup and Field Tests

Field experiments were conducted to evaluate the performance of the developed ROV cleaning system and to monitor potential environmental effects during underwater hull cleaning. Environmental monitoring and water sampling were conducted in the coastal area of Portorož, Slovenia (Figure 5).

Figure 5. Test vessel "Laho" used for field experiments with the ROV-based hull cleaning system, and the cleaning site location in Portorož, Slovenia (source: Google Earth).

The most comprehensive field test took place on 18 August 2022, when the ROV equipped with the cavitation-based cleaning module was deployed at the vessel Laho (Figure 5), located near the salt warehouse in Portorož. During this test, the WiMo multiparameter probe was mounted directly on the ROV frame and monitored the parameters throughout the entire cleaning procedure. The probe was activated and time-synchronized via Bluetooth using a mobile phone before immersion and deactivated upon retrieval of the ROV. This configuration enabled real-time measurement of key water-quality parameters in the immediate vicinity of the cleaning operation.

The WiMo probe continuously recorded seven environmental parameters: temperature, salinity, dissolved oxygen, turbidity, Chl-a, phycocyanin, and CDOM. The sampling frequency was set to 0.5 s, which provided sufficient temporal resolution given the relatively slow changes expected during cleaning. These measurements enabled the assessment of short-term fluctuations in water quality, particularly those potentially induced by biofouling removal.

In addition to in situ monitoring with the WiMo probe, laboratory analyses of seawater samples were conducted to assess metal (Cu, Zn) and Chl-a concentrations. To safely manage waste seawater produced during cleaning, the ROV was connected to a prototype onshore wastewater treatment plant, housed in a small container via a flexible hose. In this study, the purpose of the field tests was not to evaluate or validate the performance of the wastewater treatment system as an independent effluent treatment plant. Instead, the focus was on preventing the uncontrolled release of removed biofouling material and associated contaminants into the surrounding seawater during the underwater hull-cleaning process itself. In the context of this study, environmental safety refers specifically to the physical containment, capture, and isolation of dislodged biological material and particulate matter at the source, rather than to full regulatory certification of the wastewater treatment module. Laboratory analyses, discussed in Chapter 4, confirmed that high concentrations of Chl-a, Cu, and Zn generated during cleaning were effectively retained within the closed-loop system, demonstrating that the developed cavitation-based ROV cleaning concept successfully prevents the dispersion of biofouling residues and heavy metals into ambient seawater, which represents one of the key environmental risks associated with conventional in-water hull-cleaning methods. Solid residues, containing biofouling fragments and heavy metals, were collected as hazardous waste for proper disposal. A comprehensive quantitative assessment of the wastewater treatment module itself, including detailed retention efficiencies, microbial inactivation performance, and compliance with standards such as ISO 20679:2025, is beyond the scope of the present work and will be addressed in future studies as part of higher-TRL system validation and regulatory certification.

4. Results and Discussion

Figure 6 (left) shows the underwater robotic platform in action during hull cleaning, highlighting the direct in situ measurement setup of the WiMo probe attached to the ROV. This arrangement enables real-time monitoring of key environmental parameters, allowing potential effects of the cleaning process on the surrounding seawater to be detected and measured. Accordingly, the primary focus of this study is the assessment of sustainable underwater hull-cleaning from an environmental perspective, specifically to ensure that the developed cavitation-based technology does not cause secondary pollution of the surrounding seawater during or after biofouling removal. The cavitation module achieved approximately 95–98% removal of visible macrofouling, as shown in Figure 6 (right) in the before/after comparison, based on underwater video and post-cleaning diver inspections. This reduced the residual coverage to less than 5% of the original macro-organisms.

Figure 6. The ROV during an in-water hull cleaning operation in Portorož, Slovenia (**left**). The image shows the in situ deployment of the cavitation-based cleaning module and the real-time monitoring setup using the WiMo multiparametric probe. Demonstration of cleaning effectiveness using the developed cavitation-based hull-cleaning technology on a different vessel, shown out of the water for clarity (**right**). The image presents a section of the ship hull with an uncleaned area covered by marine biofouling and an adjacent cleaned area below, where biofouling has been successfully removed, leaving the antifouling paint (dark blue) largely intact. The same cavitation-based cleaning principle was applied in both cases.

Although cleaning effectiveness is not the central objective of this work, these results demonstrate that effective biofouling removal can be achieved simultaneously with environmentally responsible operation. Fouling conditions during cleaning (Figure 6, right) were moderate to severe, with small tubeworms, barnacles, filamentous algae or grass, and soft organisms covering the antifouling coating. The thickness of fouling was, on average, less than 1 cm. Post-cleaning visual and tactile inspection of the cleaned area (as shown in Figure 6, right) revealed no significant increase in roughness, no paint loss, and no primer exposure, supporting the suitability of cavitation-based cleaning for sustainable hull maintenance. While the achieved cleaning effectiveness exceeds 95% under realistic field conditions, the novelty and main contribution of this study lie in demonstrating a closed-loop, environmentally conscious hull-cleaning concept combined with real-time monitoring of potential environmental impacts. More extensive performance-oriented cleaning comparisons will be addressed in future studies at higher TRL.

4.1. Results from WiMo Probe Measurements

During the 18 August 2022 field test on the vessel Laho, the WiMo multiparametric probe recorded a continuous time series of seven water-quality parameters before, during, and after the cleaning operation.

The maximum number of data points recorded within 1.5 h is less than the expected 2700 because there was a 30 s data gap and 169 data points sampled at 3 s instead of 2 s, resulting in 2622 values. There were many spikes in the measured parameters, especially in optical sensors such as Chl-a, CDOM, phycocyanin, and turbidity. Fluorescence sensors, specifically designed to measure in situ Chl-a (a total phytoplankton/algal biomass indicator) and phycocyanin (an indicator of cyanobacteria and some other algal groups), should provide a view on changes in the seawater surrounding the vessel due to escaped parts of fouling. Although the oxygen sensor is also optical, its working principle differs from typical fluorometric methods. The LED (610–630 nm) excites an oxygen-reactive foil or membrane, and the luminescence from the membrane (not from the illuminated water) is detected by a near-infrared (NIR) photodiode (760–790 nm). It also benefits from automatic compensation for temperature and salinity. While the other four optical sensors depend on ambient light conditions—especially the Chl-a sensor—this is not the case for the oxygen sensor, and no oxygen spikes were observed during measurements on the ROV. The temperature parameter showed no spikes, while conductivity, which, along with temperature (and pressure), influences salinity, experienced spikes approaching zero. The proportion of salinity spikes was relatively low, less than 2% (see Table 3).

Table 3. Basic statistics of measured parameters with WiMo on the ROV during the hull cleaning operation. Num (without units) indicates the number of 2 s data points after removing spikes between 18:00 and 19:30 on 18 August 2022. STD represents the standard deviation from the mean value after spike removal.

Parameter	Mean	Median	STD	Num
Temperature (°C)	26.01	26.01	0.05	2622
Salinity (PSU)	38.23	38.21	0.11	2572
Oxygen (mg/L)	7.79	7.80	0.11	2622
Turbidity (NTU)	0.97	0.78	0.64	2361
CDOM (ppb)	2.23	2.22	0.41	2286
Phycocyanin (ppb)	18.81	19.20	5.25	2145
Chl-a (µg/L)	17.59	17.82	8.96	911

The procedure for removing spikes is based on histograms in Matlab (version 2025) of the parameter. In the first step, histograms of the parameter distributions were generated using 50 bins that covered the range from 0 to the parameter's maximum (spike) value. Then, a 'cut' was determined for all parameters except for salinity, to eliminate extremely high values by selecting a value within a bin where the number of low-measured values decreased significantly (<10). For salinity, a similar cutoff was used to eliminate spikes near zero salinity. In the second step, histograms were generated again from the remaining data in the same manner. This two-step process was sufficient to remove spikes from all parameters. However, the cause of their appearance is unclear and appears linked to the probe's malfunction, which is currently under examination by the producer.

As mentioned earlier, there were no spikes in temperature or oxygen parameters (Table 3), whereas salinity showed 1.9% near-zero spikes. According to Table 3, the parameters with the highest spike shares are turbidity (10.0%), CDOM (12.8%), phycocyanin

(18.2%), and the Chl-a sensor, which had the highest spike share at 65.3%. While Table 3 presents basic statistics of the parameters, Figure 7 shows their evolution over time after removing the spikes. Aside from salinity, all other quantities do not exhibit a low-frequency trend within an interval of 1.5 h, and their values fluctuate around reasonable mean and median values. The median values are close to their mean values (Table 3), with the most considerable difference between the median and mean observed in turbidity, which also has the highest ratio of standard deviation (STD) to the mean at 65%. The second-largest deviation is observed in Chl-a, with a ratio of 51%.

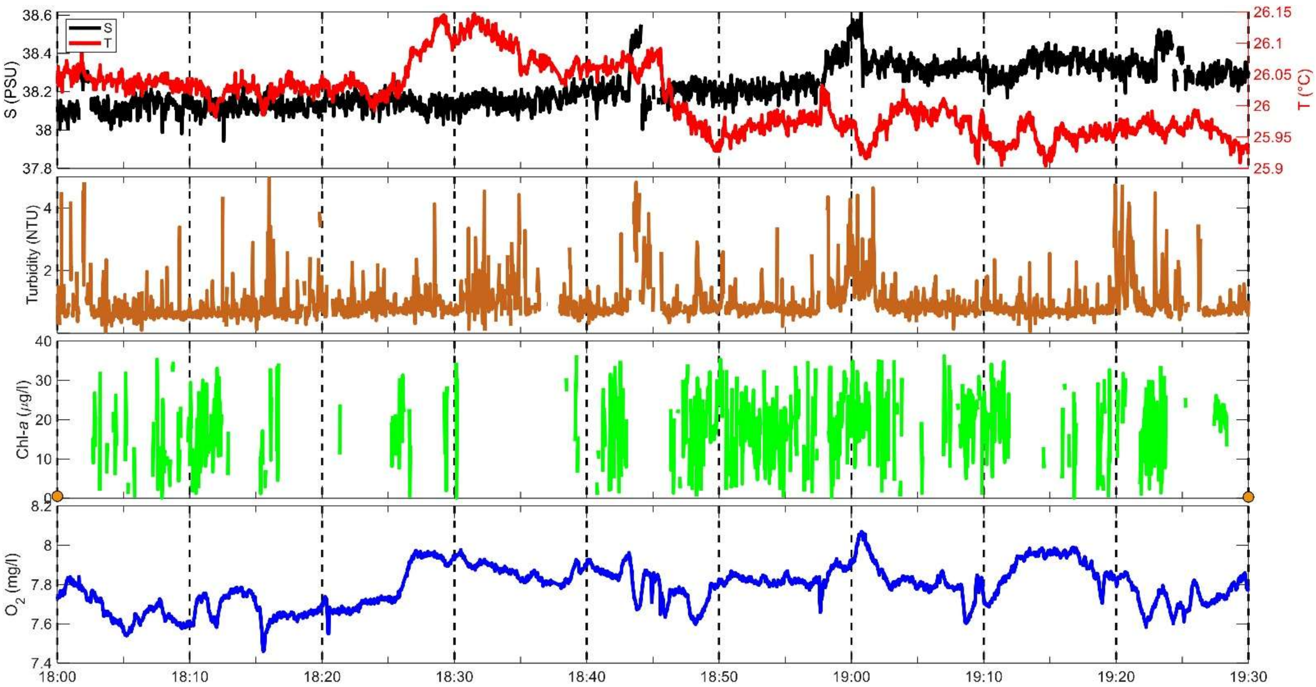

Figure 7. Time evolution over 1.5 h of measurements for five out of seven parameters recorded with WiMO plus during the ship's hull cleaning. Spikes in the data were removed. Orange dots at the beginning and end of Chl-a measurements indicate in vitro fluorometric determination of Chl-a at the start and during the cleaning operation. Evidently, the largest number of removed spikes was in the Chl-a measurements, while other parameters had a smaller share of spikes or none at all (see Table 3 for the number of measurements).

While the temperature and salinity values are reasonable for the summer period [28] and oxygen values are also plausible (93%–100% of saturation), turbidity (0.97 $\pm$ 0.64 NTU) without spikes is at the lower end of the turbidity range (1–700 FNU; NTU and FTU units are similar; see [29]). Measurements conducted in [28] were collected from 180 sampling stations in large estuaries, inland, and coastal waters within the HYPERMAQ dataset of bio-optical properties [30]. Additionally, the very peculiar Chl-a measurements obtained with WiMo are within the range of values seen in this database (0.9–180 μg/L). Typical values of CDOM (colored dissolved organic matter) and phycocyanin (used for detecting cyanobacteria) in ppb units, described by the manufacturer of the WiMO probe (the NKE company; [31]), have not been found yet in the literature for coastal waters.

Regarding the "poor performance" of 'in vivo' measurements of Chl-a, we can refer to a report by Deltares [32], which states that the median lower limit of the YSI 6025 chlorophyll sensor, at which it can be compared to laboratory spectrophotometric methods, was 5 μg/L in Dutch coastal waters. Although they could explain 72% of the chlorophyll fluorescence through in vitro measurements, most of the unexplained variation occurred at low concentrations below 5.2 μg/L. This is significant because the laboratory values were about an order of magnitude lower, suggesting potential issues with the representativeness of in situ measurements. Low concentrations of Chl-a measured in vitro (0.49 μg/L and 0.30 μg/L), shown as orange dots in Figure 7, are in line with the values measured on 17 August 2022 during regular national monitoring at the sampling station located in the center of the Bay of Piran, which ranged from 0.14 to 0.78 μg/L along the water column [33]. These low concentrations are unlikely to cause signal quenching, which is a reduction in signal intensity due to very high concentrations. However, a recent comparison study of in situ fluorometric measurements and in vitro spectrophotometric determinations of Chl-a in outdoor mesocosms in tanks [34] also shows a similar discrepancy. Their figure, which features a 'linearity check' using a more sensitive (X10) fluorometric in situ instrument (Cyclops-7F), reports in situ values that are two orders of magnitude higher than those measured in vitro. This paper does not aim to delve into the details of these differences; instead, it highlights that they are present and recognized in measurements using other field equipment besides WiMo plus. Nevertheless, the sensitivity and spiking responses of optical sensors to ambient and artificial lighting conditions on ROVs should be considered during future equipment testing, where simultaneous measurements with other (WiMO) probes are planned.

From an operational perspective, these findings underscore the need to refine sensor mounting and data synchronization methods further. For example, adding a dedicated camera view of the sensor area on the ROV and synchronizing video recordings with sensor time-series data would help better distinguish between actual water-quality variations and artifacts caused by operation-induced bubbles.

4.2. Context of Chemical and Biological Analyses

Alongside real-time monitoring with environmental sensors mounted on the ROV, diver-assisted sampling was conducted for laboratory analyses before, during, and after cleaning. This dual approach allowed for the assessment/control of sensor measurements and ensured that their placement on the ROV was optimal. Although these analyses are not the main focus of this paper, they provide important context.

The concentration limits for metals in wastewater and surface waters are not random; they are based on ecotoxicological data and consider the physico-chemical conditions of the water body. Specifically, regulatory thresholds for metals like copper and zinc are often determined using bioavailability-based standards, which employ models such as the Biotic Ligand Model (BLM) to estimate how much of the dissolved metal is biologically available and potentially toxic under specific environmental conditions (e.g., pH, water hardness, dissolved organic carbon—DOC, ionic composition) [35]. The Environment Agency in England and Wales reported in 2008 on how to establish environmentally safe concentrations for copper and zinc using the most current EU risk assessment data available at that time [36,37]. They applied Predicted No-Effect Concentrations (PNECs), which represent levels below which no harmful ecological effects are expected. For copper, they used a default PNEC of 8.2 μg/L (dissolved), derived using the Total Risk approach under a "reasonable worst-case" bioavailability scenario. For zinc, the PNEC depended on water hardness, with values of 7.8 μg/L for waters above 24 mg $CaCO_3$ L^{-1} and 3.1 μg/L for softer waters. They also accounted for natural background concentrations—1.6 μg/L for copper and 3.4 μg/L for zinc—which vary regionally. For Slovenian surface waters, environmental quality standards (NDK-OSK) define the maximum allowable concentrations to achieve good ecological status: for copper, 1 μg/L corresponds to "very good" quality, while up to 73 μg/L is considered "good"; for zinc, 4.2 μg/L represents "very good" quality, with 78–520 μg/L considered "good," depending on water hardness. These NDK-OSK values are the legally defined environmental quality standards expressed as the maximum permissible concentration for each parameter [38].

In our experimental study, copper concentrations measured in the wastewater container reached 401 ng/mL (Table 4). In addition to copper, the untreated wastewater contained 60.6 ng/mL of zinc. Reference seawater samples contained 2.5 ng/mL of copper and 5.8 ng/mL of zinc, whereas seawater collected during the cleaning of biofouling from the ship hull showed slightly increased levels of 3.5 ng/mL for copper and 10.1 ng/mL for zinc. These results demonstrate the effectiveness of the ROV equipped with the cleaning module, as the concentrations of copper and zinc in the collected wastewater were substantially higher than in the surrounding reference seawater, indicating that the system successfully removes biofouling material without significantly increasing metal concentrations in the environment. This conclusion is further supported by the observation that copper and zinc levels in ambient seawater during the cleaning operations did not increase significantly, confirming that the cleaning process effectively contains and limits the release of metals.

Table 4. Laboratory analysis of concentrations of Chl-a, copper (Cu), and zinc (Zn) in seawater before, during, and after hull cleaning with the ROV system. Reference and in situ samples were compared with wastewater collected for treatment.

Sample Type/Location	Parameter	Unit	Concentration
Reference seawater (before cleaning)	Chl-a	µg/L	0.49
Seawater during cleaning	Chl-a	µg/L	0.3
Wastewater (before treatment)	Chl-a	µg/L	7.08
Reference seawater (before cleaning)	Cu	ng/mL	2.5
Seawater during cleaning	Cu	ng/mL	3.5
Wastewater (before treatment)	Cu	ng/mL	401
Reference seawater (before cleaning)	Zn	ng/mL	5.8
Seawater during cleaning	Zn	ng/mL	10.1
Wastewater (before treatment)	Zn	ng/mL	60.6

Focus was also placed on Chl-a as a proxy for algal biomass, whether planktonic or surface-bound, during the cleaning process. The complete dataset is summarized in Table 4. The data show that the reference ambient seawater collected before cleaning and the seawater measured during the cleaning operation exhibited nearly identical Chl-a concentrations, indicating that the cleaning process did not result in a measurable increase in algal pigment concentration in the surrounding water column. Moreover, the values are very close to the long-term average summer value (0.4 µg/L) at a sampling station representative of the Slovenian sea [39] and would not compromise the ecological status of coastal waters since they are well below the boundary for the good ecological status for Type II A Adriatic coastal waters representative also for the Slovenian sea (1.5 µg/L as the annual geomean) for Slovenian waters [40].

In contrast, the seawater collected from the contained wastewater (Table 4) showed substantially higher Chl-a levels, consistent with the ROV's concentrated removal of fouling material and its conveyance to the treatment unit. These findings clearly demonstrate the efficiency of the suction and filtration mechanism in isolating and transporting the biofouling waste toward the treatment system, thereby preventing secondary contamination of the marine environment. These results suggest that the closed-loop system effectively contained the fouling removal process and prevented dispersion of biological material into the open water. The absence of a significant increase in Chl-a in ambient seawater supports the assertion that the cleaning operation did not degrade local water quality. Overall, the findings validate the environmental safety of the developed system and demonstrate its potential as a sustainable alternative to conventional underwater cleaning methods, ensuring compliance with emerging international standards for eco-friendly maritime maintenance.

These findings confirm that the developed biofouling cleaning system effectively prevents the release of heavy metals and other pollutants into the marine environment. The elevated concentrations of selected heavy metals and Chl-a in the collected wastewater highlight the efficiency of the ROV's suction and containment mechanism, which successfully directs contaminated water toward the onshore treatment unit.

4.3. Implications for Hull Cleaning Practice

The results show that the cavitation-based ROV cleaning system, integrated into a closed-loop wastewater management scheme, can remove biofouling from ship hulls without causing measurable negative effects on the surrounding marine environment. The containment of wastewater and the stark contrast between elevated Chl-a levels in the waste stream versus stable ambient levels further demonstrate the system's environmental safety and effectiveness. Future efforts should focus on optimizing wastewater throughput, reducing vibrations transferred from the high-pressure water pump via a high-pressure hose, improving sensor deployment, and expanding the range of monitored water-quality indicators to include particle-size distribution and on-site microbial community sampling.

Furthermore, the results emphasize the need for thorough environmental monitoring and sampling protocols for system operators. During hull cleaning, it is crucial to continuously track environmental and water-quality parameters that can affect both cleaning effectiveness and ecosystem health. These include oceanographic conditions (currents, waves, temperature, and salinity), physico-chemical parameters (pH, turbidity, dissolved oxygen, nutrients, Chl-a and/or other relevant algal pigments, and depth/pressure relationships), and chemical pollutants (notably metals like copper and zinc from antifouling coatings).

By incorporating such monitoring into operational routines, system operators can ensure compliance with environmental standards, identify potential anomalies in real-time, and develop a valuable dataset for long-term evaluation of the ecological footprint of underwater cleaning technologies. This approach supports the creation of sustainable, data-driven maritime maintenance practices and lays a stronger foundation for future autonomous inspection and adaptive control of cleaning processes. Planned system enhancements include adding an automated seawater sampling unit directly onto the ROV. This would enable autonomous collection of water samples for chemical and biological testing, eliminating the need for diver-assisted sampling. Such a feature would enable on-demand sampling—for example, during inspections or when onboard sensors detect anomalies—improving safety and responsiveness.

It is important to emphasize that, in future studies, we plan to enhance the performance and efficiency of the ROV prototype with the cleaning module and advance it from TRL 5–6 to TRL 9, making it suitable for industrial use. While the field tests reported in this study represent the most comprehensive trials conducted within the timeframe of the GreenHull project, we acknowledge that their relatively short duration and execution on a single vessel limit the assessment of long-term durability and adaptability. Therefore, future work will focus on extended, long-term trials involving multiple cleaning cycles, diverse biofouling compositions, and deployments in different marine environments. Such studies will enable a more robust validation of the system's durability, operational consistency, and adaptability under realistic industrial conditions.

Since the technology is still in the experimental stage, only an approximate life cycle assessment (LCA) can be performed. For comparison, we selected the LCA by Pagoropoulos et al. [41], who conducted an economic and environmental assessment of in-water hull cleaning across different technologies. They selected impact categories of costs, climate change, eco-toxicity, and invasive species. Their results demonstrate that the in-water hull cleaning is beneficial both environmentally and economically. They suggest that in-water cleaning is preferable to sandblasting when it comes to minimizing the overall environmental impact of hull maintenance. The optimal time for the first in-water hull cleaning is about 2 years after dry painting, and thereafter at shorter intervals until the next dry painting.

For the presented technology, the impact categories of eco-toxicity and invasive species are very similar to those in the LCA presented by Pagoropoulos et al. [41]. For the other two impact categories, costs and climate change, the main difference between the presented technology and the technology used in the Pagoropoulos LCA is that the presented technology uses ROV instead of divers. In the first approximation, both costs and the climate change effect are similar. Namely, human labor requires low investment and high hourly costs, while ROV requires high investment and exhibits low hourly costs. As ROV technology is not yet production-ready, its exact cost cannot be estimated. However, the cost is expected to be similar to that of robotic technologies in similar environments. For example, Tziolas et al. [42] estimate that the investment cost is recouped within about 5 years, after which robotic technology becomes cheaper than human labor. Regarding the climate change impact, the source of electricity for the ROV represents the biggest uncertainty in the difference between ROV-based and human-based in-water cleaning. Nevertheless, Pagoropoulos et al. [41] estimated significant savings in ship fuel due to cleaning, which are orders of magnitude larger than the energy consumption of the cleaning process.

The presented analysis demonstrates that the LCA results of Pagoropoulos et al. [41] also apply to the ROV in-water cleaning technology presented here. Our method is therefore both economically and environmentally viable and is best used about 2 years after dry-dock painting.

Removing biofouling alone is not enough; the system must effectively capture and treat all dislodged debris to prevent its spread into the marine environment. Future closed-loop ROV systems should also incorporate localized treatment methods, such as UV irradiation, ultrasound for breaking cells in fouling material, heating, or sterilization, directly on the robot to minimize dependence on complex onshore processing and wastewater treatment. Additionally, combining cavitation cleaning with rotating brushes, bio-inspired adhesion, autonomous navigation, and multi-robot cooperation can further improve cleaning effectiveness, lower energy use, and make systems more compact, flexible, and cost-effective. The probe with fewer ambient parameters (four or five at most) will be mounted on the ROV. Field experiments showed that it is better to use fewer relevant sensors or parameters on a probe, allowing for a smaller probe that can be mounted more effectively on the ROV. The placement criteria for the probe include: the sensors' tips should be sufficiently close to the ROV's cleaning module, yet far enough from the ROV's underwater lights and potential diver support lights.

Solid residues (sludge) from the mechanical filtration stage are classified as potentially hazardous waste under EU directives (e.g., due to heavy metals like Cu/Zn from legacy antifouling paints), requiring transport to licensed facilities for treatment/disposal [43,44]. Prototype operations during GreenHull produced minimal volumes (~10–50 kg of dry waste per test field (up to 50 m^2) vessel cleaning surface, depending on fouling severity). These waste volumes and related costs of hazardous waste disposal are negligible compared to dry-docking expenses and fuel savings from proactive maintenance. Comparable international data are reported in an Australian case study from 2013, where dry-docking hull cleaning of a 45 m vessel resulted in total cleaning costs of approximately AUD 70,200, of which about AUD 5000 (≈7%) was attributed to waste disposal, confirming that sludge management represents a relatively minor component of overall hull-maintenance costs [45].

Practical deployment in the cross-border Northern Adriatic region faces challenges from varying national transpositions of EU regulations (e.g., waste coding, transport permits under Basel Convention aspects, and discharge standards), which can delay approvals or increase administrative burdens [44]. The GreenHull project mitigated this by developing harmonized guidelines and a comprehensive waste management model, enabling consistent classification, treatment, and disposal procedures across Italy and Slovenia [43,44].

The prototype ROV is designed for flat and moderately curved hull surfaces, with an estimated minimum operating radius of approximately 1 m (limited by the 40 cm cleaning module diameter, wheelbase, and frame rigidity). Blind spots (such as behind bilge keels), highly concave or convex areas, and complex appendages like propellers and rudders pose challenges due to reduced contact stability, turbulence interference (which disrupts suction and jet efficiency), and accessibility issues. Cleaning of propellers and rudders has not been validated in field trials and would require specialized end-effectors or non-contact modes. Future improvements should include systematic testing of curvature adaptability (for example, on mock-up hull forms), computational fluid dynamics (CFD) simulations of turbulence around appendages, and dedicated modules to expand applicability to full-vessel maintenance. This outlines current operational boundaries and potential pathways for broader industrial application, aligning with the reviewer's recommendations.

Future development will focus on achieving greater autonomy, including automated hull mapping, adaptive navigation, and optimization of cavitation cleaning parameters for different surface conditions. Additionally, future closed-loop systems should aim to fully integrate environmental monitoring, real-time data analysis, and autonomous treatment within a single compact platform, ensuring both operational efficiency and strict adherence to environmental regulations. These systems will enable sustainable, scalable, and safe in-water hull cleaning practices, supporting the wider adoption of green maritime technologies across the industry.

5. Conclusions

The results of the in-field tests confirm the strong potential of the developed ROV-based cleaning system for sustainable maintenance of ship hulls and other submerged maritime structures. The integration of a cavitation-based cleaning module with real-time environmental monitoring (WiMo probe) showed that effective biofouling removal can be achieved without measurable degradation of the surrounding seawater quality. Laboratory analyses of water samples collected during different phases of the in-water biofouling removal process confirmed that the developed cleaning system effectively prevents the release of heavy metals and other pollutants into the marine environment. Elevated concentrations of selected heavy metals and chlorophyll-a detected in the collected wastewater further demonstrate the efficiency of the ROV's suction and containment mechanism, which successfully captures contaminated water and directs it to the onshore treatment unit.

Beyond demonstrating environmental safety, the findings emphasize several key technological, economic, and ecological benefits of the developed system. Technologically, combining targeted cavitation cleaning with an effective suction and containment mechanism ensures precise, controlled removal of fouling while preventing the spread of biological material or contaminants into the surrounding marine environment. Continuous, in situ monitoring with the WiMo probe improves operational reliability and allows for immediate verification of seawater stability during cleaning. From an economic standpoint, the capacity to perform hull cleaning on site—without dry-docking—greatly reduces vessel downtime and operational expenses, while the closed-loop wastewater management minimizes the need for extra mitigation measures and eliminates environmental non-compliance risks. Ecologically, stable Chl-a levels in ambient seawater demonstrate that the system effectively safeguards marine ecosystems by isolating and processing all dislodged material.

Overall, the developed ROV-based cleaning platform offers a sustainable, cost-effective, and technologically advanced alternative to traditional hull cleaning methods or a complementary solution to modern in-water hull cleaning techniques. By ensuring efficient biofouling removal, real-time environmental monitoring, and complete containment and treatment of wastewater, the system supports the shift toward environmentally responsible, regulation-compliant maritime maintenance, with significant potential for broader adoption across the maritime industry.

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Data Availability Statement: All data generated within the GreenHull project that are not confidential in nature and result from joint project activities are publicly available on the project website https://2014-2020.ita-slo.eu/greenhull, accessed on 21 December 2025. Confidential data are stored individually by each project partner. The Jožef Stefan International Postgraduate School (IPS) maintains data related to the development of the ROV and the cleaning module. The Marine Biology Station Piran stores data related to biological sample analyses and cleaning monitoring. A copy of all project data is also archived at IPS, the coordinating institution of the GreenHull project.

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the text. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors Riccardo Zanelli and Edvin Salvi were employed by the companies Cluster COMET and Salvi d. o. o., respectively. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The arrangement between project partners was established in the contract with the funder Interreg ITA-SLO and in the mutual partnership agreement. Furthermore, Salvi d.o.o. collaborated with Cluster COMET as a subcontractor, following market analysis and procurement rules; this collaboration was formalized within the project contracts and does not constitute a conflict of interest. In addition, the authors acknowledge the participation of the Slovenian company Esotech d.d., which developed the prototype of the wastewater treatment system used in the project; however, the technical development and presentation of this prototype are not the subject of this article. The project also involved the Italian partner Corila, responsible for disseminating the project and examining the legal aspects of removing marine biofouling from ship hulls. Their contributions and reports prepared within the project are publicly available on the project website (https://2014-2020.ita-slo.eu/greenhull), accessed on 21 December 2025, and are not included in this article. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

ROV	Remotely operated vehicle
Chl-a	Chlorophyll-a
NIS	Non-indigenous species
IMO	International Maritime Organization
CTD	Conductivity/salinity/temperature
CDOM	Colored dissolved organic matter
DO	Dissolved oxygen
PAR	Photosynthetically active radiation
UV	Ultraviolet
NIR	Near infrared
NA	Not available
STD	Standard deviation
LCA	Life cycle assessment
PNEC	Predicted No-Effect Concentration
ISO	International Organization for Standardization
TRL	Technology readiness level
AI	Artificial intelligence
IMU	Inertial measurement units
BLM	Biotic Ligand Model

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