Mariculture and Marine Litter: Pilot Study from the Seafloor in Shellfish Farming Areas of Mali Ston Bay (Croatia)

Marikultura i otpad u moru: pilot-istraživanje s morskog dna u području školjkarstva Malostonskog zaljeva (Hrvatska)

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Abstract

Marine litter associated with shellfish farming remains poorly characterised despite the rapid expansion of mariculture. This study analyses the composition and recovery potential of macro marine litter collected from three shellfish farming sites in Mali Ston Bay (southern Adriatic Sea) using three diver-based clean-up actions conducted between 2020 and 2022. Across approximately three cumulative hours of clean-up activity, 650.92 kg of macro marine litter was recovered from the seafloor. The collected material was dominated by operational mariculture equipment, primarily plastic farming gears such as old mussel socks ("pergolari") reused as collectors for oyster spat, plastic crates, oyster nets and ropes, together with a substantial contribution from rubber tyres likely linked to farming vessel operations and harbour use in the vicinity of shellfish farms. Mussel socks accounted for more than 200 kg (approximately 30%) of the total recovered weight, while rubber represented more than 175 kg (approximately 25%), together comprising over half of all collected material. Most items were large, structurally intact and affected mainly by surface biofouling, indicating episodic operational loss rather than fragmented consumer waste. The results show that marine litter in shellfish farming areas represents a distinct, sector-specific waste stream with a high potential for recovery and reuse, while providing quantitative insight into mariculture-related macro marine litter recovered from the seafloor. Integrating targeted retrieval actions and circular-economy approaches into mariculture management could substantially reduce marine litter accumulation on the seafloor, while supporting sustainable shellfish farming.

KEY WORDS

marine debris
shellfish farming
aquaculture
circular economy
Adriatic Sea

Sažetak

Otpad u moru povezan s uzgojem školjkaša i dalje je slabo istražen, unatoč brzom rastu marikulture. Ova studija analizira sastav i potencijal oporabe makrootpada iz mora, prikupljenog na trima lokacijama uzgoja školjkaša u Malostonskom zaljevu (južni Jadran) tijekom triju organiziranih ronilačkih akcija čišćenja provedenih u razdoblju od 2020. do 2022. godine. Tijekom ukupno približno tri sata ronilačkog angažmana s morskog dna prikupljeno je ukupno 650,92 kg makrootpada. U prikupljenom materijalu dominirala je oprema za uzgoj školjkaša, ponajprije plastična uzgojna oprema poput pergolara za kamenice, plastičnih sanduka i užadi, uz značajan udio automobilskih guma, vjerojatno povezanih s radnim plovilima na uzgajalištima i lučkim aktivnostima u blizini uzgajališta školjkaša. Pergolari iz uzgoja kamenica i dagnji činili su više od 200 kg (približno 30%) ukupne mase, dok su automobilske gume predstavljale više od 175 kg (približno 25%) zajedno čineći više od polovine ukupno prikupljenog otpada. Većina predmeta bila je velika, strukturno očuvana i zahvaćena uglavnom površinskim obraštajem, što upućuje na povremene operativne gubitke, a ne na kontinuirani unos fragmentiranog potrošačkog otpada. Rezultati pokazuju da otpad u moru u područjima uzgoja školjkaša predstavlja poseban, sektorski specifičan tip otpada s visokim potencijalom za oporabu i ponovnu uporabu. Uvođenje ciljanih akcija prikupljanja otpada i principa kružnog gospodarstva u prakse uzgoja školjkaša, uz unapređenje tehnoloških operacija radi smanjenja operativnih gubitaka opreme, može znatno doprinijeti prevenciji nakupljanja otpada na morskom dnu te održivosti marikulture.

KLJUČNE RIJEČI

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1. INTRODUCTION / *Uvod*

Marine litter is widely recognised as a persistent environmental pressure on coastal and marine ecosystems, with documented impacts on biodiversity, habitat quality and ecosystem services [1]. Plastics account for approximately 60-70% of marine litter worldwide [2,3], with an estimated 20-25 million tonnes entering the oceans annually [4]. While land-based sources dominate globally, growing evidence shows that sea-based activities, particularly fisheries and mariculture, contribute distinct marine litter fractions linked to operational gear [5,6]. In the Adriatic Sea, mariculture-related plastics have been reported to account for up to 50% of plastic marine litter in shellfish farming areas, with seafloor densities reaching up to 73 mussel socks per km^2 in farming-influenced zones. Given the long persistence of plastic-based materials, such accumulations pose a significant risk to benthic habitats [7,8].

Aquatic products, including fish, molluscs and crustaceans, play a critical role in global food security, providing nearly three billion people with at least 15% of their animal protein intake [9]. According to FAO (2024) [10], global fisheries and aquaculture production reached a record 223.2 million tonnes in 2022, with aquaculture accounting for 130.9 million tonnes and, for the first time, surpassing capture fisheries as the main producer of aquatic animals worldwide. Within this sector, commercial shellfish farming represents about 23% of total aquaculture production and constitutes a major and expanding component [11]. Bivalve mariculture is widely recognised for its positive environmental contribution. Cultivated molluscs grow by filtering plankton from seawater, eliminating the need for additional feed and promoting nutrient removal and water quality regulation. It is estimated that in 2015, farmed bivalves removed approximately 49,000 tonnes of nitrogen and 6,000 tonnes of phosphorus from marine environments globally [12]. These ecosystem services position shellfish farming as an important element of sustainable food production systems.

Despite these benefits, bivalve mariculture relies heavily on plastic-based infrastructure, creating an inherent trade-off between its environmental services and its potential contribution to marine litter through operational plastic loss [5,6]. Mariculture development became strongly dependent on plastic materials and is expected to remain so in the foreseeable future. Synthetic ropes and nets offer high mechanical strength, durability and low weight compared with natural fibres, making them essential components of fishing and farming operations. In bivalve mariculture, plastics, such as polypropylene, are used throughout all production stages, including ropes, nets, trays, mesh bags, collectors and crates in both suspended and bottom-culture systems. Culture methods include suspended longlines, intertidal tray and bag systems and bottom cultivation, all of which rely on plastic-based infrastructure for structural support and protection from predators and environmental stressors. Floating structures are commonly supported by expanded polystyrene or plastic buoys and stabilised by non-buoyant plastic ropes and lines. The extensive, long-term use of these materials increases the risk of plastic loss to the marine environment through routine handling, maintenance activities, equipment degradation, and extreme weather events. Therefore, abandoned, lost or otherwise discarded fishing gear is widely recognised as a major source of plastic input to the marine environment from the fisheries sector, including mariculture [5]. It is estimated that approximately one metre of polypropylene net is required for every kilogram of mussels produced, highlighting the scale of plastic embedded in shellfish production systems [6]. Due to biofouling and salt encrustation, used mussel socks are currently classified in Europe as special waste (European Waste Code CER 02 01 04), making their disposal costly and logistically demanding [6]. Large-scale monitoring campaigns have confirmed the frequent occurrence of mussel nets and sacks among marine litter items found along European coastlines [6]. Despite their material value, these items have traditionally been considered non-recyclable, highlighting a critical gap between the environmental benefits of bivalve mariculture and the management of its associated plastic waste streams. Within the European Union, sustainability objectives are embedded in the Circular Economy Action Plan, which promotes waste reduction, resource efficiency and sector-specific mitigation strategies, including those addressing marine litter [13].

Mali Ston Bay in Croatia represents one of the most important shellfish farming areas in the eastern Adriatic Sea, with a long historical tradition of oyster and mussel cultivation [14]. The bay is characterised by intensive farming activity and relatively enclosed hydrodynamic conditions, making it suitable for investigating marine litter associated with shellfish mariculture operations. The dominant cultivated species are the European flat oyster (*Ostrea edulis*) and the Mediterranean mussel (*Mytilus galloprovincialis*) [15]. Recent assessments indicate substantial production levels: approximately 441 tonnes of mussels and 81 tonnes of oysters were produced in 2018 across more than 200 active concession fields [16]. In Croatia, total mariculture production in 2024 amounted to 24.988 tonnes, of which 827 tonnes were Mediterranean mussel (*Mytilus galloprovincialis*) and 76 tonnes were European flat oyster (*Ostrea edulis*) [17].

This study focuses on macro marine litter, defined as debris items larger than 2.5 cm in size [18], accumulated on the seafloor at shellfish farming sites in Mali Ston Bay, treated primarily as an operational material-loss stream from shellfish farming, with emphasis on recoverability and sector-specific management options. By analysing dominant marine litter fractions and their recovery potential, the study provides sector-relevant evidence to support improved waste management and circular-economy approaches in shellfish mariculture systems.

2. MATERIALS AND METHODS / *Materijali i metode*

2.1. Study area / *Područje istraživanja*

The study presented in this paper was conducted in Mali Ston Bay, a semi-enclosed coastal area located in the southern Adriatic Sea (Dubrovnik-Neretva County, Croatia). Shellfish production in this area relies primarily on suspended longline systems using plastic-based infrastructure, including ropes, old mussel socks (pergolari), floats and plastic crates [19]. Three study sites (SITE 1 - SITE 3) were surveyed, see Figure 1. SITE 2 and SITE 3 were located directly beneath active shellfish farming structures, whereas SITE 1 represented a nearby seafloor area adjacent to multiple shellfish farming sites and a small communal harbour, reflecting the mixed operational influence of the shellfish cultivation. Sites were selected based on accessibility, cooperation with farm owners, and the presence of visible macro marine litter on the seafloor within farming areas; more details are in Table 1.

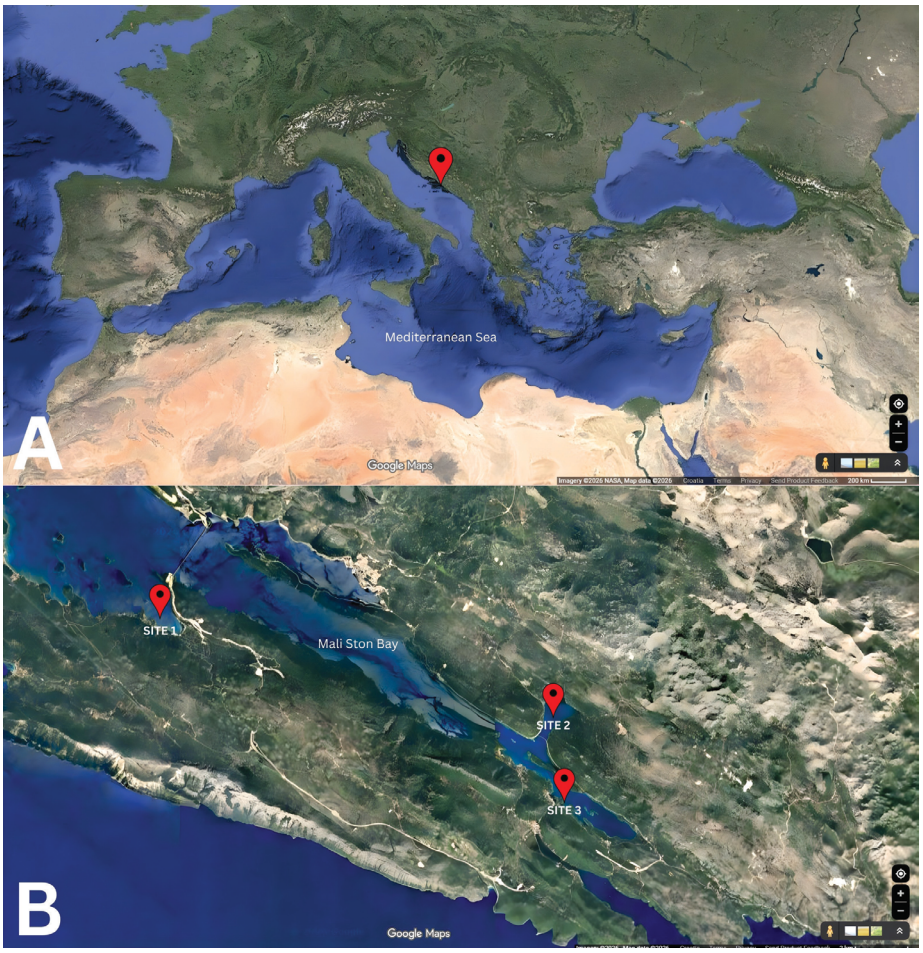


Figure 1 (A) Location of the study area within the Mediterranean Sea. (B) Location of the three sites surveyed in Mali Ston Bay (Croatia)
Slika 1. (A) Položaj područja istraživanja unutar Sredozemnog mora. (B) Položaj triju lokacija istraživanih u Malostonskom zaljevu (Hrvatska)

Source: Author's own elaboration based on Google Maps satellite imagery (https://www.google.com/maps), accessed 15 October 2026. Study site markers and labels added by the author [30]

Table 1 Characteristics of surveyed sites and diver-based clean-up efforts
Tablica 1. Obilježja istraživanih lokacija i napori ronilaca pri čišćenju

Parameter	SITE 1	SITE 2	SITE 3
Location	*Mali Ston Bay - Brijesta Bay (42°54'27.7" N, 17°31'48.7" E)*	*Mali Ston Bay - Bistrina Bay, Mušula shellfish farm (42°52'17.0" N, 17°42'04.3" E)*	*Mali Ston Bay - Sige location, between Bistrina Bay and Kuta Bay, Maškarić-Sige shellfish farm (42°50'39.9" N, 17°42'39.4" E)*
Site context	Seafloor adjacent to multiple shellfish farms and a small local communal harbour; mixed influence of mariculture and small-vessel activities; cultivation of blue mussels and European flat oyster.	Seafloor directly beneath densely arranged shellfish farming structures in a sheltered, inner bay dedicated mostly to mariculture; cultivation of blue mussels and European flat oyster.	Seafloor directly beneath shellfish farming structures within a long-established family-run mariculture concession in the central part of Mali Ston Bay; cultivation of blue mussels and European flat oyster.
Date of survey	*11 July 2020*	*14 June 2022*	*24 November 2022*
Approx. area surveyed (m^2)	~4,000	~2,000	~3,000
Depth range (m)	0-9	0-8	0-9
Access	Boat	Boat	Boat
Number of divers	13	6	5
Duration of clean-up	~60 min	~60 min	~60 min

Source: Authors' own data

2.2. Marine litter collection and processing / *Prikupljanje i obrada otpada iz mora*

Marine litter was collected during three organised diver-based clean-up actions conducted between 2020 and 2022 at selected sites in Mali Ston Bay. Although not designed as formal monitoring surveys under the European Union Marine Strategy Framework Directive [20], the recovered material was processed using MSFD-aligned classification protocols for seafloor marine litter, including item identification, material categorisation and weight-based quantification, following the MSFD Technical

Group on Marine Litter guidance for underwater visual surveys using SCUBA or snorkelling [21].

At each site, certified SCUBA divers surveyed the seafloor at depths of 0-9 m during standardised one-hour surveys. Between five and thirteen divers participated per clean-up action, covering an estimated area of 2,000-4,000 m^2 per site. All visible macro marine litter was collected manually using mesh bags and transported to shore for processing. Retrieved items were sorted, counted and weighed using a digital scale. Wet weight (kg) was recorded, including attached biofouling. Items were classified according to MSFD material categories (artificial polymers, rubber, textile, paper/cardboard, wood, metal, and glass/ceramics) and assigned to size classes (A-F) based on maximum dimension. Where possible, items were visually assessed for association with shellfish farming activities (e.g., socks, ropes, crates, floats) and grouped by likely origin (sea-based or land-based).

The clean-up actions were conducted as operational diver-based recovery activities under real field conditions, including actions organised in collaboration with third-party local stakeholders and diving groups. The number of participating divers, the duration of the clean-up actions, and the approximate surveyed areas varied by location, depending on accessibility, underwater visibility, local seabed configuration, and operational logistics. Consequently, the study focused primarily on the recovery, classification, and characterisation of collected macro marine litter rather than on standardised monitoring protocols.

2.3. Data analysis / *Analiza podataka*

Data were summarised using descriptive statistics using Microsoft Excel. Total wet weight and item counts were calculated for each site and expressed as absolute values (kg) by material category. Results were compared across the three sites to identify dominant marine litter fractions associated with maricultural operations and to assess their recovery potential. Due to the limited number of sampling events, no inferential statistical analyses were performed.

3. RESULTS / *Rezultati*

3.1. Composition of macro marine litter at shellfish farming sites / *Sastav makrootpada iz mora na mjestima uzgoja školjki*

Substantial amounts of macro marine litter were recovered from the seafloor at all three sites, with composition dominated by plastic-based materials associated with maricultural activities. The majority of items consisted of farming gear such as mussel socks and oyster lines (pergolari), ropes, floats and plastic crates. Most recovered items belonged to larger size classes (D-F) and were intact or only slightly damaged, indicating episodic loss of operational gear rather than continuous input of fragmented consumer debris. Fragmented single-use plastics were uncommon. Non-plastic materials, particularly glass and metal, were present across all sites and, in some cases, glass items were relatively abundant in terms of item counts; however, their contribution to the total recovered weight was comparatively low, with plastic materials accounting for the dominant weight fraction. Rubber exhibited site-specific variability: at SITE 1, rubber constituted the dominant weight fraction, primarily due to the presence of multiple vehicle and truck tyres associated with small-vessel harbour use and nearby farming activities. In contrast, at SITES 2 and 3, rubber was present in smaller quantities, mainly as tyres. The material composition and total weight of macro marine litter collected at each site are summarised in Table 2.

Table 2 Composition of macro marine litter collected at three shellfish farming locations in Mali Ston Bay (kg)
Tablica 2. Sastav makrootpada iz mora prikupljenog na trima lokacijama za uzgoj školjkaša u Malostonskom zaljevu (kg)

Material category	SITE 1 (kg)	SITE 2 (kg)	SITE 3 (kg)
Plastic	29.41	86.85	200.06
Glass	13.20	61.34	1.88
Metal	32.54	24.54	4.78
Rubber	140.86	34.00	2.60
Wood	0.87	0.00	0.30
Cloth/Textile	2.06	0.00	0.00
Concrete	7.50	0.00	3.02
Organic	0.00	0.00	5.11
Total (kg)	226.44	206.73	217.75

Source: Authors' own data

Clear differences in marine litter composition were observed between the investigated locations. SITE 1 was dominated by rubber tyres, while SITE 3 contained the highest proportion of plastic mariculture gear, particularly old mussel socks and other oyster farming equipment. SITE 2 showed a more mixed composition with lower total recovered mass. These differences likely reflect local farming practices, operational intensity and site-specific hydrodynamic conditions (Figure 2).

At SITE 1, a total of 226.44 kg of macro marine litter was recovered from a seafloor area of approximately 4,000 m^2 by thirteen divers. The collected material consisted predominantly of shellfish-farming equipment, including mussel socks, ropes, and plastic crates. The largest weight fraction was rubber (62.22%), mainly represented by vehicle and truck tyres associated with nautical and mariculture-related activities in the area. Plastic items (12.99%) were largely composed of discarded mussel socks, many of which were heavily colonised by biofouling organisms, including barnacles, polychaetes, and other sessile invertebrates. This extensive colonisation resulted in increased weight and structural rigidity of the recovered gear (Figure 3).

During the clean-up action at the shellfish farming area in SITE 2, a total of 206.73 kg of macro marine litter was recovered from the seafloor over an area of approximately 2,000 m^2 during a one-hour survey conducted by six divers. Plastic materials represented the dominant weight fraction, with shellfish farming socks accounting for 42.02% of the total recovered weight (Figure 4). Other frequently encountered items included plastic ropes and farming crates. Although glass items were numerous, they contributed relatively little to the overall weight.

At SITE 3, a total of 217.75 kg of macro marine litter was collected from the seafloor area of approximately 3,000 m^2 by five divers. Plastic farming gear accounted for the dominant weight fraction, 91.87%. The principal items included mussel and oyster socks, round and square plastic crates and ropes (Figure 5).

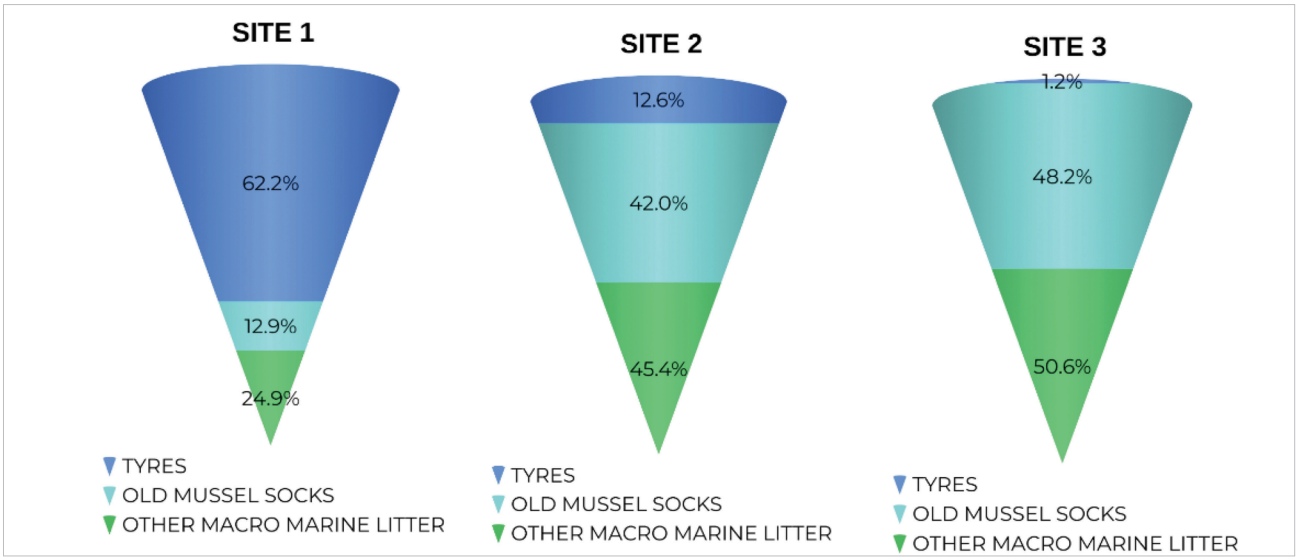


Figure 2 Relative composition (%) of dominant macro marine litter fractions recovered at the three investigated shellfish farming locations in Mali Ston Bay

Slika 2. Relativni sastav (%) dominantnih frakcija makrootpada iz mora prikupljenog na trima istraživanim lokacijama za uzgoj školjkaša u Malostonskom zaljevu

Source: Authors' own work



Figure 3 Biofouling on shellfish farming gear recovered from SITE 1:
(A) used mussel socks (pergolari); (B) construction elements of oyster farming structures

Slika 3. Obraštaj na opremi za uzgoj školjkaša prikupljenoj na LOKACIJI 1:
(A) korišteni pergolari; (B) konstrukcijski elementi sustava za uzgoj kamenica.

Source: Photographs by Iva Pozniak

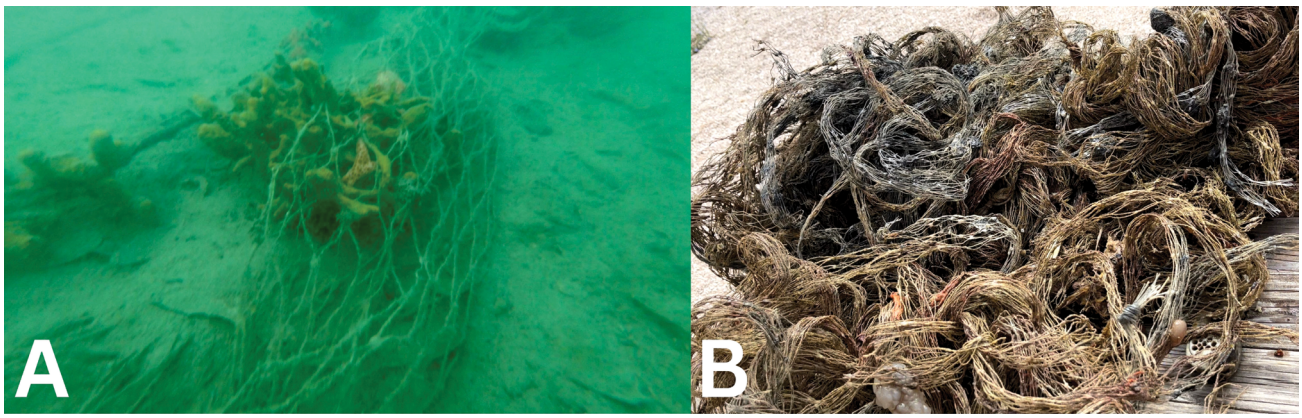


Figure 4 Used mussel socks recovered from SITE 2: (A) in situ on the seafloor; (B) after retrieval during the clean-up action

Slika 4. Korišteni pergolari prikupljeni na LOKACIJI 2: (A) in situ na morskom dnu; (B) nakon izvlačenja tijekom akcije čišćenja

Source: Photographs by Iva Pozniak



Figure 5 Shellfish farming gear recovered from SITE 3: (A) used mussel socks with dense biofouling; (B) intact plastic crates showing high potential for recycling

Slika 5. Oprema za uzgoj školjaka s LOKACIJE 3: (A) korišteni pergolari s izraženim obraštajem; (B) neoštećene plastične gajbe koje se mogu u potpunosti reciklirati

Source: Photographs by Iva Pozniak

More than 105 kg of the recovered material consisted solely of shellfish-farming socks. In addition, a substantial proportion of plastic crates and farming components (90.20 kg) were recovered in near-original condition, retaining their structural integrity with only surface biofouling. These items, therefore, exhibited high potential for mechanical recovery and reuse.

4. DISCUSSION / *Rasprava*

The three clean-up actions consistently recovered a large weight of macro marine litter, dominated by shellfish-farming operational materials, with mussel and oyster socks accounting for approximately 30% of the total weight and rubber tyres for approximately 25%.

A similar total weight of recovered macro marine litter was recorded across all three sites, despite differences in survey effort. In SITE 1, the surveyed area was approximately twice as large and involved twice as many divers compared to the other sites. At SITES 2 and 3, clean-up actions were located directly beneath active shellfish farms, and mariculture-related marine litter dominated the recovered material, reflecting operational losses during routine farming activities. In contrast, SITE 1, located near shellfish farming sites, yielded a substantially lower weight of mariculture-related marine litter (29.41 kg). Instead, tyres accounted for the largest share of the recovered material (139.14 kg), due to their high individual weight, which contributed disproportionately to the total recovered weight. This pattern indicates differences in marine litter composition linked to site function and use, suggesting that areas outside direct shellfish farms may be less burdened by mariculture-related macro marine litter. This pattern is consistent with previous findings showing that heavier macro marine litter, such as operational mariculture gear, tends to accumulate near its source, whereas lighter debris disperses more widely across the seafloor [22]. However, this interpretation remains inferential and would benefit from confirmation through more extensive spatial surveys.

The recovered farming gear was in good condition, indicating a high potential for mechanical recovery and reuse. Most plastic items retained their structural integrity despite prolonged submersion and extensive biofouling. In particular, large plastic crates and shellfish-farming socks were frequently recovered in near-original condition and could be mechanically cleaned and redirected to recycling or reuse streams. In contrast, smaller, fragmented items and mixed-material debris accounted for only a minor proportion of the total recovered weight and were generally unsuitable for recovery or reuse.

In shellfish farming practice in Mali Ston Bay, old mussel socks (pergolari) are commonly reused as oyster spat collectors (so-called "koltrine"). Prior to reuse, these materials are often temporarily left in shallow coastal waters, where natural grazing organisms help remove accumulated organic material and epibionts, facilitating their continued operational use [19]. This long-term reuse practice may additionally contribute to the structural preservation and prolonged environmental persistence of mariculture-related plastic materials observed during the clean-up actions.

Recent studies have further demonstrated the recycling and upcycling potential of discarded fishing and aquaculture plastics, including polypropylene-based materials, through applications in construction composites, packaging products and additive manufacturing, supporting the broader circular-economy relevance of recovered mariculture waste [23].

A substantial proportion of the recovered material, particularly structurally preserved mariculture-related equipment, appeared suitable for potential recovery and reuse following appropriate cleaning and processing. The predominance of intact operational farming gear may indicate that a considerable share of the material originated from unintentional loss during routine farming activities rather than deliberate disposal.

Across diverse geographic regions, studies consistently show that marine litter in shellfish-farming areas is dominated by mariculture-specific operational gear, closely matching the composition observed in this study. Evidence from the North-East Atlantic, the north-western Mediterranean (Italy), French Polynesia, and oyster-farming regions in Taiwan indicates that

buoys, ropes, nets, socks, and floats are the primary marine litter types, with losses linked to storm damage, material fatigue, and routine farming activities rather than intentional disposal [24,25,26,27]. Quantitative assessments further show that mariculture-related plastic weight is largely driven by a limited number of large, durable operational items, while consumer plastics form a minor fraction within farming systems [26]. In contrast, beach-based studies from shellfish-growing regions dominated by consumer inputs, such as clam culture areas in Vietnam, report marine litter composed mainly of single-use plastics, demonstrating that the presence of mariculture alone does not imply mariculture-derived marine litter [28].

The limited presence of fragmented consumer plastics and the dominance of intact farming gear indicate that losses primarily result from routine operations and episodic events (e.g., handling, maintenance, storms), rather than from continuous input of small consumer-derived items. This profile supports a management perspective in which seafloor macro marine litter beneath shellfish farms is considered a recoverable operational loss rather than diffuse pollution. From a mitigation perspective, the dominance of identifiable, largely single-material items shifts emphasis from awareness-based prevention toward structured retrieval and circular handling. Most recovered plastic components were structurally intact, with degradation largely limited to surface biofouling. Intervention prior to fragmentation, therefore, represents the most effective opportunity to reduce long-term environmental persistence. Regular diver- or workboat-supported retrieval, improved gear-handling practices, and designated collection points for damaged equipment could substantially reduce macro marine litter accumulation within concession areas.

The condition of recovered polypropylene based farming gear directly supports the feasibility of circular management pathways. Pietrelli et al. (2022) [6] demonstrated that polypropylene mussel socks can be effectively cleaned and mechanically recycled without significant loss of material properties, with treatment costs (~0.222 EUR/kg) comparable to landfill disposal and retained market value for recovered polymer. The predominance of intact shellfish farming gears and crates observed on the seafloor in Mali Ston Bay provides field-based evidence that materials suitable for such recycle pathways are already present in the environment and could be recovered before secondary fragmentation.

In addition to plastic farming gears, rubber tyres represent a substantial operational fraction and should also be considered within circular-economy strategies for mariculture-associated waste streams. In coastal mariculture areas, tyres are commonly used as protective elements for vessel mooring and docking, which may contribute to their accumulation in the marine environment following loss or improper disposal. Established mechanical recycling routes and emerging thermal and chemical processes, including pyrolysis and devulcanisation, enable both material and energy recovery from end-of-life tyres, with applications in pavement layers, moulded goods and insulation products [29]. Recovery prior to prolonged environmental exposure is particularly relevant in coastal settings, as it preserves material quality and facilitates integration into existing recycling chains. The tyre fraction identified in this study therefore represents not only an environmental burden, but also a recoverable resource.

Although based on a limited number of clean-up actions, the consistency of results across three sites suggests that operational material loss is a recurrent characteristic of shellfish farming systems in Mali Ston Bay. Collectively, these findings support reframing marine litter in farming concessions as a sector-specific operational by-product and highlight the potential of recovery- and recycling-oriented approaches to reduce environmental impacts while supporting sustainable mariculture.

This study does not estimate total marine litter generation rates from shellfish farming, but provides a site-based characterisation of dominant material fractions and their condition as recovered during operational clean-up actions.

5. CONCLUSION / *Zaključak*

This study demonstrates that macro marine litter associated with shellfish farming in Mali Ston Bay is largely composed of operational mariculture materials rather than consumer waste. Across three sites, 650.92 kg of macro marine litter was recovered from the seafloor within approximately three hours of diver effort. Mussel and oyster socks alone accounted for more than 200 kg (approximately 30%) of the total recovered weight, while rubber tyres contributed more than 175 kg (approximately 25%), together representing over half of all collected macro marine litter.

Most recovered items were large, structurally intact and affected mainly by surface biofouling, indicating episodic operational loss rather than long-term fragmentation. Single-use plastic and mixed-material debris accounted for only a minor fraction of the total mass. The study also demonstrated the high potential for recovery and reuse of structurally preserved mariculture-related materials from the seafloor.

These findings show that marine litter in shellfish farming areas constitutes a distinct, sector-specific waste stream with a high potential for recovery and reuse. Integrating targeted retrieval actions and circular-economy solutions into mariculture management could substantially reduce marine litter accumulation on the seafloor, while supporting the sustainable development of shellfish farming in the Adriatic Sea.

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