Scalable full-cycle marine litter remediation in the Mediterranean: Robotic and participatory solutions

SeaClear2.0

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D10.4 Cost Benefit Assessment

WP10 – Exploitation & IPR Management

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[1] R = Document, report, DEM = Demonstrator, OTHER = Software, technical diagram, etc., DMP = Data Management Plan

[2] PU = Public, C-UE/EU-C = EU Confidential under Decision 2015/444, SEN = Sensitive

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Definitions

- **Beneficiary:** A legal entity that is signatory of the EC Grant Agreement no. 101093822.
- **Consortium:** The SeaClear2.0 Consortium, comprising the list of beneficiaries below.
- **Consortium Agreement:** Agreement concluded amongst the SeaClear2.0 beneficiaries for the implementation of the Grant Agreement.
- **Grant Agreement:** The agreement signed between the beneficiaries and the EC for the undertaking of the SeaClear2.0 project (Grant Agreement no. 101093822).

Beneficiaries of the SeaClear2.0 Consortium are referred to herein according to the following abbreviations:

- **TU Delft**: TECHNISCHE UNIVERSITEIT DELFT
- **DUNEA**: REGIONALNA AGENCIJA DUNEA
- **Fraunhofer**: FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV
- **HPA**: HAMBURG PORT AUTHORITY
- **ISOTECH**: ISOTECH LTD
- **MDanchor**: M. DANCHOR LTD
- **Subsea Tech**: SUBSEA TECH SAS
- **TECNOSUB**: TÉCNICAS Y OBRAS SUBACUÁTICAS, SLU
- **TUM**: TECHNISCHE UNIVERSITAET MUENCHEN
- **UNIDU**: SVEUCILISTE U DUBROVNIKU
- **UTC**: UNIVERSITATEA TEHNICA CLUJ-NAPOCA
- **VEO**: VEOLIA PROPRETE
- **VLPF**: VENICE LAGOON PLASTIC FREE

Abbreviations

- **AI:** Artificial Intelligence
- **AUSV:** Autonomous Unmanned Surface Vehicle
- **AUV:** Autonomous Underwater Vehicle
- **BM:** Business Model
- **BVLOS:** Beyond Visual Line of Sight
- **CBA:** Cost-Benefit Analysis
- **CEA:** Cost-Effectiveness Analysis
- **DCS:** Decompression Sickness
- **EC:** European Commission
- **ESA:** European Space Agency
- **FLS:** Forward-Looking Sonar
- **FOV:** Field of View
- **GA:** Grant Agreement
- **HRSS:** High-Resolution Sub-Bottom Profiler
- **IRR:** Internal Rate of Return
- **KPI:** Key Performance Indicator
- **LARS:** Launch and Recovery System
- **LiDAR:** Light Detection and Ranging
- **MBES:** Multibeam Echosounder
- **NIR:** Near-Infrared
- **NPV:** Net Present Value
- **NGO:** Non-profit organizations
- **OSV:** Offshore Supply Vessel
- **PADI:** Professional Association of Diving Instructors
- **PLC:** Product Life Cycle
- **RDP:** Recreational Dive Planner
- **R&D:** Research and Development
- **ROV:** Remote Operated Vehicles
- **RNT:** Residual Nitrogen Time
- **SAR:** Synthetic Aperture Radar
- **SAS:** Synthetic Aperture Sonar
- **SBL:** Short Baseline
- **SI:** Surface Interval
- **SSD:** Surface-Supplied Diving
- **SSS:** Side Scan Sonar
- **SWIR:** Short-Wave Infrared
- **TBL:** Triple Bottom Line
- **TBT:** Total Bottom Time
- **UAV:** Unmanned Aerial Vehicle
- **UHI:** Underwater Hyperspectral Imaging
- **USV:** Unmanned Surface Vehicle
- **USBL:** Ultra-Short Baseline
- **UUV:** Unmanned Underwater Vehicle
- **UXO:** Unexploded Ordnance
- **YOLO:** You Only Look Once

Executive Summary

Work Package 10 (WP10) of the SeaClear2.0 project focuses on creating sustainable financial value for all participants by prioritizing market analysis over research and development (R&D). The aim is to align innovative solutions with market demand to maximize commercial viability and profitability. Deliverable D10.4 – Cost Benefit Assessment explores the saleable products and services costs, detailed in deliverable 10.3, in terms of effectiveness and impact compared to existing options.

SeaClear2.0 aims to strike a balance between cost efficiency and environmental impact, focusing on location, identification, monitoring and clean-up activities where the system's technical capabilities can provide the greatest value. The system consists of a modular team of robotic platforms, including an Unmanned Surface Vehicle (USV) for detection and collection, an Unmanned Aerial Vehicle (UAV) for surface litter detection and situational awareness, and a Remotely Operated Vehicle (ROV) for subsea litter detection and recovery. Additionally, the system features a floating litter collection mechanism (using USVs) and an autonomous tender for transferring debris from offshore to onshore.

Compared to existing technologies, SeaClear2.0 demonstrates moderate efficiency in surface litter detection and monitoring, benefiting from extended battery life (72 hours) and operational scalability. For surface litter collection, the system integrates detection and recovery functions, simplifying operations and enhancing efficiency. In seabed litter management, SeaClear2.0 outperforms traditional methods such as diver-based recovery and standalone ROV operations by offering higher precision, reduced environmental impact, and minimal personnel requirements. The system's autonomous grapple enables targeted debris collection up to 250 kg. while preserving sensitive marine habitats.

SeaClear2.0's operational costs, including personnel, maintenance, and deployment, are competitive with market alternatives. Its capital costs, excluding research and development expenses already covered by Horizon Europe, align with industry benchmarks, making the system an economically viable option for future adopters. While it may not outperform dedicated systems for isolated tasks, SeaClear2.0's integrated functionality uniquely positions it as a holistic solution capable of addressing both surface and seabed marine litter.

The system's key strength lies in its ability to combine detection and collection for both surface and seabed litter within a single operational framework. This holistic approach, supported by AI-driven software, enhances scalability and adaptability across diverse marine environments. Particularly in seabed recovery, where no existing technology matches SeaClear2.0's ecological sensitivity and precision, the system sets a new standard. The project underscores its role as a disruptive innovation in marine litter management, suggesting strong market potential and a meaningful contribution to global sustainability efforts.

1. Introduction

1.1 Overall Work Package 10 Objective

SeaClear2.0 zeroes in on curtailing marine litter pollution, particularly from plastic debris, in the Mediterranean. This goal will be realized by deploying teams of autonomous, intelligent robots to monitor and retrieve marine seafloor and surface debris, and by employing participatory practices to pinpoint site-specific measures for marine litter prevention and mitigation. SeaClear2.0 will offer innovative solutions for efficient marine litter management.

The current deliverable, D10.4 - Cost-Benefit Assessment provides a comprehensive analysis of the economic viability of the SeaClear2.0 project. This assessment will weigh the costs associated with the development, deployment, and maintenance of our solutions against other existing alternatives. By evaluating the potential risks and rewards, this deliverable will offer stakeholders a clear understanding of the project's long-term sustainability and profitability.

Lastly, D10.5 – Business Plan and Business Model will present a strategic roadmap for the commercialization of the SeaClear2.0 solutions. This deliverable will detail our go-to-market strategy, including pricing, distribution channels, and marketing initiatives. It will also define the business model, outlining how SeaClear2.0 plans to generate revenue, scale operations, and ensure a steady growth trajectory. The business plan will serve as a blueprint for attracting potential investors, partners, and customers, ensuring that SeaClear2.0 is well-positioned to make a significant impact in the marine litter management sector.

Together with already submitted D10.1 – Market & Competence Analysis and 10.2 – IPR Strategy, and 10.3 – Product & Services Definition, these deliverables form a comprehensive framework for the successful exploitation of the SeaClear2.0 project outcomes. Through market analysis, product definition, cost-benefit evaluation, and business planning, Work Package 10 aims to create a sustainable financial value for all project participants.

1.2 Deliverable Structure

This deliverable is structured in five main sections. It begins with the Analysis Framework, which provides the foundation for understanding the project's purpose and scope. It opens with an introduction offering a concise overview of SeaClear2.0 and the analysis framework's role in evaluating marine litter management technologies. Following this, the goals and objectives are articulated, outlining the specific aims of the project and the criteria for analysis. The framework also includes a comprehensive review of existing alternative methods and technologies for marine litter management divided into key areas: detection, identification, and monitoring, with further distinctions between surface and seabed methods, and a dedicated chapter to software.

Alternative Methodologies and Technologies Analysis section evaluates the methods introduced in the previous chapter. It examines their applicability, effectiveness, and limitations. Following this analysis, the deliverable sets SeaClear2.0 capabilities according to technical documentation already produced in the project.

The Benefit Analysis section then assesses the project’s overall value, considering its environmental, social, and operational benefits. This is complemented by a Cost and Effectiveness Analysis, which evaluates the financial implications of implementing SeaClear2.0, offering comparisons to existing technologies when possible.

Finally, the deliverable concludes with a summary of findings in the Conclusions section. This part synthesizes the insights gained from the analysis, emphasizing the viability, advantages, and potential impact of SeaClear2.0 in advancing marine litter management practices.

2. Analysis Framework

2.1 Introduction

A Cost-Benefit Assessment (CBA) systematically evaluates the costs and benefits of a project, aiming to determine its overall value and feasibility by including both monetary and broader socio-economic and environmental impacts. However, in the case of SeaClear2.0, this process is particularly challenging due to the intrinsic nature of its benefits. As a dual-purpose research initiative and marine litter recovery project, SeaClear2.0 generates non-quantifiable advantages such as fostering innovation through advanced robotic systems and AI tools, as well as achieving significant environmental improvements like reducing sea pollution and restoring ecosystems. These benefits are inherently complex to translate into precise monetary values. While this analysis recognizes and highlights such impacts, it focuses on comparing the technological advancements and effectiveness of SeaClear2.0 against existing and alternative methodologies. Where possible, a cost analysis will compare SeaClear2.0's technologies and methods against existing marine litter detection, identification and monitoring solutions and recovery alternatives to evaluate their relative cost-effectiveness. This includes analysing operational expenses, such as equipment and labour. Additionally, the analysis will examine the overall project cost to determine whether the investment in R&D and innovation provides a sustainable and scalable alternative to current methods. By evaluating costs, both independently and in comparison to alternatives, the assessment aims to deliver a comprehensive understanding of the project's value.

2.2 Goals and Objectives

The primary goal of this deliverable is to analyse if SeaClear2.0 technology provides better balance between cost efficiency and environmental effectiveness to solve marine litter problem when compared to existing methods and technologies. This involves comparing different options to determine which one yields the highest net benefits, accounting for both direct costs and broader socio-environmental impacts.

As stablished in *D10.1 – Market and Competence Analysis*, the marine litter market can be broadly defined as the collection of initiatives, technologies, solutions, products, and services aimed at addressing the issue of marine litter. This multifaceted market revolves around a collaborative effort that brings together diverse stakeholders to prevent, reduce, monitor, clean up, and recycle marine litter to protect the marine and coastal environment. After an analysis of SeaClear2.0 technical capabilities and operational objectives, and knowing that prevention, reduction, and recycling are vital aspects of addressing marine the litter problem, it has been concluded that the system's characteristics are best suited for monitoring and clean-up activities. The system can make a significant impact and for that reason those activities are the ones considered for the assessment.

2.3 SeaClear2.0 description

The SeaClear2.0 system consists of a team of collaborative, heterogeneous robots for in-situ mapping, detection, classification, and collection of marine litter from the seafloor and sea surface. To be precise, the system is composed of an unmanned surface vehicle (USV) called SeaCAT 2.0 that acts as a hub for an unmanned aerial vehicle (UAV), that searches for litter from the air and contributes to situational awareness; an observation unmanned underwater vehicle (UUV/ROV) called Mini-Tortuga, that searches for litter underwater using integrated sensors; a separate autonomous grapple designed to pick up the identified litter; an autonomous tender boat to transfer collected litter from offshore to onshore and surface autonomous drones to collect surface marine litter.

Fig. 1 – SeaClear2.0 complete system

Even though the idea is that the system would be introduced as a full-service package covering all stages of marine litter recovery (initial survey and monitoring, litter Identification and localization, litter collection, transfer, disposal & continuous monitoring), this deliverable includes an analysis of different components of the system capabilities individually to allow comparison with existing methods and technologies.

Surface marine litter detection and mapping in SeaClear2.0 will be autonomously performed using the floating litter collection system via omnidirectional USV's sensors (3 axis actuated above water camera and underwater camera), the cameras installed on board the UAV (RGB camera Zenmuse X5S, thermal camera Zenmuse H2OT and multispectral camera) and a camara with 70^{o} vision angle installed on SeaCat's Mini-tortuga LARS.

Regarding underwater detection, different sensors are installed on various components of the system. A multibeam sonar, installed on the USV (SeaCat), serves both as a bathymetric sonar and a global detection sensor for large targets. The Mini-Tortuga ROV is equipped with primary components specifically designed for detecting marine litter, the side-scan sonar, the Oculus M3000D multibeam sonar system, and the metal detector. Side-scan sonar provides broad coverage of the seabed, creating detailed two-dimensional imagery over a wide area, which is excellent for identifying large features or anomalies from a distance. However, while side-scan sonar is effective at longer ranges, it lacks the precision needed for close-range inspection. The Oculus M3000D multibeam sonar addresses this by delivering high-resolution, two-dimensional imagery, ideal for mid- to close-range detection of smaller or more complex objects. Together, these systems provide complete coverage, allowing side-scan sonar to quickly survey large areas while the Oculus M3000D zooms in on identified points of interest, enhancing object identification and enabling detailed observation. Adding to this, the metal detector plays a crucial role in identifying submerged objects concealed beneath sediment or covered by algae, providing an additional layer of detection that is particularly valuable in turbid environments. The inclusion of a full HD camera completes the system installed on the Mini-Tortuga, serving as a primary sensor for direct visual identification when visibility conditions permit.

Once litter has been identified, the grapple will employ high-definition cameras to re-localize targets and facilitate precise navigation. This camera-based system will not serve as a primary detection method but rather as a supporting component, enabling video-based autonomous navigation control to ensure accurate targeting and effective retrieval of previously identified litter.

2.4 Existing Alternative Methods and Technologies

The SeaClear2.0 project employs an integrated and holistic approach, combining advanced technologies and methodologies for the detection, identification, monitoring, and collection of marine litter. Unlike other entities that typically focus solely on either detection or removal and often target specific aspects, such as surface or shoreline litter, SeaClear2.0 offers a comprehensive solution that addresses both underwater and surface litter management. This unique integration of technologies makes it challenging to identify direct competitors for the entire system. Therefore, alternative methods and technologies have been considered depending on the type of litter (surface or seabed) and the action to be performed (detection, identification & monitoring, or collection).

2.4.1. Marine Litter Detection, Identification, and Monitoring

2.4.1.1. Surface Marine Litter Detection, Identification and Monitoring

Traditionally, manual surveys conducted by trained observers on boats or shorelines, as well as visual inspections from aerial platforms, were used to assess types, quantities, and locations of surface marine litter. While these methods provided essential data, they were limited in scale and resolution.

Aerial photography enabled researchers to cover larger areas and gain better insights into litter distribution, though it was limited in its ability to detect smaller debris. Satellite technology expanded the scope, allowing for extensive tracking of larger debris clusters across oceans. However, satellites still struggle to detect smaller or less concentrated items and are affected by changing surface water conditions.

The emergence of drones with high-resolution cameras has transformed surface litter monitoring by offering close-up, precise observations and access to hard-to-reach areas. Drones are particularly useful for small- to medium-scale monitoring projects and offer the unique advantage of reaching areas inaccessible to boats or planes.

Given the diversity of methodologies used for identification and monitoring of surface marine litter and in order to standardize and optimize data collection across different environments, litter types, and monitoring objectives, following key characteristics of the methodologies have been identified: platform used, sensor type, spectral resolution range, area of study, spatial resolution range, marine litter size and the method of classification [1].

Platforms for monitoring marine litter include a wide range of setups that host sensors for data collection across various environments. The platforms include satellites, aircraft, drones, vessels, small vessels/boats, USV or shore fixed locations.

The type of sensor on each platform defines how data is captured. In classification [1] sensors include passive sensors (like cameras), which rely on ambient light, and active sensors (like radar or sonar), which emit their signal to detect objects. In our classification, actual sensors have been included to simplify comparability between existing capabilities to SeaClear2.0's ones. The human eye, with its remarkable adaptability and ability to distinguish different types of litter by color, shape, and material in real-time, is also considered a sensor.

In terms of spectral resolution, sensors capture data across the electromagnetic spectrum, with categories such as Visible (400-700 nm), Near-Infrared (NIR, 700-1040 nm), Shortwave Infrared (SWIR, 1040-2500 nm), and Microwaves (>3 cm). Each spectral band serves specific identification needs, like differentiating between litter types or detecting debris in various water conditions.

The study area is classified by its proximity to the coastline, categorized as offshore (>200 m from the coastline) or coastal (0-200 m).

Spatial resolution varies depending on the platform and sensor, ranging from 0-1 m (suitable for high detail) to over 30 m (useful for broad, large-scale surveys). Spatial resolution impacts the detection limit, distinguishing between macroplastics (>5 mm) and microplastics (<5 mm) in detail.

Marine litter classification methods also vary. Human observers can visually count and categorize litter items, often using manual photo interpretation, while automated classification systems can apply algorithms for supervised or unsupervised classification based on image features. Supervised classification involves training the software with sample images, while unsupervised methods identify clusters of similar spectral characteristics independently [1 - 6].

Platform	Sensor	Spectral resolution range	Area of study	Spatial resolution range	Size of marine litter	Methodology for marine litter classification
▪ Fixed onshore location ▪ USV ▪ Small vessel/boat ▪ Vessel ▪ UAV/Drone ▪ Aircraft ▪ Satellite	▪ Human eye ▪ HD Cameras ▪ RGB Cameras ▪ Hyperspectral cameras ▪ Thermal Cameras ▪ LiDAR	▪ Visible (400-700 nm) ▪ NIR (700-1040 nm) ▪ SWIR (1040-2500 nm) ▪ SAR (3.1 – 5.6 cm)	▪ Coast (0-200 m from coastline) ▪ Offshore (> 200 m from coastline)	▪ 0 – 1 m ▪ > 1 – 3 m ▪ > 3 – 10 m ▪ > 10 – 30 m ▪ > 30 m	▪ Nanoplastics (x < 0,001 mm) ▪ Microplastics (0,001 < x < 5 mm) ▪ Mesoplastics (5 < x < 25 mm) ▪ Macroplastics (25 < x < 100 mm) ▪ Megaplastics (100 mm < x)	▪ Sighting ▪ Photointerpretation ▪ Unsupervised classification ▪ Supervised classification

Table 1 – Surface Marine Litter Identification and Monitoring classification table. Source: Adapted from Salgado-Hernanz P.M. et. al. [1]

Due to the varying detection capabilities of different optical sensors, influenced by technical specifications (such as resolution, lens quality, and light sensitivity) and environmental conditions, determining the smallest detectable object size for each sensor type at various distances was not feasible, as initially intended for comparison with SeaClear2.0 capabilities. Consequently, comparisons with existing methods and alternatives for detection, identification, and monitoring will focus on the presence of sensor types rather than their specific detection capacities. Additionally, the use of specialized software to process and enhance captured images can improve detection outcomes, especially for small or low-contrast objects, making standardized comparisons impractical for the deliverable objectives.

2.4.1.2. Seabed/Subsea Marine Litter Detection, Identification and Monitoring

Marine litter detection, identification, and monitoring initially relied on traditional methods like trawling surveys, diver observations, and towed underwater cameras. While these methods provided valuable insights, they were limited in scope, covering smaller areas and/or lacking the resolution needed in complex underwater environments. Technological advancements have since significantly improved subsea detection, identification, and monitoring, particularly with the development of specialized platforms such as Autonomous Underwater and Surface Vehicles (AUSV, USV), Remotely Operated Vehicles (ROV), Autonomous Underwater Vehicles (AUV), and Unmanned Underwater Vehicles (UUV). These platforms, paired with advanced optical, acoustic and magnetic sensors have greatly enhanced detection accuracy and coverage. These innovations enable detailed, wide-scale monitoring and allow for more comprehensive assessments of marine litter across diverse seabed environments and depths.

In academic and scientific literature, surface marine litter detection, identification, and monitoring has garnered significantly more attention than subsea approaches. A quick search on Google Scholar reveals more than 90,000 publications on surface litter detection compared to roughly 10,000 on subsea litter, highlighting a substantial gap in research focus. This discrepancy underscores the challenges and relative novelty associated with studying seabed litter, which requires specialized technology and methods due to the complexities of underwater environments.

A classification table, like that used for surface litter detection, has been developed to incorporate a range of platforms and sensors used in underwater detection and monitoring, providing a framework to evaluate SeaClear2.0's capabilities alongside established subsea monitoring methodologies.

Each sensor type’s capabilities and optimal use scenarios vary based on technical specifications and environmental conditions, making it quite complicated to standardize comparisons with SeaClear2.0. These differences mean that SeaClear2.0’s unique detection capabilities may only be meaningfully compared within specific, controlled conditions or by focusing on broad functional equivalence rather than exact performance across all sensor types. For this reason, as with comparisons of surface marine litter detection, identification, and monitoring, the presence of sensors will be considered, but not their exact technical capabilities.

Platform	Sensors	Seabed area of study	Depth Ranges	Size of marine litter	Methodology for marine litter classification
▪ Diver ▪ Vessel/boat ▪ (A)USV ▪ ROV ▪ AUV ▪ UUV	▪ Optical ○ Human eye ○ HD cameras ○ RGB cameras ○ Multispectral cameras ○ Hyperspectral cameras ○ LiDAR ○ PPG Sensor ▪ Acoustical ○ SSS ○ MBES ○ HRSS ○ SAS ○ FLS ○ SBSS (CHIRP) ▪ Magnetic ○ Magnetometers (including): • Fluxgate • Proton • Overhauser ○ Gradiometers	▪ Intertidal Zone 0 - ~10 m. ▪ Sublittoral Zone 10 - 50 m. ▪ Continental Shelf 50 - 200 m. ▪ Upper Continental Slope 200 - 1,000 m. ▪ Lower Continental Slope 1,000 - 3,000 m. ▪ Shallow Deep-Sea 3,000 - 4,000 m. ▪ Deep Abyssal Zone 4,000+ m.	▪ < 1 m. ▪ 1 to 3 m. ▪ 3 to 5 m. ▪ 5 to 10 m. ▪ 10 to 30 m. ▪ 30 to 50 m. ▪ 50 to 100 m. ▪ 100 to 300 m ▪ + 300 m.	▪ Nanoplastics (x < 0,001 mm) ▪ Microplastics (0,001 < x < 5 mm) ▪ Mesoplastics (5 < x < 25 mm) ▪ Macroplastics (25 < x < 100 mm) ▪ Megaplastics (100 mm < x)	▪ Sighting ▪ Photointerpretation ▪ Unsupervised classification ▪ Supervised classification

Table 2 – Seabed Marine Litter Identification and Monitoring classification table. Source: Adapted from Salgado-Hernanz P.M. et. al. [1] and Madricardo, F. et al. [7]

2.4.2. Marine Litter Collection

Even if few classifications on clean-up existing technologies have been already published [7-15], present deliverable utilises its own classification as developed in *D10.1 – Market and Competence Analysis.* This classification allowed identification of direct and potential competitors of SeaClear2.0 system regarding marine litter collection. It also considered indirect and substitutive competitors when methods/technologies are currently being applied.

Once methods and technologies had been identified, those that have more similarities with SeaClear2.0 system/components have been considered for analysis. As mentioned, analysis has been performed considering surface and seabed marine litter collection.

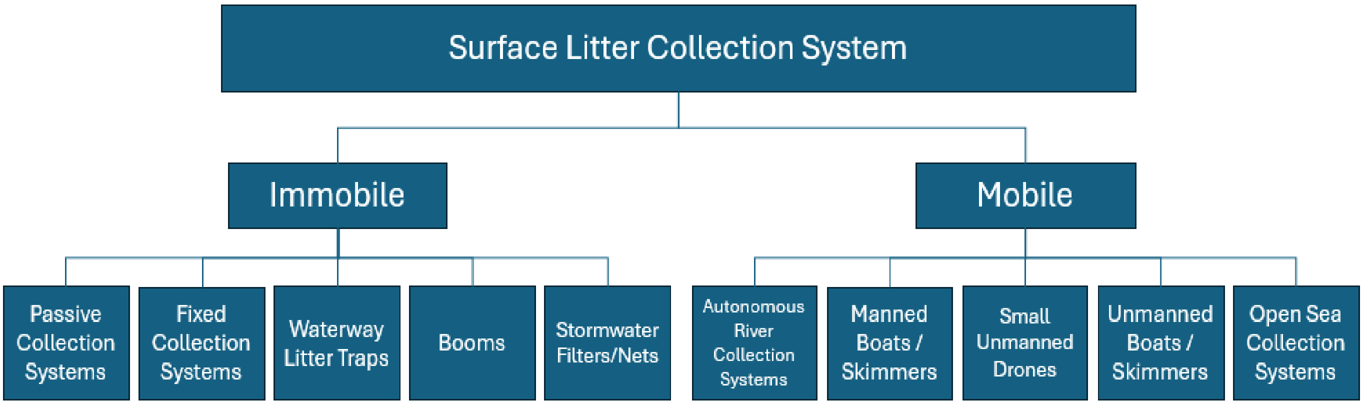


Fig. 2 – Surface Litter Collection Systems Classification

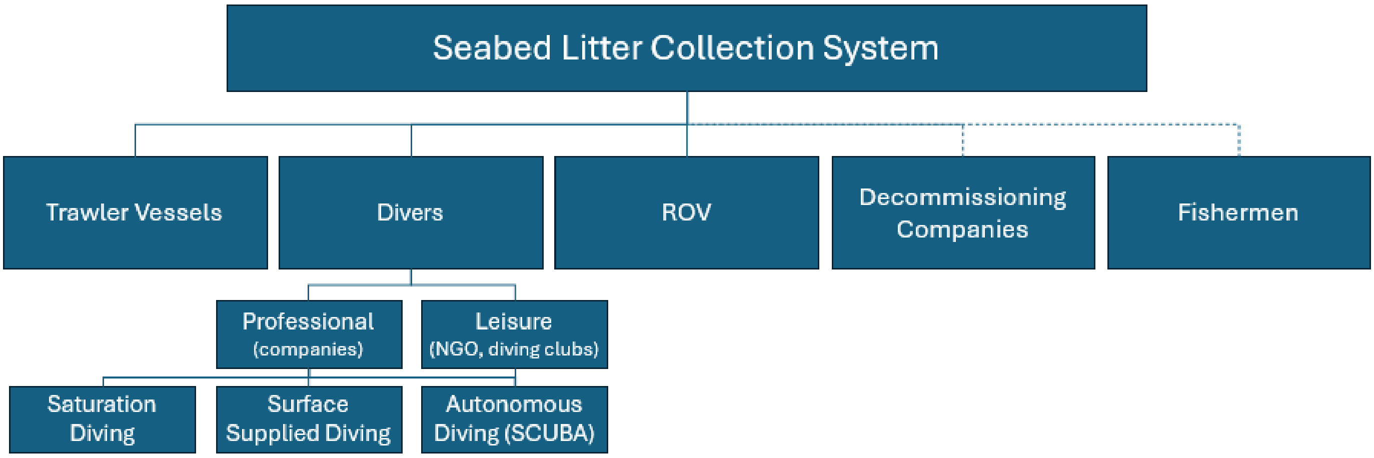


Fig. 3 – Seabed Litter Collection Systems Classification

2.4.2.1. Surface Marine Litter Collection

Regarding the two types of marine litter analyzed, surface litter exhibits a greater variety of technologies and methods for its collection, with direct competitors existing for two elements composing SeaClear2.0: the floating litter collection system via omnidirectional USV and the SeaCat collecting basket.

Small-unmanned drones/skimmers are a direct alternative to the floating litter collection system via omnidirectional USV. Even if technology exists already on the market, special mention to SMURF from ORCAUBOAT and JELLYFISHBOT by IADYS, it has to be considered that the main improvement and contribution of SeaClear2.0 resides on the capacity of the sensing system to autonomously detect and map the surface litter. Since the surface litter may be located beyond USV camera field of view (FOV), an UAV is introduced into the system. The combination of these system elements will be thoroughly examined when discussing the detection, identification, and monitoring of marine litter.

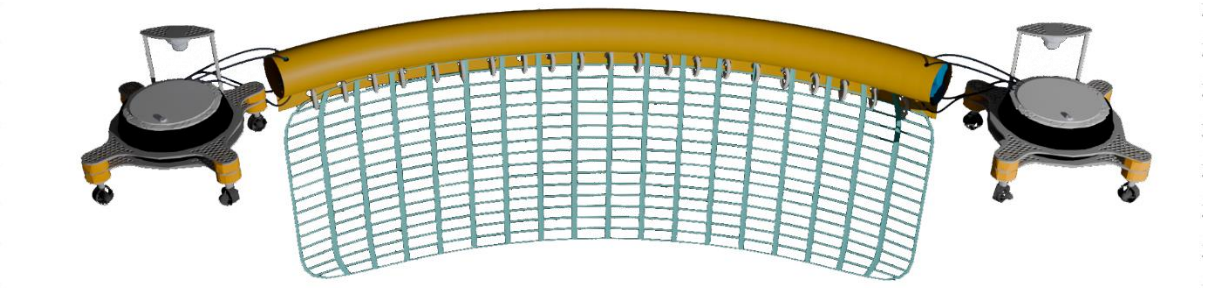


Fig. 4 – Floating litter collection system via omnidirectional USV

The manned and/or unmanned boats/skimmers are similar to the SeaCat basket concept. To maximize the collection and retention of floating litter, the SeaCat is equipped with a basket located between the hulls of the catamaran. The basket is equipped at its front with a PE skimmer plate which oscillates with the water movement. Once the floating litter enters the basket with the SeaCat sailing over it, it will be trapped, being blocked by the skimmer plate.

Those two methods/technologies would be the ones compared in surface marine litter analysis.

Fig. 5 – SeaCat collecting basket detail

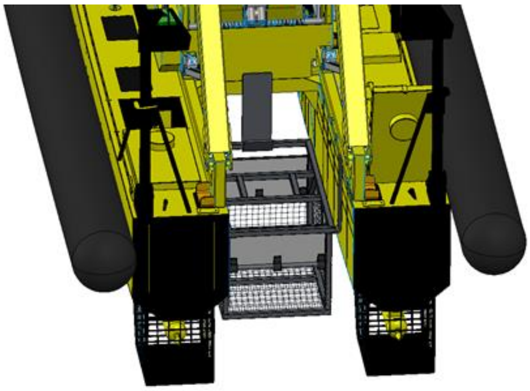


Fig. 6 – SeaCat collecting basket location

2.4.2.2. Seabed Marine Litter Collection

Seabed marine litter removal activities generally use two primary methods: trawling and diver-based operations. In trawling, vessels—often fishing vessels—are equipped with specialized nets, chains, and hooks designed to collect debris from the seafloor. This approach is typically applied in deeper waters with soft substrates but proves inefficient and potentially damaging when used on hard, rocky seafloors. Trawling is non-selective, indiscriminately collecting both debris and marine organisms and often causing damage to seabed habitats and subsea flora. This physical disturbance can uproot and destroy benthic communities, including delicate corals and seagrasses, leading to long-term ecological impacts. While organisms collected during trawling can be returned to the water, many may suffer harm or die due to the physical trauma caused by the operation.

Diver-based marine litter removal is classified into two categories. The first category includes leisure divers, who play a significant role in addressing marine litter, particularly in shallow and accessible coastal areas. These efforts, often coordinated by environmental organizations, diving clubs, or NGOs, are typically voluntary and community driven. They aim to raise public awareness and mitigate marine pollution through hands-on clean-up activities, entirely non-commercial and reliant on volunteer divers. Such initiatives reflect a commitment to environmental stewardship without financial gain.

The second category involves professional diving companies, whose participation is generally project-based and tied to commercial interests or specific business opportunities. While not primary actors in large-scale marine litter removal, these companies are engaged when specialized expertise and equipment are necessary. Professional divers often handle complex projects, such as removing large or hazardous debris, which require advanced technical skills and substantial financial resources. Such operations may be funded by government bodies, private companies, or international organizations that prioritize mitigating environmental impacts.

In contrast to marine litter removal, professional diving companies are extensively involved in the field of Unexploded Ordnance (UXO) identification and render-safe operations. These projects address the detection, identification, and neutralization of explosive remnants from past military activities and demand highly specialized skills and equipment. Although UXO recovery is not strictly classified as marine litter removal, both activities involve the safe extraction and disposal of hazardous materials from the seabed. Given these similarities, UXO recovery could represent a relevant, potential activity for SeaClear2.0, aligning with the technical capabilities required for marine litter recovery.

Remotely Operated Vehicles (ROVs) are increasingly employed in seabed litter removal, particularly in settings where traditional methods such as trawling or diver-based operations are impractical or hazardous. ROVs offer a non-intrusive, technology-driven approach to litter recovery, capable of reaching greater depths than human divers and effectively navigating complex underwater landscapes. Equipped with manipulator arms, suction devices, or specialized grippers, ROVs are suited for selectively retrieving marine debris, from plastics and derelict fishing gear to larger, potentially hazardous items. ROVs are particularly useful in environments that pose risks to human divers, including deep-sea areas and sites with unstable substrate conditions.

However, deploying ROVs for marine litter recovery can be costly, and their use is often economically feasible only for funded projects or in cases where environmental priorities justify the investment. While ROVs are effective in litter collection without the bycatch impact of trawling, their operational scope is generally limited to large-scale, targeted clean-up efforts. Their strategic use aligns well with projects that balance environmental conservation with technical precision, making ROVs well-suited for complex litter removal scenarios, especially when used in synergy with other methods for deep or hard-to-access debris.

Decommissioning companies with specialized equipment contribute primarily to subsea operations focused on dismantling and removing obsolete or abandoned underwater structures. Although they have the expertise and equipment necessary to adapt these technologies for marine litter recovery when justified by project needs, they are not typically involved in marine litter removal activities due to the high operational costs associated with their deployment.

Although fishermen are essential stakeholders in marine litter management, their role in litter collection is largely passive, besides their participation in designated and funded clean-up campaigns that target specific litter removal efforts. Across various locations, programs exist to support the management of marine litter recovered during routine fishing operations. Notably, these programs operate without financial compensation, relying instead on the voluntary contributions of fishermen.

In the SeaClear2.0 system a self-designed grapple is used to marine litter recovery in an ecologically responsible and targeted manner. The smart grapple utilizes advanced grasping mechanisms and integrated sensors for selective debris collection, ensuring the exclusion of marine fauna and the preservation of habitats such as coral reefs and seagrass beds. Its vectored thrusters provide precise six-degrees-of-freedom control, enabling accurate maneuvering and collection of diverse debris types, including large and irregular items such as tires and pipes.

From the methods described, only divers and ROV are considered for analysis.

Fig. 7 – SeaClear2.0 grapple

2.4.3. Software

The SeaClear2.0 focuses on software development tailored to manage its various system elements, specifically targeting navigation, control, communication, and data processing across Unmanned Surface Vehicles (USVs) and Unmanned Aerial Vehicles (UAVs). While the primary objective is not to commercialize the software directly, the project emphasizes creating robust, innovative solutions that could have potential for broader applicability. By addressing unique challenges such as efficient power management of thrusters, enhanced pose estimation, and AI-driven litter detection, the software's evolution could present opportunities for commercialization in niche markets. This includes standalone modules, such as the UAV-winch control system or advanced surface litter detection algorithms, which may cater to industry needs beyond the project’s scope. As development progresses, evaluating the scalability and adaptability of these solutions for external applications will help determine their viability for future sale or licensing.

Some companies already incorporate object localization and classification in their systems, such as Advanced Navigation with their Hydrus models. These systems offer out-of-the-box capabilities including precision GPS waypoint navigation, position hold, follow-me maneuvers, geo-fencing, and automatic return-to-home if the radio signal is lost, along with drag-and-drop mission planning for easy and efficient setup of complex missions. Similarly, BlueBoat Marine Robotics and L3Harris'

ASView provide proprietary control systems designed for autonomous and remote operation of unmanned vehicles, enhancing navigation, control, and the conversion of manned vessels to autonomous platforms. However, the SeaClear2.0 software is still in the research and innovation phase, with its full capabilities yet to be defined. A complete assessment of its benefits and comparisons with existing solutions will only be possible after the final demonstration of the project, when its readiness and performance are fully established.

3. Alternative methodologies and technologies analysis

3.1 Surface Marine Litter Location, Identification, and Monitoring

Among the wide array of existing technologies and methodologies for surface marine litter location, identification and monitoring, this chapter focuses only on those solutions that offer capabilities and outputs comparable to those of SeaClear2.0, not considering other mentioned alternatives.

The analysis here will prioritize the determination of cost-related factors, as personnel, material, equipment and time needed to perform the location, identification and monitoring of surface marine litter within 1 km². This will allow, in following chapters, the calculation of inspection costs per km², enabling subsequent comparisons.

3.1.1. Visual observation from surface mobile platforms

Human observation from a vessel involves trained observers visually locating, identifying and recording marine litter from the deck. Observers typically use binoculars and standardized protocols to estimate the type, quantity, and location of litter on the water's surface.

Observation can be carried out from different types of vessels which, besides stability, maneuverability and other sailing characteristics, have different observation points height that affect the distance of visibility. Large vessels, like ferries, provide a broad visual angle and, with their high speed, are suitable for monitoring open-sea areas [16]. Medium-sized vessels, such as research and fishing boats, with an observer height of around 4–6 meters above sea level, can monitor both open sea and coastal zones [17]. Small vessels, including motorboats and sailboats, place the observer at a height of roughly 1–2 meters above sea level and are typically used in coastal monitoring [18]. Here, the observer height refers to the vertical distance from the observer's eyeline to the water surface (calculated as the deck height plus the observer's eye level). Increased observer height may reduce the detectability of smaller litter items, and vessel speed also affects the ability to spot floating debris [19].

Considering that the observation from boats should ensure the detection of litter items in the size range of 2.5 cm to 50 cm, and according to following table from MSFD Technical Subgroup on Marine Litter [3], it can be assumed that from a small vessel sailing at 6 knots with an observer at 2 mts. elevation from the sea level the transect allowing acceptable marine litter observation on surface is of 5 mts. If considering a medium-sized vessel (observer at 6 mts.), at same speed, transect width would be of 8 mts.

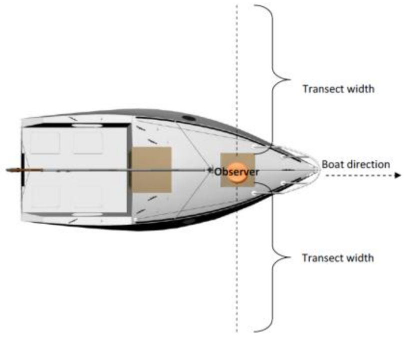


Fig. 8 – Visual observation schema. Font: DeFishGear [2].

Observer's elevation above the sea level	2 knots (3.7 km/h)	6 knots (11.1 km/h)	10 knots (18.5 km/h)
1 m	6 m	4 m	3 m
3 m	8 m	6 m	4 m
6 m	10 m	8 m	6 m
10 m	15 m	10 m	5 m

Table 3 – Transect width depending on height of observation and vessel speed. Source: MSFD [3]

To facilitate the calculation and comparison of different surface marine litter detection, identification, and monitoring methods, it is assumed that the study area is a straight line without turns or obstacles.

A surface area of 1 km² (10^6 m^2) whose transect width is d (in meters) has a length L (in meters) given by:

$$L = \frac{10^6}{d}$$

If inspection velocity is v (km/h), then time needed to conclude the inspection will be:

$$t = \frac{10^3}{d\ x\ v}\ [h]$$

Following table shows the time needed in hours to inspect 1 km², considering previous information.

Type of vessel /Speed	2 knots (3.7 km/h)	6 knots (11.1 km/h)	10 knots (18.5 km/h)
Small (observer at 2 mts)	19 h 18 m	9 h 1 m	7 h 43 m
Medium-sized (observer at 6 mts)	13 h 31 m	5 h 38 m	4 h 30 m

Table 4 – Time needed for 1 km2 of inspection with visual observation.

Considering that the maximum survey period during which observers can maintain focus attention is 60 minutes [20], two observers are required to cover 8 hours shift of survey. At minimum, a skipper is required for the small boat and a skipper plus a sailor are required for the medium boat.

3.1.2. Image-based observation from Unmanned Aerial Vehicles (UAVs)

The use of UAVs for locating, identifying, and monitoring marine litter is emerging as an effective, efficient, and widely adopted method. However, these systems still face certain limitations: adverse weather conditions, such as strong winds and poor visibility, can hinder their effectiveness by impacting flight stability and image quality, and limited battery life constrains the area they can survey without requiring recharges or replacement batteries, which is particularly challenging for large-scale monitoring [20-25].

In terms of reliability, UAV locating, identifying, and monitoring is generally dependable for specific types of marine litter, though this can vary based on the methods and scale used. UAVs equipped with high-resolution RGB and multispectral cameras are especially reliable for detecting and classifying, particularly when integrated with machine learning algorithms [23,26]. Furthermore, comparisons between UAV-based monitoring and traditional methods, such as vessel or observer-based approaches, indicate that UAVs often achieve similar or slightly improved detection rates for surface-level litter, highlighting their reliability in this application [21,22].

For locating, identifying, and monitoring floating marine macrolitter, UAVs (drones) are typically operated at altitudes between 45 and 65 meters, achieving a ground sampling distance of around 2 cm per pixel. This altitude range allows a good balance between high image resolution for accurate detection of items and sufficient area coverage to make the survey efficient [21,22]

The optimal speed for UAV inspections during locating, identifying, and monitoring floating marine macrolitter varies based on specific conditions and desired coverage. Generally, UAVs are operated at speeds that enable both efficient area coverage and high-resolution image capture. UAVs typically maintain lower speeds when capturing high-resolution images of litter in smaller survey areas, while higher speeds may be used in extensive or less litter-dense regions.

Speeds around 18-36 km/h are typical for smaller, high-resolution surveys, as these speeds allow the UAV to capture clear images while balancing battery consumption and flight stability [27].

In order to obtain a comparable metric, it is considered that UAV is flying at an altitude of 50 mts with a speed of 25,2 km/h (both within an already accepted range). FOV of drone cameras used is of an angle of 50°, as the Rededge-P camera used in SeaClear2.0's UAV.

To obtain transect at sea surface level, following formula is applied:

$$Wt = 2\,x\,h\,x\tan(\frac{FOV}{2})$$

Where:

Wt = Width of Transect at surface sea level

h = UAV flying altitude

FOV = camara field of view in angle degrees

The width of the transect (in this case considering transect as full width, instead of two segments as in Fig. 7) is approximately 46,63 meters.

Applying the previous chapter formula, an UAV would need 51 minutes to survey 1 km².

Small AUVs, such as portable or commercial models, typically require 1–2 personnel for operation. An operator manages the deployment, programs the mission, and oversees recovery, ensuring the AUV performs its tasks effectively. In some cases, a technician may be involved to assist with data analysis, troubleshooting, or routine system maintenance. Medium AUVs, often used for research or survey-grade applications, require a slightly larger team of 3–5 people. This includes an operator responsible for mission programming and navigation, a technician or engineer to conduct pre-launch checks, calibration, and maintenance, and a data analyst who processes the collected information. For offshore or complex deployments, a deck crew may also be needed to handle the AUV during launch and recovery.

The following table provides insights into commercial survey UAVs, revealing an average communication range of 9-10 km and flight autonomies of 45 minutes aprox., with only a few exceptions reaching up to 90 minutes. These limitations significantly constrain operational range and area coverage, as UAVs must return to base for battery changes or recharging before their autonomy is exhausted. This reduces their effective range and area that can be inspected in a single flight.

Considering that it takes 51 minutes to inspect 1 km², most UAVs in the analysis would be unable to complete a square kilometre survey in one flight. For example, UAVs with a flight autonomy of 45 minutes, such as the DJI Mavic 3 Enterprise or DJI Matrice 300 RTK, would fall short by approximately 6 minutes, necessitating additional flights to complete the task.

Moreover, the operational range is further limited by the "round-trip" requirement to return for battery replacement, reducing the usable area for each flight. This is especially problematic in BVLOS (Beyond Visual Line of Sight) missions, where the communication range may be sufficient, but flight autonomy prevents full utilization of that range.

These constraints underscore the importance of strategic mission planning to maximize efficiency, incorporating recharging and maintenance intervals while minimizing downtime for large-scale surveys.

Drone Model	Manufacturer	Communication Range	Flight Autonomy	Inspection Equipment Capabilities
DJI Mavic 3 Enterprise	DJI	Up to 15 km	Up to 45 min	High-resolution camera, thermal imaging
DJI Mavic 3M	DJI	Up to 15 km	Up to 43 min	Multispectral imaging for agriculture and mapping
DJI Phantom 4 RTK	DJI	Up to 7 km	Up to 30 min	High-precision RTK module, 20 MP camera
Parrot Anafi USA	Parrot	Up to 4 km	Up to 32 min	Thermal imaging, 32x zoom, high-resolution video
senseFly eBee X	senseFly	Up to 8 km	Up to 90 min	RGB, multispectral, thermal payload options
Quantum Systems Trinity F90+	Quantum Systems	Up to 7.5 km	Up to 90 min	PPK/RTK accuracy, multispectral and LiDAR payloads
WingtraOne GEN II	Wingtra	Up to 10 km	Up to 59 min	High-resolution RGB cameras, multispectral options
Delair UX11	Delair	Up to 5 km	Up to 59 min	Multispectral and RGB payloads, RTK/PPK accuracy
Microdrones mdMapper1000DG	Microdrones	Up to 5 km	Up to 45 min	LiDAR, RGB, multispectral, thermal imaging
PrecisionHawk Lancaster 5	PrecisionHawk	Up to 2 km	Up to 45 min	High-resolution RGB cameras, multispectral sensors
DJI Matrice 300 RTK	DJI	Up to 15 km	Up to 55 min	Wide range of payloads: LiDAR, thermal, RGB
DJI Air 3	DJI	Up to 20 km	Up to 46 min	Dual-camera system with high resolution
DJI Air 3S	DJI	Up to 20 km	Up to 45 min	Advanced visual imaging capabilities
DJI Mavic Air 2	DJI	Up to 10 km	Up to 34 min	48 MP camera, HDR video
DJI Air 2S	DJI	Up to 12 km	Up to 31 min	20 MP camera, 1-inch sensor, HDR imaging
DJI Mavic Air	DJI	Up to 2.5 mi	Up to 21 min	12 MP camera, 4K video
Parrot AR.Drone 2.0	Parrot	Wi-Fi range	Approx. 12 min	Basic video recording and real-time streaming
PrecisionHawk Lancaster 5	PrecisionHawk	Up to 2 km	Up to 45 min	Multispectral sensors, high-resolution cameras

Table 5 – Sample of survey AUV operational range and capabilities.

3.1.3. Image-based observation from surface mobile platforms

Marine litter image-based observation from surface mobile platforms is an emerging approach in environmental surface marine litter location, identification, and monitoring that leverages surface mobile devices (such as boats equipped with cameras or USV) to detect, classify, and quantify marine litter using imagery. Transitioning from human observation to image-based from surface mobile platforms in marine litter monitoring offers substantial advancements [20-24].

The capabilities of these image-based observation systems depend largely on the type of platform and sensors used and the method employed to manage, and process acquired data. Data and acquisition and management, platforms and sensors were analysed on previous chapters, involve real-time processing, onboard storage with post-processing, and cloud-based management with machine learning integration. Real-time processing enables platforms to analyze images in situ, quickly identifying marine litter. When real-time data transmission isn't feasible, platforms can store images and sensor data onboard for later analysis, a method often used for high-resolution, multispectral imagery that requires complex post-processing for detailed results. Cloud-based storage and machine learning allow data to be processed remotely, supporting large-scale analysis, pattern recognition, and easy sharing with research teams, regulatory bodies, and conservation organizations.

If the same camera as the one used on UAV, same FOV and accuracy range, installed on the bow of the platform, transect would be the same: 46,63 meters

Considering that USV have an average operational speed of 5.4 – 9.0 km./h [20], time needed to inspect 1 km² (if 7,5 km/h speed is considered) is: 2 hours and 52 minutes.

The number of people required to capture and analyze marine litter using image-based observation from surface mobile platforms varies based on the mission complexity, operational setup, and technology employed. During the capture phase, a team typically includes 1/2 platform operators for navigation or remote monitoring (e.g., for manned boats or USVs), a sensor technician to ensure proper functioning of cameras and troubleshooting issues, and 1/2 mission supervisors or scientists to oversee data collection. At a minimum, three technical personnel are required to operate such systems effectively. In addition, if considering analysis *in situ*, 1/3 data processing specialists are required to manage real-time or post-processed imagery, with onboard or software tools, depending on the resolution and complexity of the data.

3.2 Seabed Marine Litter Location, Identification, and Monitoring

The analysis considers both existing, traditional methods already in use and emerging alternatives, that offer capabilities and outputs comparable to those of SeaClear2.0. It must be noted that currently, *there is no off-the-shelf in situ detection technique (technology) that is operational (TRL 7–9) for systematic seafloor monitoring of plastic litter in diverse marine environments. Current options lack the necessary detail to fully meet objectives for exposure, effects, and risks assessment of seafloor plastic litter* [28]. Several already existing platforms and sensors are combined to perform such activities[28,29].

Sensors considered span acoustic, optical, spectral, and magnetic sensing modalities, each offering unique advantages and limitations. While some systems excel at large-scale detection of macrolitter, others are tailored for detailed analysis of material types and smaller debris.

Multibeam sonar systems emit multiple acoustic beams to map the seafloor or underwater objects. They excel in covering large areas and producing detailed bathymetric maps. MBSS systems are highly effective for detecting larger objects and generating three-dimensional models of the underwater environment. However, their resolution is generally not fine enough for smaller litter objects, making them suitable primarily for macroplastic and debris detection.

Forward-Looking Sonar provides 2D acoustic imagery by emitting high-frequency sound waves in a forward-facing direction. This technology is particularly useful for short-range applications where precise imaging is needed. Although effective for detecting well-defined objects, its performance diminishes when identifying fragmented or small-sized debris.

Side Scan Sonar uses acoustic beams emitted sideways to create images of the seafloor, making it an excellent choice for detecting objects over wide areas. This technology is commonly employed for shipwreck searches and marine debris surveys. While it is adept at recognizing large objects, its ability to classify material types is limited, and it struggles with smaller or scattered plastics.

Synthetic Aperture Sonar enhances the resolution of traditional sonar by combining multiple acoustic pings to create high-definition images. It is effective for detecting small objects, provided the platform is stable and the environment allows precise navigation.

CHIRP (Compressed High-Intensity Radiated Pulse) sonar emits a single beam with a wide frequency range to enhance penetration and resolution. It is frequently used in shallow water for geological studies and object detection. While it is versatile and cost-effective, its coverage is limited compared to multibeam systems.

High-definition cameras capture visual data with excellent detail and are often used for surface or shallow water applications. They require clear water and good lighting conditions to be effective. HD cameras are instrumental in capturing high-resolution imagery for post-processing but are less effective in turbid or deep-sea environments.

RGB cameras use the visible spectrum to capture images and are typically employed in detecting surface or near-surface litter. They rely on color differences to identify objects but are highly dependent on visibility conditions and cannot penetrate deeper or murky waters.

Multispectral imaging uses sensors to detect light across multiple specific wavelengths. This technology is effective in distinguishing between material types based on their spectral signatures. It is particularly useful for identifying plastics in controlled environments, though its performance may decline in deep or murky conditions.

Hyperspectral cameras extend the capabilities of multispectral systems by capturing data across a much broader and continuous spectrum. This allows for highly detailed analysis of material properties, including polymer types. Hyperspectral imaging is highly effective in laboratory settings or clear waters but is more expensive and requires significant computational resources for data analysis.

LiDAR (Light Detection and Ranging) uses laser light to measure distances and create detailed topographical maps. It is widely used in terrestrial and aerial applications but has limited effectiveness underwater due to light absorption and scattering in water. In marine environments, it is mainly used for shallow water surveys.

PPG (Photoplethysmography) sensors measure changes in light absorption to detect volumetric variations. While commonly used in medical and physiological monitoring, their application in marine litter detection is less established and likely limited to specialized research scenarios.

X-ray imaging is used to penetrate objects and reveal their internal structure. It is typically employed in laboratory settings for analysing material composition. Its application in marine litter detection is rare due to the technical challenges of deploying such systems in underwater conditions.

Magnetometers detect variations in the Earth's magnetic field caused by metallic objects. They are frequently used for locating ferrous materials like shipwrecks or discarded machinery. While effective for metallic debris, they are not suited for non-metallic litter like plastics.

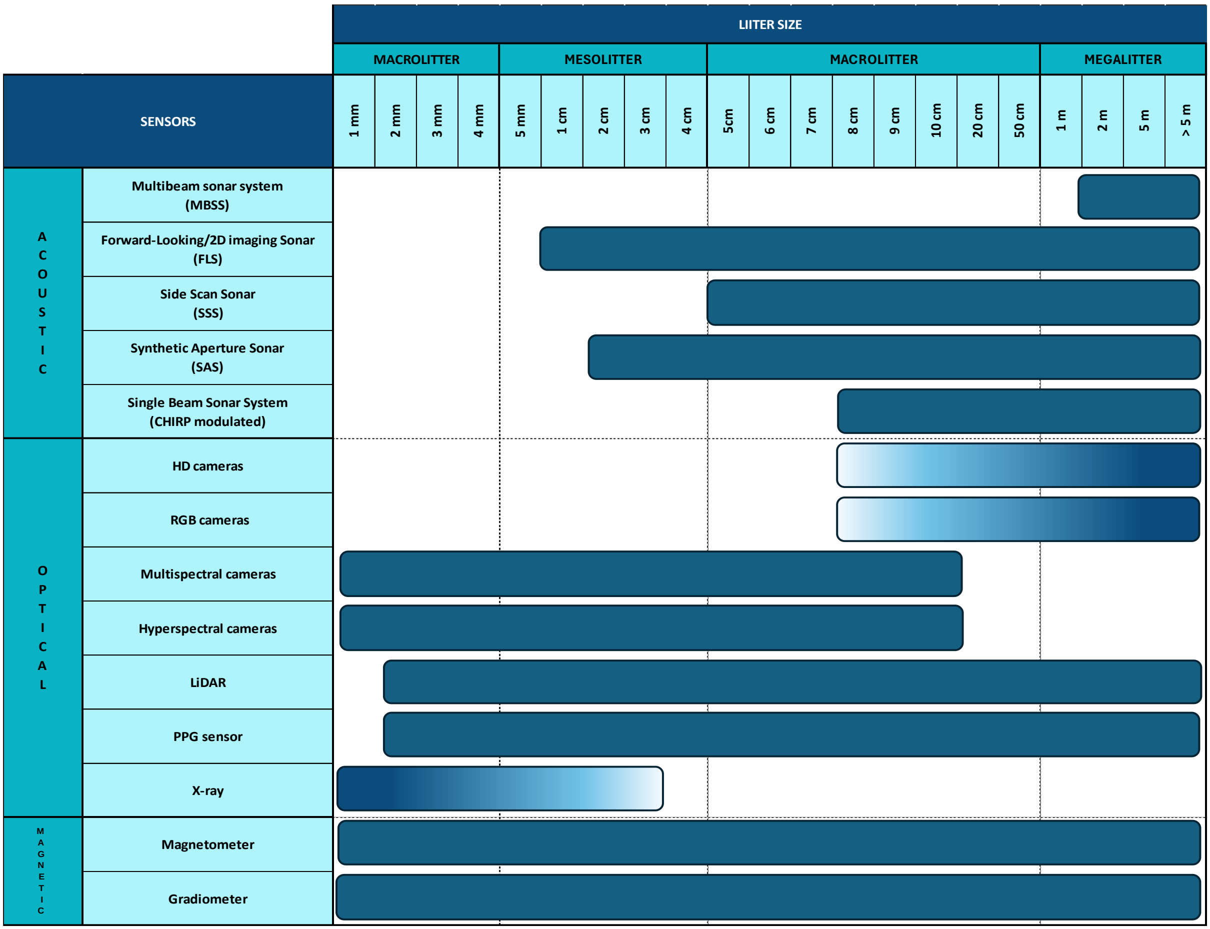
Gradiometers measure the gradient of a magnetic field and are often employed for more sensitive detection of metallic objects. Like magnetometers, they are effective for metallic items but have limited application in detecting plastics or other non-metallic debris.

Not all sensors can be integrated into every platform, as illustrated in the following table. To simplify the analysis of the numerous possible combinations, this study focuses exclusively on platform capabilities. It assumes that sensor performance remains consistent across platforms, delivering the same results for locating, identifying, and monitoring seabed marine litter.

SENSORS		PLATFORMS						
		ROV	(A)USV	AUV/UUV	Vessel/boat		Diver	
					Installed	Towed		
ACOUSTIC	Multibeam sonar system (MBSS)	✓	✓	✓	✓	✓	✓	Shallow
		✓		✓				Deep
	Forward-Looking/2D imaging Sonar (FLS)	✓	✓	✓	✓		✓	Shallow
		✓		✓				Deep
	Side Scan Sonar (SSS)	✓	✓	✓	✓	✓		Shallow
		✓		✓		✓		Deep
	Synthetic Aperture Sonar (SAS)			✓		✓		Shallow
				✓		✓		Deep
	Single Beam Sonar System (CHIRP modulated)	✓	✓		✓			Shallow
		✓						Deep
OPTICAL	HD cameras	✓	✓	✓	✓	✓	✓	Shallow
		✓		✓		✓		Deep
	RGB cameras	✓	✓	✓	✓	✓	✓	Shallow
		✓		✓		✓		Deep
	Multispectral cameras	✓					✓	Shallow
		✓						Deep
	Hyperspectral cameras	✓					✓	Shallow
		✓						Deep
	LiDAR	✓		✓			✓	Shallow
		✓		✓				Deep
	PPG sensor	✓		✓			✓	Shallow
		✓		✓				Deep
	X-ray	✓						Shallow
		✓						Deep
MAGNETIC	Magnetometer	✓	✓	✓	✓	✓	✓	Shallow
		✓		✓		✓		Deep
	Gradiometer	✓	✓	✓	✓	✓		Shallow
			✓	✓		✓		Deep

Table 6 – Compatibility of detection sensors with marine platforms. Source: Adapted from Sandra, M. et al. [28]

Each of these systems has strengths and limitations, and their suitability depends on the specific objectives, conditions, and environments of the detection tasks. Following table tries to resume sensors detection range according to litter size.



		LIITER SIZE																				
		MACROLITTER				MESOLITTER					MACROLITTER								MEGALITTER			
	SENSORS	1 mm	2 mm	3 mm	4 mm	5 mm	1 cm	2 cm	3 cm	4 cm	5cm	6 cm	7 cm	8 cm	9 cm	10 cm	20 cm	50 cm	1 m	2 m	5 m	> 5 m
ACOUSTIC	Multibeam sonar system (MBSS)																			●	●	●
	Forward-Looking/2D imaging Sonar (FLS)						●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Side Scan Sonar (SSS)										●	●	●	●	●	●	●	●	●	●	●	●
	Synthetic Aperture Sonar (SAS)							●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Single Beam Sonar System (CHIRP modulated)													●	●	●	●	●	●	●	●	●
OPTICAL	HD cameras													●	●	●	●	●	●	●	●	●
	RGB cameras													●	●	●	●	●	●	●	●	●
	Multispectral cameras	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●						
	Hyperspectral cameras	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●						
	LiDAR		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	PPG sensor		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	X-ray	●	●	●	●	●	●	●	●													
MAGNETIC	Magnetometer	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Gradiometer	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

Table 7 – Sensor's detection size range. Source: Adapted from Sandra, M. et al. [28]

3.2.1 Divers

Marine diving encompasses various methods, each tailored to specific depths, durations, and operational needs. The three types of diving are Autonomous Diving (SCUBA), Surface-Supplied Diving (SSD), and Saturation Diving. Each approach offers unique capabilities, with distinct advantages and limitations based on factors such as breathing gas management, dive depth, and environmental conditions. While SSD and Saturation Diving are critical for industrial and scientific operations at greater depths, SCUBA diving stands out for its flexibility and accessibility, in shallow waters.

Surface-Supplied Diving (SSD) involves a constant supply of breathing gas delivered from the surface via an umbilical cable. This method ensures safety through continuous communication and monitoring, enabling longer dive durations and extended operational depths of up to 50 meters, according to international industry standards. It is commonly used in commercial activities such as underwater installations or inspections, where precision and extended bottom time are essential.

Saturation Diving is the most advanced and resource-intensive method. It is used primarily for deep-sea operations where divers work at extreme depths for prolonged periods. By living in pressurized habitats and breathing a specialized gas mixture like Heliox, saturation divers can remain at depth for days or weeks (maximum 28 days), minimizing decompression risks.

Autonomous Diving (SCUBA), the most accessible form of diving, relies on divers carrying their own breathing gas supply. SCUBA diving is highly versatile, enabling mobility and flexibility for tasks in shallow to moderate depths, less than 30 meters. This self-contained approach makes it the preferred method for recreational and scientific diving.

SCUBA recreational divers, supported by NGO-type initiatives, have proven to be a reliable and cost-effective resource for identifying and monitoring marine litter. These divers, who explore underwater environments primarily for enjoyment, provide consistent and valuable data. With the support of NGOs providing tools, training, and support to standardize data collection, information obtained is standardized and valid for further studies. Programs such as Professional Association of Diving Instructors' (PADI) Dive Against Debris® train divers to document and report marine litter during their dives using an app, building a database that is both extensive and highly detailed.

3.2.1.1. Diving Limits

When diving, divers subject their bodies to increased pressure, measured in bars (metric) or atmospheres (imperial, abbreviated as ata). On land or at the water's surface, humans experience the pressure of 1 bar due to the surrounding atmospheric air. However, when submerged, water pressure increases by 1 bar for every 10 meters of depth and decreases as the diver ascends toward the surface. In addition to water pressure, gases such as air used for breathing also undergo compression underwater, resulting in changes to their volume and density. As pressure increases with depth, the gas volume decreases while its density rises.

Underwater pressure also impacts the body in other significant ways. Nitrogen, a major component of breathing air, dissolves into body tissues under increased pressure. The deeper a diver descends and the longer they stay submerged, the more nitrogen is absorbed into the body. Upon ascending, the reduced pressure causes nitrogen to expand. If this excess nitrogen is released too rapidly for the body to eliminate it, it can form bubbles in the tissues, leading to a serious medical condition known as decompression sickness (DCS). Symptoms of DCS can range from joint and limb pain, numbness, and breathing difficulties to unconsciousness and, in severe cases, death.

Given the physiological effects of increased underwater pressure and nitrogen absorption, each diving method inherently has limitations on bottom time—the period from when a diver leaves the surface to when they begin ascending from their maximum depth. To facilitate comparison between diving methods, it is useful to consider bottom time limits under the condition that no decompression stops are required, and that air is gas used on the dives. The no-decompression limit represents the maximum time a diver can spend at a specific depth without needing to pause during ascent to safely eliminate excess nitrogen.

According to PADI's Recreational Dive Planner for SCUBA diving and US Navy Rev.7 Diving Tables for SSD, below suggested maximum time to spend in certain water depths without requiring a decompression stop.

Depth	**10 mts.**	**12 mts.**	**14 mts.**	**16 mts.**	**18 mts.**	**20 mts.**	**22 mts.**	**25 mts.**	**30 mts.**	**35 mts.**	**40 mts.**	**50 mts.**
SCUBA diving	219'	147'	98'	72'	56'	45'	37'	29'	20'	14'	9'	-
SSD	232'	163'	92'	74'	63'	48'	39'	33'	25'	15'	10'	6'

Table 8 – Maximum bottom time without decompression stops.

In addition to physiological limitations, air consumption is a critical factor to consider in SCUBA diving. On average, a recreational diver with reduced/low activity consumes 25 liters of air per minute, independently of the pressure. Considering that standard scuba tank for recreational diving is 15 liters at a filling pressure of 200 bar it holds 3.000 L of air at atmospheric pressure. However, divers are advised to reserve a portion of this air for safety, ensuring that the tank is never emptied completely. As a safety measure pressure gauges indicate that when cylinder pressure is under 50 bar, diver is entering air reserve zone meaning that dive must conclude never leaving less than approximately 30 bar pressure on the cylinder (450 L of air at atmospheric pressure).

At the surface, this volume would last approximately 102 minutes (calculated as total air volume minus safety reserve divided by 25 L/min). However, air consumption measured at atmospheric pressure increases with depth due to the higher ambient pressure (Boyle-Mariotte law), significantly affecting the bottom time available to divers.

The relationship between depth and cylinder air supply time is illustrated in the following table:

Depth	Absolute Pressure (bar)	Air Consumption equivalence at atmospheric pressure (L/min)	Ø bottom time (min.)
10 m	2	50	51
12 m	2,2	55	46
14 m	2,4	60	43
16 m	2,6	65	39
18 m	2,8	70	36
20 m	3	75	34
22 m	3,2	80	32
25 m	3,5	87,5	29
30 m	4	100	26
35 m	4,5	112,5	23
40 m	5	125	20

Table 9 – Maximum bottom time according to cylinder air supply.

When using SCUBA diving method, maximum bottom time has been calculated using two different criteria being the most restrictive (marked in red) the one considered as real bottom time appliable.

Depth	Bottom Time according to no decompression diving	Bottom Time according to cylinder supply	Real bottom time in SCUBA diving
10 m	219’	51’	51’
12 m	147’	46’	46’
14 m	98’	43’	43’
16 m	72’	39’	39’
18 m	56’	36’	36’
20 m	45’	34’	34’
22 m	37’	32’	32’
25 m	29’	29’	29’
30 m	20’	26’	20’
35 m	14’	23’	14’
40 m	9’	20’	9’

Table 10 – SCUBA diving maximum bottom time.

A diver’s field of view for detecting marine litter on the seabed depends on a multitude of factors. These include environmental conditions such as water turbidity, lighting, depth (most colors are lost as depth increases) …, as well as the characteristics of the seabed itself, including its texture, color, composition (e.g., sand, rocks, vegetation…).

Additionally, the characteristics of the litter itself are critical, with size being the most important factor. Larger objects are more easily spotted, whereas smaller debris like microplastics may be nearly invisible, especially if they blend with the seabed. Other factors include the color and contrast of the litter against the background, as well as the diver's experience and observational skills.

These combined factors determine the likelihood of detecting and accurately identifying marine litter during an underwater survey. All considered, macrolitter should be established as the minimum size of plastics to be effectively detected during a divers' survey. Smaller debris, like mesoplastics or even microplastics, would be potentially detected if divers focus closely on the substrate, if using specialized equipment, or sampling methods for accurate identification, which are impractical in larger-scale visual surveys conducted by divers.

No formal academic literature regarding diver's field of view in relation with speed during underwater inspections have been found. For that reason, assumptions regarding observation width and speed are based on the extensive experience of TECNOSUB, a professional diving company with over 50 years of expertise in underwater projects and considering that:

- An adopted air consumption rate of 25 l/min, which corresponds to a low activity intensity.
- Long bottom times (calculated based on the maximum bottom time), meaning that the speed at the beginning of the dive is not the same as the speed at the end of the dive.
- Diver activity requires visual attention across the entire transect width.

Based on these considerations, TECNOSUB estimates a maximum average speed of 5 meters per minute along the seabed, with an observation width of 4 meters.

It is considered that this balance between speed and coverage ensures effective detection of marine macro litter.

Applying already used formulas, time needed to inspect 1 km², considering that area under survey is a straight line without turns or obstacles, is 833 hours and 20 minutes.

If considering megalitter, debris bigger than 1 m, there have been few projects that had stablished that speed could be between 0.001 and 0.006 km²/hour, being 166 h 40 min to 1.000 hours needed for an area of 1 km².

Either value makes it entirely impractical to perform location, identification, and monitoring operations on a large scale with divers, even without considering diving limits.

3.2.2 Vessel/boat

As already seen when detailing surface marine litter location, identification, and monitoring capabilities are determined by sensors used instead of vessel/boat's characteristics. Also, sensor's capabilities are affected by environmental factors, either with sensors installed on the vessel or towed.

3.2.3 ROV

When appeared, ROV revolutionized underwater operations with their real-time capabilities and sensor integration. However, their vessel-depending tethered nature introduces inherent limitations in mobility, deployment complexity, and operational range that limits its effectiveness for large-scale seabed marine litter presence survey/inspection.

The underwater speed of an ROV depends on its design, size, and intended purpose. Generally, observation ROVs operate at speeds ranging from 2 to 5 knots (approximately 3.7 to 9.3 kilometers per hour), as it can be seen on table of analyzed ROVs, and they can integrate different sensors, that as in other platforms will determine range, accuracy and speed of inspections.

Managing an ROV underwater survey typically requires a team of 2/3 people, depending on the mission's complexity. The ROV pilot/operator (1/2 people) navigates the vehicle, operates its cameras and sensors, and ensures it follows the planned survey path. The ROV technician (1/2 people) is responsible for maintaining the vehicle's systems, including power, thrusters, and sensors, while performing pre-deployment checks, troubleshooting, and post-mission maintenance. Additionally, 1/2 data processing specialists handle the collected data, including video, sonar, and sensor outputs, cleaning and analyzing it to generate actionable results. However, it is possible for two experienced, well-trained, and knowledgeable individuals to cover all three roles (pilot, technician, and data processor) efficiently in less complex missions or with automated support systems.

ROV Model	Manufacturer	Maximum Speed	Operational Depth	Survey/Inspection Capabilities
BlueROV2	Blue Robotics	2 knots	Up to 100 meters	HD camera, open-source software.
AC-ROV 100	AC-CESS Co. UK Ltd.	2 knots	Up to 100 meters	Compact design, high-quality camera.
GNOM Mini	Indel-Partner Ltd.	2 knots	Up to 120 meters	High-quality camera, compact design.
GNOM Pro	Indel-Partner Ltd.	2 knots	Up to 150 meters	High-quality camera, suitable for confined spaces.
LBV150-4	Seabotix Inc.	2.5 knots	Up to 150 meters	Integrated lighting and sonar systems.
Deep Trekker DTG3	Deep Trekker Inc.	2.5 knots	Up to 200 meters	4K camera, robust lighting.
Outland 1000	Outland Technology	2.5 knots	Up to 300 meters	High-resolution camera, LED lighting.
Seabotix LBV300	Seabotix Inc.	3 knots	Up to 300 meters	Integrated sonar and camera systems.
Falcon	Saab Seaeye	3 knots	Up to 300 meters	High-resolution cameras, sonar systems.
VideoRay Pro 4	VideoRay LLC	4.4 knots	Up to 305 meters	Integrated camera and optional sonar.
Ocean Modules V8	Ocean Modules	3 knots	Up to 1,000 meters	Advanced imaging .
Mini ROV Falcon DR	Saab Seaeye	3 knots	Up to 1,000 meters	Enhanced imaging for deep-water inspections.
Seaeye Tiger	Saab Seaeye	3 knots	Up to 1,000 meters	High thrust, payload capacity for inspections.
Observer	Sub-Atlantic	3 knots	Up to 1,000 meters	Modular design, suitable for inspections.
Seaeye Lynx	Saab Seaeye	3 knots	Up to 1,500 meters	Observation and inspection class.

Table 11 – Sample of survey ROV operational range and capabilities.

3.2.4 (A)USV

USVs provide a highly effective alternative to traditional vessel-installed and towed equipment, combining autonomy, cost-efficiency, and adaptability. Equipped with advanced navigation systems and positioning, they offer precise path-following and data collection. Moreover, their ability to integrate diverse sensors, such as multi-beam echo sounders, side-scan sonars, and cameras, ensures comprehensive, high-quality data acquisition.

Their operational costs are significantly lower, as they consume less fuel, simplify deployment logistics and eliminate onboard crew requirements. Operating an USV typically requires a small team of 2-3. A

USV operator (1/2 people) oversees navigation and mission execution, ensuring the vehicle follows the planned route and objectives. A payload technician (1 person) manages onboard sensors and equipment, handling setup, calibration, and maintenance. For missions involving detailed data analysis, a data processing specialist (1/2 people) may process and interpret collected information.

USV Model	Manufacturer	Maximum Speed	Operational Range	Battery Endurance	Survey/Inspection Capabilities
BlueBoat	Blue Robotics	6 knots	Up to 3 km	>1 km	Open-source USV for bathymetric surveys and water quality monitoring. Only SSS available off the shelf. Other equipment to be installed by buyer.
Hydrone	Seafloor Systems Inc	2/3 knots	Up to 2 km	8 hours	HydroLite Echosounder, Teledyne RDI River Pro ADCP, Sontek M9 ADCP.
TriDrone USV	Seafloor Systems Inc	2/3 knots	Up to 1 km	8 hours	HydroLite Echosounder, Teledyne RDI River Pro ADCP, Sontek M9 ADCP.
Echoboat-160	Seafloor Systems Inc	2/3 knots	Up to 2 km	8 hours	Multibeam Sonar (SeaRAY, Sonic 2020, Norbit iWBMS), Starfish 990 or 453OEM sidescan sonar, Teledyne Odom E20 dual frequency echosounder, PingDSP, Teledyne RDI or Sontek ADCP's, Applanix INS.
Echoboat-240	Seafloor Systems Inc	3/4 knots	Up to 2 km	8 hours	Multibeam Sonar (Teledyne RESON SeaBat T50/T20, R2Sonic 2024, DVL, ADCP, Sound Velocity Profiler).
HydroCat-550	Seafloor Systems Inc	4/6 knots	Up to 2 km	6 - 12 hours (even more)	Multibeam Sonar (Integrated Dual Head Teledyne RESON, SeaBat T50/T20, Norbit, R2Sonic, PingDSP, Applanix, towed Klein Sidescan Sonar, etc).
CEE-USV	CEE HydroSystems	5 knots	Up to 5 km	-	High-performance survey boat with GNSS positioning and live video.
REAV-28	HydroSurv	5 knots	Up to 1.5 km	4.5 / 9 hours	Survey sensors to be installed by buyer.
The Otter	Maritime Robotics	6 knots	-	20 hours	Survey sensors to be installed by buyer.
Apache 4	CHCNAV	Up tp 11.6 knots	-	6 hours	Acoustic Doppler Current Profiler and capability to add sensors.
iBoat BS3	Hi-Target Surveying Co. Ltd	11.7 knots	Up to 3 km	4,5 h	High-performance USV with single-beam echo sounder and GNSS positioning.
iBoat BS12	Hi-Target Surveying Co. Ltd	11.7 knots	Up to 3 km	4,5 h	Built-in positioning and directional GNSS receiver, SBES and 360° Omnidirectional camera . Capability to incorporate Acoustic Doppler Current Profiler, Single Beam Echo Sounder Side-scan Sonar, Multi-parameter Water Quality Meter.
SR-Surveyor M1.8	SeaRobotics Corporation	5 knots	Up to 10 km	-	Edgetech 2205 (bathymetry, sidescan), LiDAR and Acoustic Doppler Current Profiler optional.
SR-Utility 3.6	SeaRobotics Corporation	11 knots	-	-	Fluorometers, DGPS, RTK GPS, Vector GPS, Inertial Navigation Sensors, Single Beam Echo, Sounders, Multibeam Echo Sounders, LIDAR, Sub-Bottom Profilers, Side Scan Sonar, Imaging Sonar, CTD, Transmissometers, Spectrometer, Magnetometer, ADCP/ADP, USBLs, Video Systems
C-CAT 3 ASV	L3Harris	9 knots	Up to 50 km	-	Coastal and offshore data collection with real-time data transmission.
C-WORKER 7 ASV	L3Harris	4 knots	Up to 50 km	25 days	Can accommodate up to 500kg of survey equipment.
C-WORKER 7 ASV	L3Harris	3.5 knots	-	48 hours	10U 19-inch rack unit to fit survey equipment.
DriX	iXblue	16 knots	Up to 5.000 km	-	Deepwater hydrographic surveys with MBES and capability to incorporate additional sensors.
Inception Class Mark II	Unmanned Survey Solutions	3.5 knots	Up to 5 km	-	Modular USV for inland and coastal hydrographic surveys. Could carry up to 66 litres of equipment including Single-Beam, Multi-Beam, Side Scan Sonar…
ME120	OceanAlpha	6 knots	Up to 10 km		Multi-purpose USV for hydrographic surveys and environmental monitoring, Singlebeam echo sounder, multibeam echo sounder, ADCP, 3D LiDAR scanner, side-scan sonar, forward-looking sonar, water quality sonde.

Table 12 – Sample of survey (A)USV operational range and capabilities.

3.2.5 AUV/UUV

AUVs and UUVs are advanced, untethered systems optimized for subsea inspection and survey missions, utilizing sophisticated navigation and decision-making capabilities overcoming the challenges of limited underwater communication. Moreover, like USVs, they can integrate diverse sensors ensuring data acquisition, even if the gathered data cannot be immediately transmitted due to communication constraints.

Model	Manufacturer	Type	Operational Range	Maximum Depth	Speed	Battery Endurance	Survey/Inspection Capabilities
Sparus II	IQUA Robotics	AUV	Approx. 74 km	200 m	2.5 knots	Up to 8 hours	Lightweight hovering vehicle suitable for research, monitoring, and surveillance tasks with customizable payloads.
Iver4 900	L3Harris	UUV	Approx. 74 km	300 m	2.5 knots	Up to 20 hours	Long ingress/egress missions with adaptable sensor payloads.
Yuco	Seaber	AUV	Up to 50 km	300 m	2 knots	Up to 10 hours	Micro-AUV designed for shallow water missions, environmental monitoring, and data collection with high reliability.
REMUS 300	HII	UUV	Up to 300 km	305 m	5 knots	Up to 30 hours	Versatile UUV for mine countermeasures, hydrographic surveys, and intelligence, surveillance, and reconnaissance (ISR) operations.
Seaglider	Kongsberg	AUV	Thousands of km	1,000 m	0.5 knots	Several months	Long-duration missions for measuring temperature, salinity, and oceanographic data.
HUGIN	Kongsberg	AUV	Up to 1,100 km	3,000 to 6,000 m	4 knots	Up to 100 hours	Equipped with sonar, echo sounder, cameras, lasers, sub-bottom profilers, and sensors for high-resolution surveys.
Bluefin-21	General Dynamics	UUV	Up to 450 km	4,500 m	4.5 knots	Up to 25 hours	Modular design for search, salvage, archaeology, exploration, oceanography, and mine countermeasures.
REMUS 6000	HII	UUV	Up to 150 km	6,000 m	5 knots	Up to 22 hours	Hydrographic surveys, mine countermeasures, and environmental monitoring.
SeaRaptor	Teledyne Marine	AUV	Up to 400 km	6,000 m	3 knots	Up to 30 hours	Modular design supports various sensors for geophysical surveys, environmental monitoring, and infrastructure inspection.

Table 13 – Sample of survey AUV/UUV operational range and capabilities.

Operating an AUV/UUV typically requires a small team of 2-3 people, as with the USV. An operator (1/2 people) and a technician (1 person). Since data is not processed in real-time, the team size for post-mission analysis can vary depending on the volume, complexity, and type of data acquired, as well as whether the data is analyzed on-site or at a separate location, and what the data will be used for, potentially requiring additional personnel for processing, interpretation, and application-specific analysis.

3.3 Surface Marine Litter Collection

As analysed in previous chapters, surface marine litter collection alternatives to be considered comparable to SeaCela2.0 are following mobile systems: small-unmanned drones, manned boats/skimmers, and unmanned boats/skimmers.

These technologies offer innovative, efficient, and scalable alternatives to traditional manual methods for surface marine litter collection. While manual collection is labor-intensive and time-consuming, and not considered in present analysis, these alternatives provide a more effective approach to removing floating debris.

3.3.1 Small-unmanned drones

Small-unmanned drones for surface marine litter collection are no longer just emerging technologies; they are a present reality, widely available and increasingly used as an effective alternative for cleaning up floating debris in aquatic environments. With several off-the-shelf models currently being commercialized by companies, these solutions represent a Technology Readiness Level (TRL) 9, indicating they are fully developed, market-ready, and operational in real-world conditions.

Name	Manufacturer	Payload Capacity	Autonomy	Operational Range	Speed	Frontal capacity / Work surface	Operation Mode
Smurf 50	Orcauboat	Up to 50 kg	Up to 8 hours	Unknown	Unknown	-	Autonomous
PixieDrone	The Searial Cleaners	Up to 60 kg	Up to 6 hours	500 mts.	Up to 2 knots	1,157 m	Remote-Controlled
WasteShark	RanMarine Technology	Up to 180 kg	Up to 8 hours	Up to 5 km	Up to 3 knots	1,182 m	Autonomous / Remote-Controlled
Wastewhale	Orcauboat	Up to 500 kg	Up to 8 hours	Unknown	Unknown	15 m	Autonomous
Jellyfishbot	IADYS	Up to 80 kg	Up to 8 hours	Up to 1 km	1 knot	1.000 m^2 / hora	Remote-Controlled
ClearBot	Clear Robotics	Up to 200 kg	Up to 4 hours	Up to 5 km	Up to 3 knots	-	Autonomous
Seadron	Ona Safe & Clean	Up to 250 L.	Up to 8 hours	-	Up to 1.5 knots	3.700 m^2 / hora	Remote-Controlled

Table 14 – Sample of surface cleaning small-unmanned drones operational range and capabilities.

Operating surface marine litter collection drones typically require a small team, with personnel needs varying based on the drone's complexity and operational mode. Autonomous drones generally need 1/2 operators for mission planning, monitoring, and maintenance, while remote-controlled drones require 2/3 personnel, including a pilot, an observer, and a maintenance technician if pilot can't perform such tasks.

As previously established, to facilitate the calculation and comparison of different surface marine litter collection methods, it is assumed that the study area is a straight line without turns or obstacles. Using the known data and assuming that the litter collected does not exceed the payload capacity, the time required to clean a surface area of 1 km²:

Name	Time
PixieDrone	233 hours 26 minutes
WasteShark	152 houres 22 minutes
Seadron	270 hours 40 minutes
Jellyfishbot	1.000 hours

Table 15 – Time to clean surface of 1km^2.

3.3.2 Manned/Unmanned boats/skimmers

Specifically designed workboats are used in ports, marinas, and coastal areas to collect and remove floating debris, plastics, and other waste from water surfaces. Traditionally, these vessels have been manned, requiring onboard operators for navigation and waste collection. Recent advancements, however, are leading to the development of unmanned and autonomous systems, while retaining the basic designs and collection techniques of existing models.

These boats generally have greater collection capacities compared USVs making them more effective for large-scale waste removal. However, their size and design often limit their operations in areas that are difficult to access, where smaller and more agile USVs are better suited.

Name	Manufacturer	Autonomy	Working Speed	Collection Width	Payload Capacity	Operation Mode
CatClean-85	Ona Safe & Clean	18 hours (battery) llimited (at low speed)	1,5/2,5 knots	2.4 meters	Up to 1,000 kg	Manned (min. 1 pax)
Envirocat All-Electric Eco 8.5	MMS	8 hours	7 knots	2.55 meters	1,500 kg	Manned (min. 1 pax)
Envirocat Harbour	MMS	193 litres fuel	9 knots	3.80 meters	4,000 kg	Manned
Versi-Cat	Liverpool Water Witch	-	-	2.5 meters	1,000 kg	Manned (min. 1 pax)
Omni Catamaran	ELASTEC	8-10 hours (battery)	4-5 knots	2.8 meters	1,000 kg	Manned (min. 1 pax)
Mobile Skimmer	4Ocean	-	-	13 meters	-	Manned 2 pax
TH Series	Aquarius Systems	-	-	2.5 meters	Up to 5,400 kg	Manned 2 pax
AQS	Aquamarine	-	-	-	-	Manned
JLGC-A220	Julong	-	-	3.2 meters	4,000 kg	Manned
CleaWat	CleaWat	-	-	-	-	Manned
Class 3 Clearbot	Clear Robotics	8 hours	3 knots	2.3 meters	500 kg / 1,500 kg	Auntonomous

Table 16 – Sample of surface cleaning vessels operational range and capabilities.

For comparison purposes:

Name	Time
CatClean-85	112 hours and 29 minutes
Envirocat All-Electric Eco 8.5	30 hours and 14 minutes
Envirocat Harbour	15 hours and 47 minutes
Omni Catamaran	42 hours and 51 minutes
Class 3 Clearbot	78 hours and 15 minutes

Table 17 – Time to clean surface of 1km^2.

3.4 Seabed Marine Litter Collection

Even if trawling, whether conducted by specialized vessels or adapted fishing boats, has been a traditional method of seabed litter cleanup, it is not considered a viable option for environmentally sustainable recovery efforts and is therefore excluded from this analysis. This method involves dragging nets indiscriminately across the seabed, causing extensive damage to marine habitats such as coral reefs and seagrass beds. Furthermore, trawling operates as a non-selective process, capturing everything in its path without distinction, including marine fauna and fragile ecosystems. The significant bycatch and collateral damage associated with this method make it incompatible with the principles of targeted and ecologically responsible litter recovery.

Similarly, companies specializing in dredging, decommissioning, and wreck salvage are unsuitable for seabed marine litter recovery. Their operations are designed for large-scale removal—often employing cranes with capacities of up to 4,000 tons—rather than addressing lightweight or dispersed litter. Moreover, the methods they use are inherently non-selective, indiscriminately removing sediment, litter, and marine organisms. Combined with their significant financial and logistical demands due to reliance on large-scale industrial techniques, these factors render them inefficient for seabed cleanup operations and therefore not considered in this analysis.

3.4.1 Divers

In any of the type of diving—SCUBA, Surface Supplied Diving (SSD), and Saturation Diving—seabed litter recovery operations require varying amounts of time depending on the type of debris being collected. As discussed in previous chapters, while time-limiting factors (e.g., decompression limits or oxygen supply) restricts the overall duration of underwater work, the nature and complexity of the recovery task itself determines operational efficiency. For example, collecting small debris such as bottles or cans typically requires minimal effort, as divers can gather them into a net bag while swimming along the seabed. Conversely, recovering larger items, such as a bicycle, involves additional steps. Time must be dedicated to securing the object with rigging equipment, such as attaching it to a crane hook or an inflatable lift bag, before it can be safely brought to the surface. An even more complex operation, such as retrieving a washing machine, demands more time and effort for rigging and securing due to the object's size and weight.

If also considering variable factors such as the density of marine litter on the seabed, the distance between debris items, and the need for safety precautions (e.g., surfacing during the lifting of heavy loads) make it nearly impossible to define a homogeneous parameter to compare recovery methods. Instead, this chapter evaluates the resources required for a specific intervention based on the type of diving employed. The analysis considers personnel, equipment, and material needed under different operational scenarios, facilitating cost assessment and enabling comparisons. Resources required vary according to depth. Based on commercial diving operations governed by Spanish national legislation, European standards, and industry guidelines—most notably those from the International Marine Contractors Association (IMCA)—the following distribution has been considered:

3.4.1.1. Dives up to -30 m.

This is the depth limit under normal circumstances for diving with SCUBA or using a portable surface supply system, without requiring a full system (a hyperbaric chamber) on board. Although SCUBA diving could be performed from a small zodiac or similar craft, the scenario under consideration involves recovering a large object that cannot be lifted and brought to the surface by the divers themselves and/or being carried on board a small craft. Consequently, the vessel must be equipped with a small crane suitable for handling the recovery operations and with enough space on deck to receive litter recovered. Therefore, the vessel used can be the same for both SCUBA and SSD, whereas a vessel capable of accommodating saturation diving equipment, or one equipped with an integrated saturation diving system, is required if this diving technique is the one used.

Diving technique	Minimum Diving Team	Diving Equipment	Vessel Type	Vessel Crew
SCUBA	3	Personal equipment	Small barge, multicat or tug	2
SSD	5[30]	Surface Supplied Portable Equipment	Small barge, multicat or tug	2
Saturation	9[30]	Saturation Equipment	Saturation Diving Support Vessel (SDSV) Offshore Support Vessels (OSV) Multipurpose Vessels	Min. 15

Table 18 – Diving resources requirements in dives up to -30 mts.

3.4.1.2. Dives from -30 to -50 m.

Diving operations exceeding -30 meters exceed the limits of SCUBA. At these depths, SSD requires utilizing a full system including a hyperbaric chamber, dive control station, breathing gas supply system, umbilical… This setup requires approximately 150 m^2 of deck space. For this reason, vessels typically used for diving operations up to -30 meters, such as small barges or tugs, are insufficient for deeper operations. Larger vessels that can accommodate the necessary equipment must be considered.

Diving technique	Minimum Diving Team	Diving Equipment	Vessel Type	Vessel Crew
SCUBA	Out of limits			
SSD	5 [30]	Full Surface Supplied System	Tug, workboat, small OSV, diving support vessel	Min 4
Saturation	9 [30]	Saturation Equipment	Saturation Diving Support Vessel (SDSV) Offshore Support Vessels (OSV) Multipurpose Vessels	Min. 15

Table 19 – Diving resources requirements in dives from -30 mts to -50 mts.

3.4.1.3. Dives from -50 m.

According to IMCA[30], diving operations exceeding -50 meters can only being performed using saturation diving systems. Saturation diving requires a fully integrated setup that includes a hyperbaric living chamber, a transfer chamber, and a diving bell to transport divers to and from the worksite depth. The vessel must also be equipped with advanced systems, such as life support monitoring, gas management systems, and comprehensive emergency response equipment, including a dedicated hyperbaric rescue system.

The deck space requirement for a saturation diving system is significantly larger than for SSD operations, often exceeding 300 m^2. Due to these requirements, only large, specialized vessels designed or heavily retrofitted for saturation diving operations are suitable for use at these depths.

3.4.2 ROV

There are various types of ROVs, each designed for specific tasks, and each with its own specifications, such as size, power requirements, payload capacity, and the potential for integrating specialized sensors like cameras, sonars, or manipulators. These characteristics determine their suitability for different underwater operations, including the recovery of marine litter.

Type of ROV	Capabilities	Main Applications	Examples
Micro and Mini ROVs	Compact, highly portable, limited depth and payload capacity.	Aquaculture inspections, small-scale underwater observations.	Deep Trekker DTG3, VideoRay Scout
Observation-Class	Equipped with cameras and basic sensors; portable; limited payload capacity.	Visual inspection of ship hulls, underwater structures, marine habitats.	BlueROV2, VideoRay Pro 5
Inspection-Class	Sonar, high-resolution cameras, and environmental sensors; moderate payload.	Inspecting pipelines, subsea equipment, and underwater construction.	Falcon ROV, Seaeye Tiger
Light-Work-Class	Small manipulator arms, basic cutting tools; compact and versatile.	Cable inspection, light repairs, marine litter collection.	Saab Seaeye Cougar
Work-Class	Multiple manipulator arms, tools for heavy lifting; high power and precision.	Offshore oil and gas operations, wreck salvage, underwater construction.	Perry XLX-C, Schilling UHD
Heavy-Work-Class	Advanced thrusters, multiple tools, capable of lifting large objects.	Large-scale offshore construction, wreck salvage, wind turbine installation.	Quantum ROV, Triton XLX

Table 20 – Type of ROVs.

Considering the various types of ROVs described in the table, a light-work-class ROV emerges as the most suitable option for recovering marine litter weighing up to 100 kg. However, it must be considered that, even though the payload capacity of light-work-class ROVs includes the weight of mission-specific equipment such as robotic arms or specialized tools, along with the capacity to lift and transport items back to the surface in one operation, manipulator arms are not traditionally designed for recovering marine litter. Their primary purpose is to operate equipment or interact with subsea installations. As a result, while the payload capacity may technically be sufficient, factors such as the size, shape, and material of the object to be recovered can significantly influence the ROV's ability to perform the task. As an example to illustrate these limitations, any valve, gauge, or component to be managed by an ROV is typically designed with specific features to facilitate ROV manipulation, a concept commonly referred to as diving-free solutions. For instance, subsea valves intended for ROV operation are often equipped with oversized torque interfaces or T-bar handles, specifically designed to be easily gripped and rotated by an ROV's manipulator arms. Similarly, control panels or instrumentation on subsea installations include large, clearly marked buttons and levers that are engineered to accommodate the limited dexterity and precision of standard ROV manipulators. These adaptations highlight the inherent challenges of ROV manipulator when interacting with objects that lack such specific modifications, such as marine litter.

ROV Model	Manufacturer	Payload Capacity	Description
Falcon	**Saab Seaeye**	100 kg.	Inspection-class ROV designed for subsea observation and light intervention tasks.
Mojave	**Sub-Atlantic**	120 kg.	Lightweight ROV designed for inspection and light intervention tasks in shallow waters.
Comanche	**Sub-Atlantic**	215 kg.	Lightweight ROV designed for inspection and light intervention tasks in shallow waters.
Panther-XT Plus	**Saab Seaeye**	220 kg.	Work-class ROV offering high thrust and precision for complex underwater tasks, including marine debris recovery.
Leonard	**Saab Seaeye**	Up to 240 kg.	Electric work-class ROV.
Atom	**SMD**	150 kg	Compact work-class ROV designed for drill support, survey and light construction duties.
XLX-C	**FET Perry**	350 kg	Work-class hydraulic ROV
Supporter 3000	**Kystdesign**	400 kg.	Work-class ROV

Table 21 – Sample of ROVs capabilities.

The effective operation of a remotely operated vehicle (ROV) requires several components: the vehicle itself, a control unit for navigation and real-time monitoring, umbilical cables to provide the necessary power and communication link between the ROV and the surface, and mission-specific tools such as sensors and manipulators. Deployment and retrieval of the ROV require a small crane, davit, or dedicated launch and recovery system (LARS) to ensure safe and efficient handling. Additionally, the support vessel must be stable and equipped with sufficient deck space to house the control unit and store additional equipment. To standardize comparisons, the same vessel used for surface-supplied diving operations at depths ranging from -30 to -50 meters is also considered for ROV operations.

At a minimum, any operation must include at least one trained ROV operator to pilot the vehicle and manage its functions, as well as one technician to handle maintenance and troubleshoot any technical issues.

4. SeaClear2.0 capabilities

The overall evaluation of the SeaClear2.0 capabilities is based on available data from the work done within the respective work packages. At the time of publication of this deliverable, almost two years of the overall project duration had passed. All tasks of the technical projects' work packages (WP) have commenced, ensuring steady progress across all planned activities. While the advancements in technology have not yet been tested within the system, they have been validated in the laboratory and are now in the final stages of production, ready for assembly and initial real-world testing. Given the absence of contingencies suggesting otherwise, it is determined that the systems will perform at their maximum capacity without limiting factors, assuming that the progression of the system's control facets continues as initially planned.

Building on this foundation, the forecasted capabilities of the SeaClear2.0 system as follows:

- Surface marine litter location, identification, and monitoring, performed basically with UAV, is limited by Seacat's speed, which is 5 knots (9.26 km/h) and max. flying altitude of the tethered UAV, 50 mts. As considered in previous chapters, acceptable observation width is approximately 46,63 meters.

  As already detailed, a surface area of 1 km² (10^6 m^2) whose transect width is d (in meters) has a length L (in meters) given by:

  $$L = \frac{10^6}{d}$$

  If inspection velocity is v (km/h), then time needed to conclude the inspection will be:

  $$t = \frac{10^3}{d\ x\ v}\ [h]$$

  Applying the formula, SeaClear2.0 system would need 2 hours and 19 minutes to survey 1 km².

- In the case of seabed marine litter location, identification, and monitoring the most restrictive speed is ROV's one. Assuming that SeaClear2.0 system's ROV swims at 2 knots (1,03 m/s) with a visibility of one meter (1 m each side = 2 m width) it makes a scanned area of 2,06 m2/s. To inspect 1 km², mini-Tortuga will need 134 hours and 50 minutes.

  Also to be mentioned that if only SeaCat's sensors are used (MBSS), speed and observation range increase.

- Considering that the distance between two SeaCat's hulls is 0.8 m and operational speed 2 knots, around 3.000 m2 to collect surface marine litter would be covered every hour.

  If considering floating litter collection system via omnidirectional USV, also part of SeaClear2.0 system, with a known thrust force as detailed in *D3.4: Floating litter collection systems design report*.

  Using drag equation to estimate the speed:

$$D = \frac{1}{2} pv^2 C_d A$$

Where:

T = D = 411.42 NT (thrust equals drag)

(thrust as per USV characteristics)

ρ = 1025 kg/m3 (density of seawater)

Cd = 0.5 C (typical drag coefficient for boats)

A = 10 m² (reference area, an estimated value)

The speed would be approximately 0.41 meters per second (m/s) under the assumed conditions. If increasing the drag coefficient to 1.5 to consider the towed net, speed would be around 0.28 m/s.

With a net of 10 meters, it will take 99 hours and 18 minutes to clean an area of 1 km².

If analysing collecting capacity and assuming 0,25 kg/m2 average litter density (+/- 6 to 8 plastic bottles), this is 0,75 T/hour or 6T/day. This would require 3 rotations/hour, 250 kg each.

- The productivity of seabed litter collection is constrained by the tender's payload capacity (approximately 250 kg). With the tender completing one rotation every 30 minutes (10 minutes to load, 10 minutes to transport to shore, and 10 minutes to return), this equates to 500 kg per hour or 4 tons over an 8-hour workday. Therefore, the maximum seabed litter collection capacity is up to 4 tons per day.

5. Benefit Analysis

As already mentioned when presenting CBA, quantifying the economic value of environmental benefits, innovation through advanced robotic systems and AI tools, and the broader economic impact of SeaClear2.0, especially when considering its potential scalability on a global scale, is inherently complex and nearly impossible to calculate with precision. Generalizable evaluations are complicated by the fact that the costs and possible benefits of interventions are influenced by factors specific to the context in which they are implemented [31,32].

For example, the restoration of marine biodiversity—resulting from reduced marine litter—has cascading effects on ecosystem stability, which indirectly supports industries like fishing and tourism, but assigning a monetary value to these outcomes involves substantial uncertainty. Similarly, the mitigation of microplastics in oceans reduces health risks for marine species and humans, yet the long-term societal savings from these improvements are difficult to estimate. Additionally, the innovation driven by SeaClear2.0, such as advancements in underwater robotics and AI systems, has potential spillover effects into other industries, including aquaculture and environmental monitoring, further complicating precise economic quantification.

For that reason, this section focusses on presenting a comparative multi-criteria analysis of existing evaluated methods & technologies for marine litter location, identification, monitoring, and collection, benchmarked against the approaches proposed by SeaClear2.0. By examining key operational performance metrics, personnel requirements, and equipment needs, this analysis aims to highlight the relative advantages and limitations of each method. The figures shown in the tables represent averaged data from the existing alternatives studied, providing an overview of their common characteristics and performance metrics.

Surface Marine Litter Detection, Identification and Monitoring				
	Visual Observation	**Image-based observation (UAV)**	**Image-based observation (USV)**	**SeaClear 2.0 (considering tethered UAV)**
Efficency (time for 1 Km² inspection)	4 h 30 min	51 minutes	2 h 52 min	2 h 19 min
Speed	10 knots	13.77 knots	4 knots	5 knots
Accuracy / Litter Size	> 2.5 cm	> 2.5 cm	> 2.5 cm	> 2.5 cm
Operational Range	n/a	9 - 10 km	4 km	3 km
Battery Endurance	n/a	45 min	8 hours	72 hours (linked to SeaCat)
Maintenace, recharge downtime for 1 Km² inspection	n/a	Yes	No	No
Operation Mode	Manual	Semi-Autonomous / Autonomous	Semi-Autonomous / Autonomous	Autonomous
Support vessel need	Yes	No	No	No
Personnel	Min. 2 Crew + 2 observers	1-2 Operators	1-2 Operators	1-2 Operators
Real-time processing	Yes	Depending on sensors and data managment software	Depending on sensors and data managment software	Yes
Operational limits (Beaufot scale)	7	5	3	Operational - 3 Transit - 5
Subsea observation	No	No	Yes, depending on sensors	Yes

Table 22 – Surface Marine Litter Location, Identification, Monitoring methods and technologies comparison.

Seabed Marine Litter Detection, Identification and Monitoring				
	ROV	(A)USV	AUV/UUV	SeaClear2.0 (limited by ROV capabilities)
Efficency (time for 1 Km² inspection)	Depending on sensors Same sensors considered, speed comparable factor	Depending on sensors Same sensors considered, speed comparable factor	Depending on sensors Same sensors considered, speed comparable factor	Depending on sensors Same sensors considered, speed comparable factor
Speed	2 to 5 knots	4 knots	3.5 knots	2 knots
Accuracy / Litter Size	Depending on sensors (min. considered 2.5 cm)	Depending on sensors (min. considered 2.5 cm)	Depending on sensors (min. considered 2.5 cm)	Depending on sensors (min. considered 2.5 cm)
Operational Range	n/a	4 km	325 km	3 km
Operational Depth Range	Depending on sensors Same sensors considered	Depending on sensors Same sensors considered	Depending on sensors Same sensors considered	Depending on sensors Same sensors considered
Battery Endurance	n/a	8 hours	20 hours	72 hours (linked to SeaCat)
Operation Mode	Manual	Semi-Autonomous / Autonomous	Autonomous	Autonomous
Support vessel need	Yes	No	No	No
Personnel	Min. 2 operators	2-3 Operators	2-3 Operators	1-2 Operators
Real-time processing	Depending on sensors and data managment software	Depending on sensors and data managment software	No	Yes
Operational limits (Beaufot scale)	3	3	4	Operational - 3 Transit - 5
Surface observation	No	Yes	No	Yes

Table 23 – Seabed Marine Litter Location, Identification, Monitoring methods and technologies comparison.

Surface Marine Litter Collection				
	Small Unmanned Drones	Boats / Skimmers		SeaClear 2.0 (including UAVs + net)
		Manned	Unmanned	
Efficency (time for 1 Km² cleaning)	218 h 49 min	50 h 20 min	78 h 15 min	99 h 18 min
Payload Capacity	185 kg	2.000 kg	500 kg	250 kg
Autonomy	7 h	n/a	8 h	72 h
Operational Range	Aprox. 3 km	n/a	unknown	3 km
Speed	2 knots	5.5 knots	3 knots	5 knots
Operation Mode	Autonomous / Remote-Controlled	Manned	Autonomous	Autonomous
Personnel	1-2 Operators	Min. 1 crew	1-2 Operators	1-2 Operators

Table 24 – Surface Marine Litter Collection methods and technologies comparison.

Seabed Marine Litter Collection					
	Divers			ROV	SeaClear 2.0
	Scuba	SSD	Saturation Diving		
Max. Depth	30 mts	30 / 50 mts	300 mts	455 mts	300 mts (for demo purposes 100 mts)
Payload	n/a (According to vessel's crane specs)	n/a (According to vessel's crane specs)	n/a (According to vessel's crane specs)	215 kg	250 kg
Litter shape	n/a	n/a	n/a	Manipulable with ROV	n/a
Rigging time	Yes	Yes	Yes	No	No
Vessel	Small barge, multicat or tug	Small barge, multicat or tug / Tug, workboat, small OSV, diving support vessel	Saturation Diving Support Vessel Offshore Support Vessels Multipurpose Vessels	Small barge, multicat or tug	No
Personnel	3	5	9	2	2
Crew	Min. 2	Min. 4	Min. 15	Min. 2	0
Operation Mode	n/a	n/a	n/a	Manual	Autonomous
Surface collection	No	No	No	No	Yes

Table 25 – Seabed Marine Litter Collection methods and technologies comparison.

SeaClear2.0 may not outperform dedicated systems in specific tasks, but its true strength lies in its versatility. Unlike specialized technologies such as UAVs, USVs, or ROVs, which are optimized for specific functions, SeaClear2.0 offers a fully autonomous solution that integrates both detection and collection for surface and seabed operations. This all-in-one capability is the system's greatest advantage, making it uniquely suited for comprehensive marine litter management.

In surface marine litter detection and monitoring, SeaClear2.0 demonstrates moderate efficiency. While it outperforms traditional visual observation and matches the performance of other autonomous vehicles like USVs, this is expected, as the USV's speed is the primary factor limiting the AUV's performance within the system. However, when compared to AUVs alone, SeaClear2.0 appears less efficient. On the positive side, one of SeaClear2.0's most notable strengths is its exceptional battery endurance of 72 hours, significantly surpassing both UAVs and the analyzed USVs. Although its operational range is limited to 3 km, falling short of UAV capabilities, this limitation is offset by its ability to operate independently of support vessels, adding flexibility and reducing operational complexity.

For seabed marine litter detection and monitoring, SeaClear2.0 is primarily defined by the capabilities of the sensors mounted on its ROV, making these characteristics central to its performance. Its speed aligns with that of ROVs and is slightly slower than UUVs, while its depth capability of 300 meters is not depreciable, even though it does not reach the maximum depths achievable by specialized ROVs. The system's standout feature remains its exceptional battery endurance, allowing for extended missions without frequent recharging. Furthermore, SeaClear2.0's real-time data processing capability offers a significant advantage over systems that depend heavily on post-mission data analysis.

In surface marine litter collection, the system performs well compared to alternatives like small unmanned drones or boats/skimmers. While it may not match the payload capacities of larger systems, its 250 kg capacity is suitable for targeted operations. Its autonomy ensures minimal human intervention. Although its efficiency in cleaning is slightly lower than dedicated surface skimmers, its ability to integrate collection with detection adds significant value, especially in complex scenarios.

In seabed marine litter collection is where the system excels. Its depth range of 300 meters and payload capacity of 250 kg position it as a strong alternative to ROVs. Unlike diver-based methods, which require significant human resources and support vessels, SeaClear2.0 operates autonomously with minimal personnel. Additionally, SeaClear2.0's ability to handle both detection and collection at the seabed level distinguishes it from most other systems that focus solely on one aspect.

6. Cost Analysis

When analyzing the costs of each method or technology, two types of costs are to be considered, the capital and operational ones. This involves quantifying the initial investments required for system acquisition (capital costs), such as purchasing platforms like UAVs, USVs, ROVs, and the sensors used, while operational costs include recurring expenses during deployment and usage, such as personnel, maintenance, or support vessel operations. Daily capital costs would consider 5-year lifespan with lineal amortization.

To ensure consistency in this analysis, sensors used in SeaClear2.0, and its costs, will be applied as the standard across all platforms, thereby homogenizing their detection capabilities and capital costs.

Operational costs for personnel would be also considered homogeneous for operators/technicians (450 €/day). Maintenance costs would be calculated following maintenance cost as a percentage of machine replacement cost formula, assuming a 5-year lifespan for the equipment components and considering an 8% maintenance percentage due to the accelerated material degradation caused by exposure to sea conditions and high-tech involved.

Even though several companies representing each platform type/technology (e.g., UAVs, USVs, ROVs, surface cleaners…) were contacted to gather detailed cost data, the limited number of responses received means that the analysis might not be as representative as initially expected. Despite this, the calculations will proceed using the available information, performing the analysis while acknowledging the potential limitations introduced by the lack of comprehensive industry feedback.

The analysis does not include the specific models and company names to comply with the non-disclosure agreements signed with some of the companies that provided cost information.

6.1 SeaClear2.0

In the context of a *saleability* study comparison, the capital costs for SeaClear2.0 will focus exclusively on the production costs of the system and the purchase costs of the sensors. This approach excludes the expenses associated with research and development (R&D), as these costs have already been financed through the Horizon Europe program. By narrowing the scope of capital cost evaluation to production and sensor acquisition, the study can provide a realistic assessment of the costs that would be directly incurred by potential future adopters or operators of the system, excluding partners profits that would be considered in the definitive financial plan developed in deliverable 10.5 – Business plan and business model.

Hardware	
SeaCat	165.000,00 €
SeaDragon	85.000,00 €
Surface litter collection system	15.000,00 €
ROV	34.000,00 €
UAV	15.000,00 €
Grapple	90.000,00 €
Sub-Total	**404.000,00 €**
Sensors	
MBES	120.000,00 €
USBL	12.000,00 €
Imaging sonar	21.000,00 €
Side Scan Sonar	10.000,00 €
Wi-Fi/radio	5.000,00 €
Controls	30.000,00 €
Sub-Total	**198.000,00 €**
TOTAL	**602.000,00 €**

Table 26 – SeaClear2.0 Capital Costs.

To compare the capital costs of SeaClear2.0 with other existing methods and technologies, the analysis focuses on specific system components rather than the entire system. Although SeaClear2.0's key advantage is its ability to function as an integrated system, handling detection, identification, monitoring, and cleaning for both surface and seabed litter simultaneously, only components directly involved in surface litter collection—such as the USV and SeaCat—will be considered. Other elements like the AUV, ROV, and grapple are excluded as they could not be viewed as directly relevant to this specific task.

Regarding operational costs, personnel (2 operators) and maintenance would be considered. The maintenance cost as a percentage of machine replacement cost formula will be used, assuming a 5-year lifespan for the equipment components and considering an 8% maintenance percentage due to the accelerated material degradation caused by exposure to sea conditions.

6.2 Visual observation from surface mobile platforms (boats/vessel)

For the analysis of visual observation from surface mobile platforms, the leasing costs of boats or vessels include crew, fuel, and maintenance, as well as permits and licenses. Costs of binoculars, and other necessary observation tools, along with safety gear such as life vests, emergency kits, and protective equipment, are considered negligible and only observers (2) cost is considered.

Small barge, multicat or tug's daily rate can be established in 4.500 €. Considering that this type of vessels can be found in any location, no mobilization costs are considered.

6.3 UAV

UAVs are categorized based on size, purpose, and operational capabilities. By size, they include large UAVs like military-grade systems used for long-range surveillance or combat missions, medium UAVs such as those for agricultural monitoring or mapping, and small or micro UAVs, popular for recreational use or close-range inspection tasks. UAVs are also classified by function, including reconnaissance UAVs for surveillance, commercial UAVs for delivery or infrastructure inspection, and combat UAVs equipped for defense applications. Additionally, they can be distinguished by their operating environments, with fixed-wing UAVs for long flights, rotary-wing UAVs for hovering and maneuverability, and hybrid models that combine the advantages of both.

Since the AUV used in the SeaClear2.0 system is a rotary-wing off-the-shelf model, the capital acquisition cost is considered equivalent to the standard market price for similar commercially available units, which is 15.000 €. Two operators and maintenance cost, as per previously defined method, also considered.

6.4 ROV

The ROV market is well-established and offers a wide range of vehicle types tailored to specific operational needs. Observation or inspection-class ROVs are ideal for locating, identifying, and monitoring marine litter, while light-work ROVs are better suited for collecting marine litter, as they can accommodate manipulators and payloads required for retrieval tasks. For these reasons, two different sets of prices will be used for comparison, one for each task. An observation ROV cost would be around 24.000 € and a light-work ROV 95.000 €.

Besides ROV itself, capital cost for the comparison includes side-scan sonar, the multibeam sonar system and the USBL that mini-Tortuga incorporates. When considering seabed removal operations, a gripper of minimum 100 kg load capacity has also to be included in the capital costs.

Regarding operational costs, while a small barge, multicat, or tug (4.500 €/day) can be an option for deploying observation or inspection-class ROVs, a larger tug, workboat, or small OSV (10.000 €/day) would be required for operating light-work ROVs. Not only must space for deploying equipment, such as Launch and Recovery Systems (LARS), be considered, but also vessel stability and the ability to maintain position are critical to ensure effective litter pick-up operations. Additionally, the vessel must be equipped with a crane to recover litter collected by the ROV once it surfaces. This operation can be complex and potentially unsafe, particularly when handling heavy loads, necessitating a thorough risk assessment to address safety concerns and operational challenges. Two ROV operators are considered for either ROV type, considering that crew is available in launch and recovery operations.

6.5 (A)USV

Even if the (A)USV market is still in its growth phase, there are already existing applications in defense, surveillance, research, and environmental monitoring. Defense-oriented (A)USVs, in particular, present more advanced capabilities compared to other sectors, driven by significant investments in technology development. These systems often feature autonomous navigation, high-endurance designs, and sophisticated sensor arrays tailored for complex missions such as mine detection, maritime security, and reconnaissance.

For this analysis, (A)USVs with similar characteristics as SeaCat have been considered. From the offers received, and only focusing on those with similar capabilities, the average purchase cost of an (A)USV is 47.000 €. If considering multibeam sonar and USBL, as mounted on the SeaCat, cost increases to 179.000 €.

As (A)USV can be operated from shore, no vessels are required for deployment. Two operators to be included as operational costs, besides maintenance.

6.6 AUV/UUV

As observed in the (A)USV market, the AUV/UUV sector offers a diverse range of vehicles tailored to specific operational needs, with costs varying significantly based on capabilities, size, and intended applications. For instance, an AUV designed for operations at depths up to 3,000 meters, is priced between 2 to 6 million €. In contrast, smaller models suitable for less demanding tasks such as shallow water surveys, up to 300 mts. or habitat mapping, are available at approximately at 150.000 €.

As in (A)USV, AUV/UUV can be operated from shore, no vessels are required for deployment. Two operators to be included as operational costs, besides maintenance.

6.7 Small-unmanned drones

Surface marine litter skimmers and drones vary in price based on their control systems. Autonomous skimmers, equipped with advanced navigation and decision-making capabilities, typically range from 40.000 € to 70.000 €, reflecting their higher level of technology and independence from constant human oversight. In contrast, remotely controlled skimmers, which rely on manual operation, are more budget-friendly, with prices ranging from 20.000 € to 25.000 €

For our analysis, we consider a system priced at 40.000 €. This choice is based on its balance of technical capabilities, operational autonomy, and the fact that it is already commercially available. The selected system offers a practical solution comparable to SeaCat, making it an ideal candidate for assessing cost-effectiveness in surface marine litter clean-up operations.

Considering its deployment from shore, only one operator and maintenance costs would be considered.

6.8 Manned/unmanned boats/skimmers

Although a pilot product was introduced during the summer of 2024, the operational reality of boat/skimmers used for surface marine litter collection continues to rely on manned systems.

Due to the highly customized design of the equipment and the diverse operational requirements, only a limited number of indicative quotations with comparable capabilities to SeaClear2.0 have been evaluated. These quotations, averaging 85.000 €, exclusively involve manned boats.

Two crew members are considered to operate the vessels.

6.9 Diving operations

SCUBA recreational divers, supported by NGO initiatives, engage in seabed recovery efforts that are inherently philanthropic, making it impossible to assign a cost for analysis. This method, rooted in volunteerism and non-commercial efforts, is well-suited for localized clean-up actions in specific areas, particularly at depths of up to 30 meters. However, its lack of commercial scalability and economic viability excludes SCUBA-based recovery from consideration in this cost analysis.

When considering SSD operations up to 30 meters depth, a minimum diving equipment cost of 450 € per day, along with the use of a small barge, multicat, or tug (4.500/day €), must be accounted for. As previously mentioned, such operations require a minimum team of five personnel. Even if the cost for team might vary depending on country where operations are performed, a cost of 570 €/day per diver is to be considered.

SSD operations from 30 to 50 mts would need full SSD equipment at a daily rate of 3.200 € and a larger tug, workboat, or small OSV (10.000 €/day) is to be employed to guarantee equipment installation on board. Same team size can be considered. As previously mentioned, due to type of vessel availability, no mobilization costs are taken into account.

Saturation diving operations are carried out from specialized vessels, with lease costs varying widely based on factors like vessel size, capabilities, seasonal demand, and project specifics. For a small vessel during a mid-demand season, daily rates typically range from 50.000 to 100.000 € (a cost of 75.000 € is considered for the analysis), covering the vessel, crew, and standard saturation diving systems. Additional costs such as mobilization, fuel, and compliance may apply, and prices can escalate during high-demand periods or for projects requiring advanced technology like dynamic positioning systems.

Even if crew is included in vessel cost, saturation diving team personnel is to be added to the daily cost. A saturation diving team is composed by different specialized technicians with different salaries but to simplify a rate of 1.000 €/day per technician is considered.

7. Cost-Effectiveness Analysis

Due to the nature of operational costs being inherent to the functioning of the methods rather than the presence or abundance of marine litter, 1 km² inspected or cleaned will be adopted as the standardized comparable unit for surface marine litter either detection, identification & monitoring or cleanup. This metric ensures consistency and comparability across different techniques and locations regardless of specific litter densities.

The subsequent tables present a cost comparison of various methods and technologies for surface marine litter management.

Surface Marine Litter Detection, Identification and Monitoring				
	Visual Observation	**Image-based observation (UAV)**	**Image-based observation (USV)**	**SeaClear 2.0 (considering tethered UAV)**
Efficency (time for 1 Km² inspection)	4 h 30 min	51 minutes	2 h 52 min	2 h 19 min
Capital Costs	**n/a**	**15.000 €**	**47.000 €**	**192.000 €**
Capital Costs (daily, 5 year life-span)	**n/a**	**8 €**	**26 €**	**105 €**
Platform Cost	n/a	15.000 €	47.000 €	180.000 €
Sensors Cost	n/a	cameras included	cameras included	12.000 €
Operation Costs (daily)	**5.400 €**	**901 €**	**902 €**	**908 €**
Vessel (including crew)	4.500 €	n/a	n/a	n/a
Operators	900 €	900 €	900 €	900 €
Maintenance	Included in vessel rate	1 €	2 €	8 €
Hourly Costs (8 hours/day)	675 €	114 €	116 €	127 €
Cost for 1 Km² inspection	**3.038 €**	**97 €**	**333 €**	**294 €**

Table 27 – Surface Marine Litter Detection, Identification and Monitoring costs comparison.

Surface Marine Litter Collection			
	Small Unmanned Drones	**Manned Boats / Skimmers**	**SeaClear 2.0 (SeaCat + UAVs & Net)**
Efficency (time for 1 Km² cleaning)	218 h 49 min	50 h 20 min	99 h 18 min
Capital Costs	**40.000 €**	**85.000 €**	**180.000 €**
Capital Costs (daily, 5 year life-span)	**22 €**	**47 €**	**99 €**
Platform Cost	40.000 €	85.000 €	180.000 €
Sensors Cost	non additional	non additional	non additional
Operation Costs (daily)	**902 €**	**904 €**	**908 €**
Operators	900 €	900 €	900 €
Maintenance	2 €	4 €	8 €
Hourly Costs (8 hours/day)	115 €	119 €	126 €
Cost for 1 Km² surface cleaning	**25.265 €**	**5.979 €**	**6.332 €**

Table 28 – Surface Marine Litter Collection costs comparison.

For subsea litter, the standardized comparable unit is defined as one operation day. Even though other operational effectiveness units, such as quantity, accuracy, volume, or weight detected/collected, might offer a valid perspective, they are only applicable in areas with a known density of marine litter. This specificity makes it challenging to extrapolate these measures to other locations where litter distribution and density are unknown.

Seabed Marine Litter Detection, Identification and Monitoring				
	Observation ROV	(A)USV	AUV/UUV	SeaClear2.0 (SeaCat + ROV)
Capital Costs	**166.000 €**	**189.000 €**	**292.000 €**	**341.000 €**
Capital Costs (daily, 5 year life-span)	**91 €**	**104 €**	**160 €**	**187 €**
Platform Cost	24.000 €	47.000 €	150.000 €	199.000 €
Sensors Cost	142.000 €	142.000 €	142.000 €	142.000 €
Operation Costs (daily)	**5.400 €**	**908 €**	**913 €**	**915 €**
Vessel (including crew)	4.500 €	n/a	n/a	n/a
Operators	900 €	900 €	900 €	900 €
Maintenance	n/a	8 €	13 €	15 €
Cost for 1 day of operations	**5.491 €**	**1.012 €**	**1.073 €**	**1.102 €**

Table 29 – Seabed Marine Litter Detection, Identification and Monitoring costs comparison.

Seabed Marine Litter Collection					
	Diving Operartions			Light-work ROV	SeaClear 2.0
	SSD (up to 30 mts)	SSD (up to 50 mts)	Saturation Diving		
Capital Costs	n/a	n/a	n/a	**327.000 €**	**516.000 €**
Capital Costs (daily, 5 year life-span)	n/a	n/a	n/a	**179 €**	**283 €**
Platform Cost	n/a	n/a	n/a	185.000 €	374.000,00 €
Sensors Cost	n/a	n/a	n/a	142.000,00 €	142.000,00 €
Operation Costs (daily)	**7.800 €**	**16.050 €**	**84.000 €**	**5.414 €**	**923 €**
Vessel (including crew)	4.500 €	10.000 €	75.000 €	4.500 €	n/a
Diving Equipment	450 €	3.200 €	included on the vessel	n/a	n/a
Divers/Operators	2.850 €	2.850 €	9.000 €	900 €	900 €
Maintenance	n/a	n/a	n/a	14 €	23 €
Cost for 1 day of operations	**7.800 €**	**16.050 €**	**84.000 €**	**5.594 €**	**1.205 €**

Table 30 – Seabed Marine Collection costs comparison.

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Although the comparison with specific systems is not entirely unfavorable to SeaClear2.0, and it excels as the best solution for seabed marine litter collection, its greatest strength lies in its versatility, as already seen in the Benefit Analysis chapter.

Even though systems designed for different purposes cannot be seamlessly integrated to replicate SeaClear2.0's capabilities, the following table offers a conceptual evaluation of combining alternative solutions to approximate a similar level of full-range functionality. For seabed marine litter detection, identification, and monitoring, the (A)USV is excluded, as these tasks are assumed to be feasible using the lightweight ROV that is already required for seabed litter removal. Similarly, for surface marine litter collection, while the optimal alternative might be a manned skimmer, it is excluded to avoid duplicating costs. Instead, the leased vessel needed for deploying the ROV is assumed to include a surface recovery system.

	COMBINED ALTERNATIVE		SeaClear2.0
	Image-based observation (UAV)	**Light-work ROV**	
Capital Costs	**15.000 €**	**327.000 €**	**567.000 €**
Capital Costs (daily, 5 year life-span)	**8 €**	**179 €**	**311 €**
Platform Cost	15.000 €	185.000 €	404.000 €
Sensors Cost	cameras included	142.000,00 €	163.000 €
Operation Costs (daily)	**5.415 €**		**925 €**
Vessel (including crew)	n/a	4.500 €	n/a
Operators	900 €		900 €
Maintenance	15 €		25 €
DAILY COSTS	**5.602 €**		**1.236 €**

Table 31 – Full-range functionality costs comparison.

8. Conclusions

The SeaClear2.0 system represents a significant step forward in addressing marine litter, one of the current global challenges, politically manifested in the EU Horizon 2020 programs as well as the 2021-2030 United Nations Decade of Ocean Science for Sustainable Development.

By offering an integrated pioneering solution that combines detection, identification, monitoring, and collection into a single autonomous solution capable to operate effectively across a range of scenarios, from coastal areas to offshore environments, positions SeaClear2.0 as a potential game changer in the fight against marine pollution.

Not having considered in present deliverable limitations of the human physics, even if mentioned on the introductory sections, when detailing seabed collection capabilities or detailed speed recovery performance of the grapple, the system excels on seabed marine litter recovery-arguably the most overlooked aspect of marine litter management today. While surface-oriented systems for recovery and, increasingly, prevention are becoming more common, there is no technology on the market capable of addressing seabed litter without causing significant harm to the seabed and marine habitats, as traditional trawling methods do.

Regarding surface marine litter, while SeaClear2.0 may not be the most effective method when its tasks (detection, identification, monitoring, and collecting) are considered separately, its unique approach offers a distinct advantage that is challenging to evaluate comparatively. The system's coordination involves the UAV operating autonomously in search mode to detect litter, followed by transmitting the detected litter's coordinates to USVs for collection. After this stage, the UAV transitions to a situational awareness mode, providing ongoing oversight of the area. Upon receiving the litter collection coordinates, the USVs autonomously generate and execute optimal path plans to efficiently retrieve the litter. This approach represents a disruptive innovation compared to existing methods, equipping the system with capabilities that have been unprecedented until now.

The AI software, with its real-time processing and object identification capabilities, adds significant value to the entire system and, although developed as an integral part of the project, has the potential to be marketed as a standalone product.

Even though the development of the individual elements of the system and their seamless coordination will ultimately dictate the direction of how SeaClear2.0 can enter the market, the current benefits are already evident, and there is a strong indication that a viable market exists for such an innovative solution.

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