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Report

SMARTER - Surveying microplastic release from aquaculture nets and ropes using different technologies for emission reduction

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Summary (English)

The SMARTER project aimed to assess and model microplastic (MP) emission scenarios from aquaculture infrastructure, primarily nets and ropes, and evaluate the effectiveness of existing mitigation strategies under realistic operational conditions. The net and rope materials tested included nylon, high-density polyethylene (HDPE) and ultra-high-molecular-weight polyethylene (UHMWPE). The project combined laboratory tests, field measurements, and service site assessments to understand how material properties, usage patterns, and operational practices influence MP release.

Key Findings:

1. **Material Type Influences MP Emissions:** Laboratory abrasion tests showed nylon nets may release up to five times more MP particles than polyethylene-based alternatives like HDPE and UHMWPE, suggesting the multifilament structure of nylon may be more susceptible to abrasion than the thicker monofilaments in HDPE or the abrasion resistant UHMWPE.
2. **Coating Effects Depend on Material Compatibility:** Coatings significantly increased MP release from nylon nets, especially with the premium formulation, possibly due to increased coating thickness compared to the standard coating. UHMWPE nets showed no such increase, suggesting stronger coating integration and higher resistance to mechanical wear.
3. **Impact of Net Age and Location:** Used nets released more MP than new ones, particularly in areas identified by service personnel as high abrasion zones (just below the surface and at the net bottom). Coating residuals were a probably a large contributor to MP. This effect was most noticeable in nylon and UHMWPE nets sampled at the end of their service/usable life. HDPE showed less variation, possibly due to the sample not being coated and being taken before the end of the nets service life.
4. **Cleaning Technologies and MP Emissions:** Accelerated net cleaning trials using pressure washing, cavitation washing, and AUV brushing showed low MP concentrations in surrounding waters that were indistinguishable from environmental background levels. However, microscopy revealed that AUV brushing caused less severe coating damage compared to the more abrasive pressure and cavitation cleaning.
5. **Ropes and Recycled Materials:** Recycled polyolefin ropes released more MP particles than virgin material ropes. Used UHMWPE ropes also emitted significantly more MP particles than new ones, a major part of emissions were likely due to residual coatings. Rope structure further influenced MP production.
6. **Field and Service Site Observations:** Field sampling during net cleaning operations indicated sporadic MP emissions, with variability potentially influenced by net age and cleaning history but mostly sampling conditions (e.g. presence of lice skirt). At service sites, land-based net washing generated detectable MP, but effective filtration systems prevented particles from reaching the marine environment.

Conclusions and Outlook:

SMARTER has demonstrated that MP emissions from aquaculture gear are a result of complex interactions between material choice, product age and cleaning methods. Nylon nets, especially when coated, and certain recycled ropes represent potentially higher-emission configurations, while HDPE and UHMWPE appear to offer more robust, lower-emission alternatives (although further validation is needed). Despite environmental sampling challenges, the results underscore the importance of tailored mitigation strategies—such as choosing robust materials, compatible coatings and adopting less abrasive cleaning technologies to reduce MP release.

The project's emission data and protocols provide an industry benchmark and a foundation for regulatory frameworks. Given that many of the tested technologies are already commercially available, the aquaculture sector can take immediate steps to reduce MP emissions by incorporating SMARTER's findings into procurement and maintenance routines. Long-term, SMARTER's data should be expanded to provide a more robust basis for guiding future innovation and environmental policy development within the industry, while future regulatory assessments should consider multiple sustainability perspectives (e.g. material recycling suitability).

Sammendrag (Norsk)

SMARTER-prosjektet har hatt som mål å undersøke og modellere utslippsscenarier for mikroplastutslipp (MP) fra akvakulturinfrastruktur, primært notlin og tau i oppdrettsnøter, og evaluere effekten av eksisterende tiltak for å redusere utslipp under realistiske driftsforhold. Notlin- og taumaterialene som ble testet inkluderte nylon, høytetthetspolyetylen (HDPE) og polyetylen med ultrahøy molekylvekt (UHMWPE). Prosjektet kombinerte laboratorietester, feltmålinger og prøvetaking i renseanlegg på en notservicestasjon for å forstå hvordan materialegenskaper, bruksmønstre og driftspraksis påvirker MP-utslipp.

Viktige funn:

1. **Materialtype påvirker MP-utslipp:** Slitasjetester i laboratorie viste at nylon notlin kan frigjøre opptil fem ganger mer MP enn polyetylenbaserte alternativer som HDPE og UHMWPE, noe som tyder på at multifilamentstrukturen i nylon notlin kan være mer utsatt for slitasje enn de tykkere monofilamentene i HDPE, eller det mer slitesterke UHMWPE -materialet.
2. **Effekter av coating avhenger av samhandling med notlinet:** Coating økte MP-utslippet fra nylon notlin betydelig, spesielt med premium-formelen, muligens som følge av økt coatingtykkelse sammenlignet med standard coating. UHMWPE-notlin viste ingen slik økning, noe som kan tyde på sterkere binding mellom notlin og coating og høyere motstand mot mekanisk slitasje.
3. **Effekt av alder på not og område:** Brukte nøter slapp ut mer mikroplast enn nye, spesielt i områder identifisert av servicepersonell som soner med høy slitasje (like under vannoverflaten og på bunnen). Coatingrester var sannsynligvis en stor bidragsyter til mikroplast. Denne effekten varmerkbar for nylon- og UHMWPE-nøter som ble prøvetatt ved slutten av levetiden. HDPE viste mindre endring etter bruk, trolig på grunn av at prøven ikke hadde coating, og at notlinprøven ble tatt før notas levetid var over og ikke viste tegn til svekkelser.
4. **Rengjøringsteknologier og mikroplastutslipp:** Akselererte rengjøringforsøk av not med bruk av høytrykksspyling, kavitasjonsvasking og AUV-børsting, viste lave mikroplastkonsentrasjoner i omkringliggende vann som ikke kunne skilles fra miljømessige bakgrunnsnivåer. Mikroskopi viste imidlertid at AUV-børsting forårsaket mindre skade på coating sammenlignet med mer abrasiv trykk- og kavitasjonsrengjøring.
5. **Tau og resirkulerte materialer:** Resirkulerte polyolefintau dannet mer mikroplast enn tau av nytt materiale. Brukte UHMWPE-tau slapp også ut betydelig mer mikroplast enn nye, mye på grunn av rester av coating. Taustrukturen påvirket også produksjon av mikroplast.
6. **Observasjoner fra felt og serviceverksted**: Feltprøvetaking under notvasking indikerte sporadiske MP-utslipp, med variasjon potensielt påvirket av notens alder og rengjøringshistorikk, men hovedsakelig prøvetakingsforhold (f.eks. tilstedeværelse av luseskjørt). På notservicestasjon frembrakte landbasert notvasking påvisbar mikroplast, men effektive filtreringssystemer forhindret at partiklene nådde det marine miljøet.

Konklusjoner og utsikter:

SMARTER har vist at MP-utslipp fra akvakulturutstyr er et resultat av komplekse samspill mellom materialvalg, produktets alder og rengjøringsmetoder. Nylon-notlin, spesielt når de er påført coating, og visse resirkulerte tau, representerer potensielt høyere utslipp, mens HDPE og UHMWPE ser ut til å tilby mer robuste alternativer med lavere utslipp (selv om ytterligere validering er nødvendig). Til tross for utfordringer med miljøprøvetaking, viser resultatene at det er mulig å innføre skreddersydde tiltak mot MP-utslipp fra nøter – som å velge robuste notlin-materialer, kompatibel coating og ta i bruk mindre abrasive rengjøringsteknologier.

Prosjektets utslippsdata og protokoller gir en bransjestandard og et grunnlag for regelverk. Gitt at mange av de testede teknologiene allerede er kommersielt tilgjengelige, kan akvakultursektoren ta umiddelbare skritt for å redusere MP-utslipp ved å innlemme SMARTERs funn i anskaffelses- og vedlikeholdsrutiner. På lang sikt bør SMARTERs data utvides for å gi et mer robust grunnlag for å veilede fremtidig innovasjon og utvikling av miljøpolitikk i næringen, mens fremtidige regulatoriske vurderinger bør vurdere flere bærekraftsperspektiver (f.eks. egnethet for materialgjenvinning).

1 Introduction

1.1 Background

Microplastics (MP; plastic particles smaller than 5 mm) are widespread pollutants found throughout the marine environment, from tropical regions to polar waters and across all environmental compartments. In European waters, MP concentrations have been reported at levels as high as 103 particles L^{-1} in nearshore surface waters and up to 210 particles kg^{-1} in subtidal sediments, depending on the location and environmental matrix.[1] Evidence indicates that MP, along with associated chemical contaminants, can exert a range of toxic effects on both marine organisms and humans.[2] While the majority of marine MP originates from land-based sources (approximately 80%),[3] a notable fraction stems from direct emissions linked to human activities within the marine environment. The fisheries and aquaculture sectors, in particular, have become increasingly reliant on plastic-based infrastructure and equipment, which can abrade and degrade, releasing MP over time. Plastics used in these industries not only contribute to environmental MP pollution but may also contaminate the seafood they produce (Figure 1).[4] Given that a significant portion of the produced seafood is consumed by humans—and is often marketed as clean and healthy—there is a clear need to explore strategies for reducing MP emissions from these sectors.

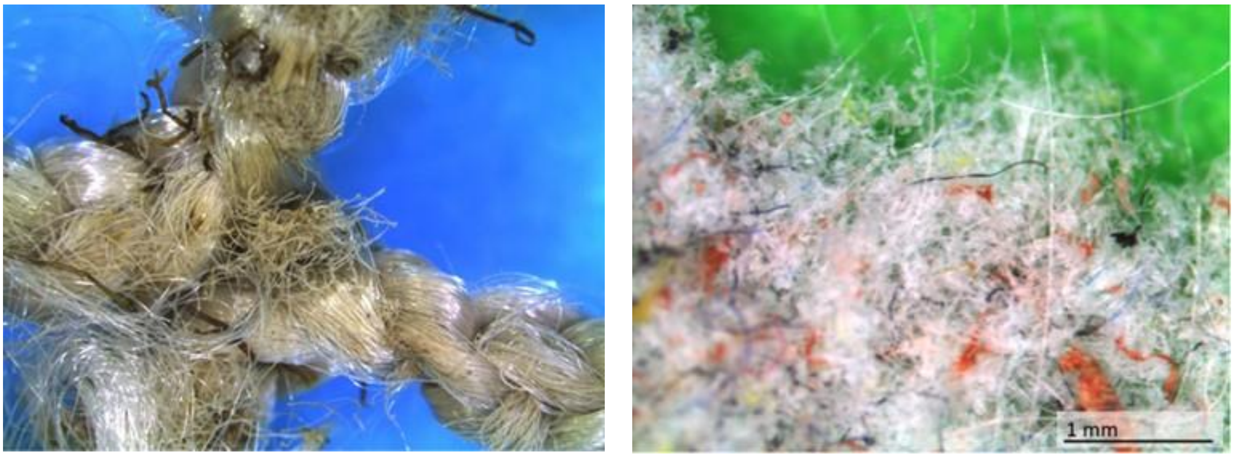


Figure 1: Wear on aquaculture nets from high pressure cleaning (left). Microplastics collected from abrasion testing of various materials for fishing gear (right, FHF-project 901669). Photos: Heidi Moe Føre, SINTEF Ocean.

Among the various potential sources of MP emissions from aquaculture operations, nets are considered one of the most significant. They account for approximately 75% of all submerged surfaces at a typical farm site.[5] Traditionally constructed from nylon multi-filaments, nets have more recently incorporated alternative polymers such as high-density polyethylene (HDPE) and Ultra-high-molecular-weight polyethylene (UHMWPE).[6] To enhance durability, these nets are commonly coated with wax-, resin-, or acrylic-based formulations designed to protect against UV degradation, support in-situ cleaning, and minimize abrasion. However, these coatings degrade over time, ultimately exposing the underlying polymer to environmental stressors such as UV radiation and mechanical wear, both of which contribute to MP release. Depending on their chemical makeup, the coatings themselves may also serve as a direct source of MP emissions. Additional sources of MP emissions in aquaculture include feeding pipes,[7] ropes,[8] and polyethylene (PE) components found in structural elements like floating collars and sinker tubes.[6] MP emissions from feeding pipes were hypothesized under the FHF-funded "TRACKPLAST" project (Grant no. 901519) and investigated as part of the work conducted in the FHF-funded "MicroRED" project (Grant no. 901658). Ropes have been indirectly evaluated in another FHF-funded study (Grant no. 901669). In contrast, little is currently known about emissions from collars or sinker tubes. However, visual inspections of these structures at the end of their service life often reveal surface abrasions, suggesting they may also contribute to MP pollution.

Aquaculture nets deployed in the marine environment are frequently subject to biofouling by organisms such as algae, mussels, and hydroids. This can lead to reduced water exchange through the net, resulting in a decline of oxygen available to the cultured fish as well as hampering the removal of excretion products. Moreover, biofouling can facilitate the presence of pathogens in close vicinity to the fish.[9, 10] To prevent the build-up of biofouling material on the net, regular in-situ cleaning is conducted, often performed as frequently as once a week. The process typically involves the use of pressured water jets emitted from rotating discs mounted on a cleaning rig, which dislodge and flush biofouling organisms from the net into the surrounding water.[10] However, this cleaning method also affects the integrity of the net coatings. Biocidal coatings—applied to inhibit biofouling—are often damaged or abraded during cleaning, leading to their partial removal along with the fouling organisms.[11] Anecdotal reports suggest that even non-biocidal coatings may be similarly affected. In addition, the net material itself is vulnerable to mechanical stress during cleaning, commonly resulting in shrinkage and, in some cases, physical degradation such as wear and tear.[12] Although pressure cleaning has evolved in recent years from the use of 'high' pressure (up to 400 bar) to 'low' pressure (<100 bar) techniques, in combination with increased water volumes, net cleaning is still considered a key factor that may accelerate the release of MP from aquaculture nets. The resulting particles, often containing bioactive or toxic substances from degraded coatings, may pose a higher ecological risk than MP from other sources. It is therefore essential to quantify these emissions both locally and at broader national scales to better understand their impact and guide mitigation efforts.

In response to the drawbacks of traditional pressure washing with water jets, two alternative cleaning methods have recently emerged in the Norwegian aquaculture sector: cavitation-based cleaning and brush-based grooming. Cavitation-based systems generate air bubbles through water jets; these bubbles implode upon contact with the net surface, releasing energy that dislodges attached biofouling organisms. Experimental studies involving biocidal coatings have shown this technique to be significantly less abrasive than conventional pressure washing,[11] suggesting it may result in reduced MP emissions. Brush-based grooming adopts a different preventative approach. Rather than periodically removing established biofouling, this method involves the daily brushing of net surfaces to prevent organisms from settling and developing. Although this technique has not yet been formally assessed in aquaculture, analogous applications in hull cleaning indicate that maintaining a surface free of early-stage fouling requires less abrasive force.[13] Both cavitation-based cleaning and brush-based grooming show promise in reducing the release of MP from aquaculture nets and coatings when compared to traditional pressure washing methods.

An additional strategy to mitigate MP emissions from aquaculture is the adoption of alternative net materials. Traditional nylon nets are composed of very thin fibres, which tend to have relatively low resistance to abrasion. Abrasion resistance can be improved either by using thicker fibres—such as those found in HDPE nets—or by selecting inherently stronger materials like UHMWPE. The application of protective coatings can also play a significant role in reducing net material degradation.[14] These coatings not only help to limit direct abrasion of the net fibres but may also reduce MP release by creating a smoother surface that discourages biofouling attachment. A smoother net surface may require less mechanical force for cleaning and lower friction when using brushes, further minimizing wear. Additionally, coatings formulated with more durable materials can enhance resistance to damage during routine washing operations, thereby further reducing the likelihood of MP generation.

Comparable strategies can be applied to reduce MP emissions from ropes. Modifying rope design—through the use of alternative structures, materials, or protective coatings—may enhance resistance to wear and thereby reduce particle release. For example, findings from the FHF-funded project on fishing gear ropes (Project no. 901669) demonstrated that replacing conventional twisted polyolefin ropes with alternative rope types can significantly lower plastic waste resulting from mechanical degradation.

1.2 Project organisation

The SMARTER project brought together Norwegian research institutes with competence in the sampling, extraction and advanced characterisation of MP, and industry partners with extensive experience in aquaculture technology development and farm operations. The project was coordinated by SINTEF Ocean, with contributions from NORCE, SINTEF Industry, ScaleAQ, Watbots, Brynsløkken and NCE Aquatech Cluster A reference group comprising representatives from AkvaGroup, Grieg Seafood, and Sjømat Norge provided technical knowledge and helped to quality assure the work conducted.

2 Objectives

The **main goal** of SMARTER was to assess and model MP release from aquaculture structures and to quantify the reduction of MP emissions by introducing feasible measures under relevant environmental conditions.

The main and sub-goals were achieved through the following **objectives**:

- Use of a combination of laboratory and field studies to study and quantify MP release from aquaculture nets and conduct end of life condition assessment to evaluate the impact of innovative technologies (i.e. polymer formulation, net coating type and net cleaning method) on reducing MP emissions (WP1).
- Use of a standardised, laboratory-based abrasion test system to evaluate the MP emission from ropes comprised of different polymers and to assess the impact of coating ropes on reducing MP emissions (WP2).
- Use of knowledge and data gained from SMARTER and from other FHF-funded projects to model and compare the flow of MP emissions from Norwegian aquaculture facilities under different scenarios representing traditional approaches and innovative technological solutions (WP3).

Figure 2 provides an overview of the of the project structure and how the individual WPs are closely linked to each other.

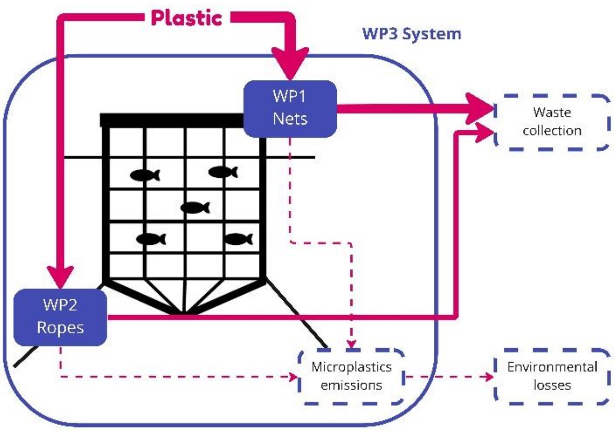


Figure 2: SMARTER project structure.

The SMARTER project was designed with the expectation that its results would enable the aquaculture industry to identify optimal combinations of net materials, coatings, and cleaning technologies that effectively reduce MP emissions. In addition, the project aimed to provide data on rope materials with the lowest MP emission potential and assess the feasibility of rope coatings as an additional mitigation strategy. An ambition of SMARTER was to integrate the knowledge generated within the project with insights from previous and ongoing initiatives to develop a comprehensive model of MP release. This model encompasses the primary plastic-based components used in aquaculture operations—such as nets, ropes, feeding pipes, moorings, cage collars, and sinker tubes. By adopting this integrative approach, the project sought to produce accurate emission estimates and offer the industry a holistic understanding of MP sources.

Over the longer term, the emission scenarios developed through SMARTER are expected to support the identification of aquaculture farm components that should be prioritised for mitigation efforts. In addition, the project's results have the potential to serve as an industry benchmark for current MP emissions, providing a critical reference point for evaluating the effectiveness of future mitigation measures and technologies. This baseline will also help ensure that new materials and innovations entering the market do not unintentionally increase MP emissions. By combining standardised laboratory testing methods with ambitious field sampling—and supplementing these with lab-based analyses of MP release, material abrasion, and weight loss—SMARTER establishes a framework for evaluating new aquaculture products and technologies going forward. Finally, the emission baseline data and predictive models generated by the project can offer regulatory agencies and policymakers the evidence base necessary to consider the integration of MP emission thresholds into future environmental legislation and regulatory frameworks for the aquaculture sector. Importantly, these early data have strong potential to be expanded, enhancing the robustness of SMARTER's findings, while the preliminary emission model can be further developed and refined as new data become available.

3 Project execution

3.1 MP release from nets

3.1.1 Effects of net material, coating, and age (laboratory experiments)

Background: Possible damage on aquaculture nets has previously been investigated in the RobustNet-project.[12] It was found that shrinkage of the nets, hard particles within the twines, and general wear and tear were important reasons for loss in netting strength. While shrinkage led to structural changes within the knitted netting structure, consequently reducing the load carrying capacity of the twine, it does not include excessive damage to the polymer fibres, and probably results in limited MP emissions. General wear and tear, sometimes affected by the presence of hard particles, will often cut individual fibres and reduce the load carrying capacity of the netting, again most likely resulting in limited MP production under moderate wear (Figure 3). However, abrasion damage is occasionally observed, with obvious removal of material that produces MP (Figure 3). This damage is often local and covers a limited area, for instance where netting is squeezed between ropes or the rotating discs in net cleaners.

In SMARTER, we chose to focus on abrasion damage for evaluating the potential for MP release in a laboratory study. The RobustNet-project found that contact with rotating discs in net cleaning equipment was a major source of abrasion damage. Thus, test equipment and procedures were developed to simulate the observed abrasion damage under field conditions, and the equipment was used to assess loss in netting strength. In SMARTER, this equipment has been utilized to develop methods for evaluating MP-production from nets and ropes. All test materials were subjected to the same abrasive loads, and their MP production could then be compared to evaluate their relative resistance to abrasion and MP release.

The laboratory abrasion studies (both nets and ropes) represent a 'worst case' scenario that is relevant for only a small percentage of the entire net structure (i.e. areas where the net/rope is in contact with other surfaces that create friction). As such, this should not be compared to field data in terms of absolute quantities of MP produced through a combination of multiple mechanisms.

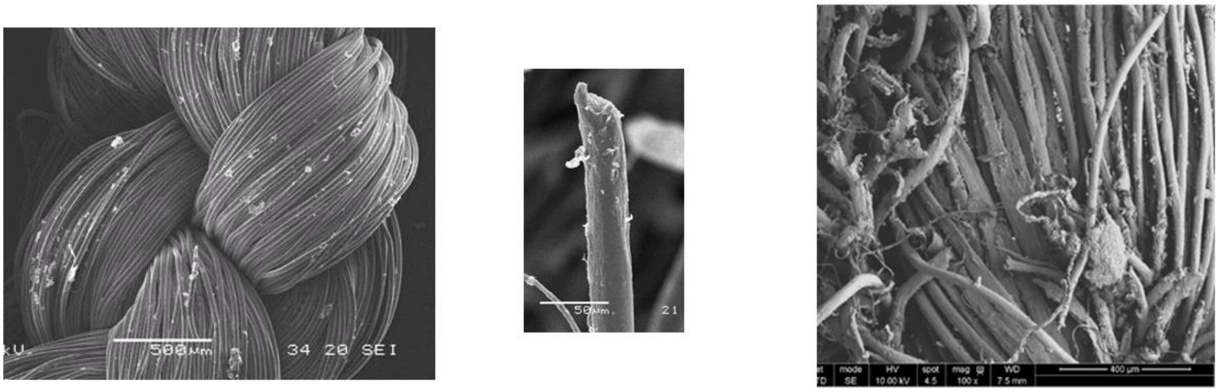


Figure 3: Electron microscopy images. From left to right: netting twine with undamaged fibres, cut fibre, area of netting with abrasion damage (probably from contact with high pressure cleaner disc).

Experimental set up

To assess the effects of net material, coating, and net age on MP release, standardised abrasion tests were conducted in the laboratory using an abrasion machine specifically designed for nets and ropes (MILA 200 WET, Buraschi Italia).[14] The device features a rotating drum with a circumference of 63 cm covered with an abrasive surface and a water tank, allowing tests to be performed under wet conditions (Figure 4a).

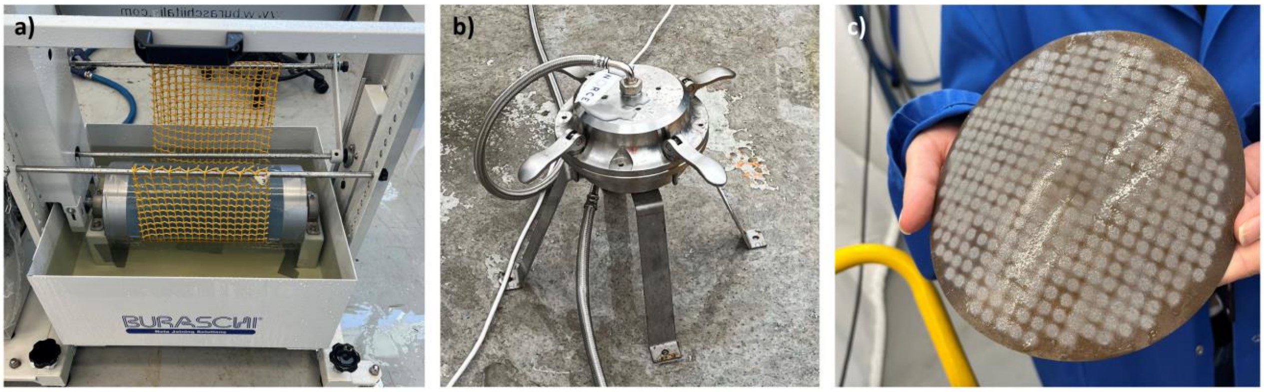


Figure 4: a) Buraschi abrasion equipment, b) the NORCE filtration unit used for all MP sampling, and c) a filter with collected particles.

The test included four different net materials (Table 1): nylon, HDPE, and two types of UHMWPE. All materials were tested in their new, unused state. Additionally, nylon and UHMWPE were tested with both standard and premium Brynsløkken coatings applied to unused nets (Figure 5).

Finally, three types of used nets were sourced to assess the effect of aging:

1. **Nylon:** A net that had reached the end of its service life was evaluated (three years old, used for two whole seasons, approximately a total of 36 months). Samples were collected from the jump fence, just below the surface, and the middle section of the net.
2. **HDPE:** A 5-year-old net that had been used for two seasons at sea (in total 23 months). The net was not considered at the end of its service life but sacrificed for testing in a different project. Samples were taken from just below the surface, the middle, and the bottom of the net.

3. **UHMWPE:** A 7-year-old net that had been in use for three seasons. A copper coating had been applied for at least the final season. Samples were collected from just below the surface, the middle, and the bottom of the net.

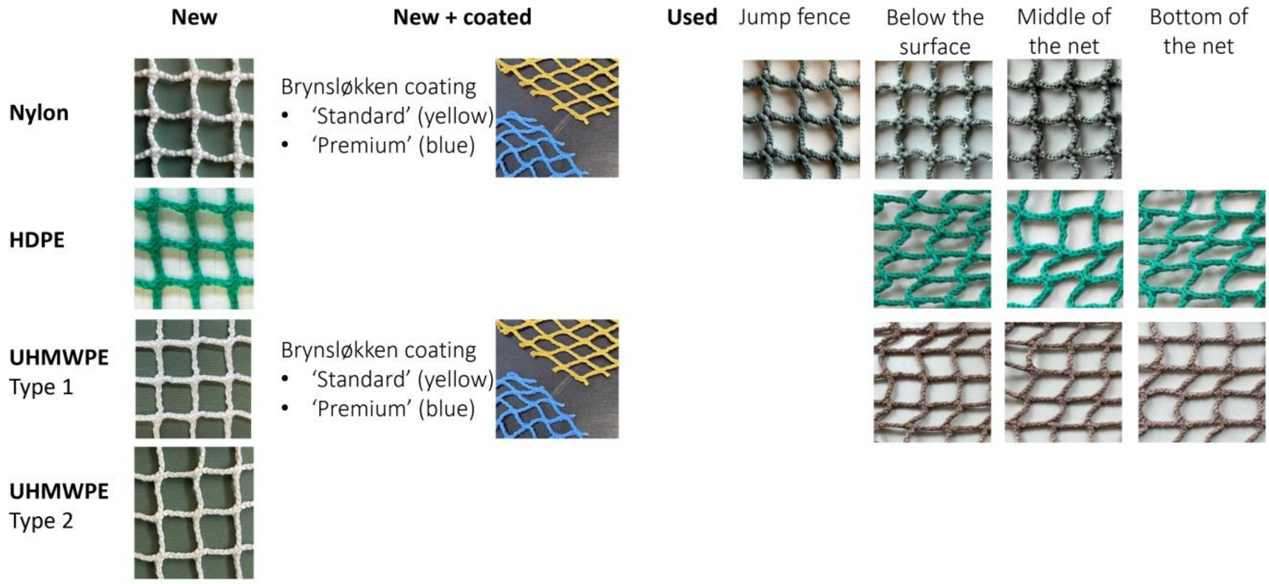


Figure 5: Four net materials in three conditions included in laboratory MP production experiments.

Table 1: Overview of combinations of net material, coating, and age tested (n=3) in the laboratory.

Net material	New	New, coated		Used			
		Standard	Premium	Jump fence	Below surface	Middle	Bottom
Nylon							
HDPE							
UHMWPE: Type 1							
UHMWPE: Type 2							

Sections of nylon and UHMWPE netting, each approximately 3 m² in size, were coated with either the standard or premium coating (Figure 5). The uncoated nylon netting weighed 46% more than UHMWPE netting, which is expected due to UHMWPE's higher strength-to-weight ratio. However, UHMWPE netting absorbed around 30% more coating than nylon netting. For both netting materials, the amount (mass) of premium coating taken up was almost twice the amount of standard coating.

Abrasion tests were conducted on three replicate samples per net type. Each sample measured approximately 35 × 100 cm and was pre-conditioned by soaking in freshwater for at least 16 hours prior to testing. The abrasion setup consisted of a cylindrical drum system with an abrasive surface and circulating water. The water filtration system to collect the MP particles consisted of a pump connected to a filtration unit (NORCE filtration unit, Figure 4b,c).

Before each test, the abrasion tank and filtration system were thoroughly cleaned by flushing with freshwater for three minutes. Fresh abrasive paper (1200 grit) was applied to the drum before each trial to ensure consistent abrasion conditions. Prior to testing each net material, the water tank was filled and circulated through the filtration system into a clean filter to obtain a reference (blank) sample to account for potential background contamination. Then, the netting sample to be analysed was installed in the machine (Figure 4). It was fixed at one end, placed under the abrasive drum, and pretensioned by attaching a 100 g weight in each twine at the free end. The weight was sufficient to ensure consistent contact between the netting sample and drum for all materials. Each net material was subjected to three replicate abrasion tests. During each test, the drum completed 20 rotations, followed by a three-minute rinsing phase with simultaneous filtration to collect any released MP particles. These particles were captured on two filters: a 500 µm filter to retain larger MP particles (MP_{LARGE}) and a 10 µm filter for smaller MP particles (MP_{SMALL}).

Following abrasion, the collected material was rinsed off the filters and resuspended using a solution of 30% ethanol in Milli-Q water to facilitate subsequent separation and analysis. The resuspended samples were then filtered and concentrated using two types of filters: a 300 µm nylon membrane filter (diameter ~4.5 cm, PLASTOK, UK) for the MP_{LARGE} fraction, and an 8 µm cellulose nitrate (ACN) filter (diameter ~4.5 cm, Sartorius, Germany) for the MP_{SMALL} fraction. After filtration, all filters were dried and examined under a stereomicroscope to assess the presence, morphology, and type of retained particles. Any particles displaying characteristics inconsistent with the original net material—such as differing colour, shape, or texture—were subjected to chemical analysis using pyrolysis gas chromatography-mass spectrometry (PyGC-MS). This allowed for the differentiation between particles originating from the net material and potential external contaminants, such as residues from the abrasive sandpaper used on the drum, which were not present in blank samples. Particles identified in large quantities as unrelated to the net samples were excluded from further analysis. The remaining MP mass in both size fractions (MP_{LARGE} and MP_{SMALL}) was then determined by gravimetric analysis, ensuring that only particles originating from the net material were included in the final quantification.

Before statistical analysis, all MP release data were blank-corrected by subtracting the particle mass measured in the corresponding blank sample (obtained from reference filtration prior to abrasion) from each of the three replicate values for the same net material. This correction ensured that only particles generated through abrasion were considered, excluding any potential airborne or background contamination. The corrected data, expressed as the mass (mg) of particles in both the large (MP_{LARGE}) and small (MP_{SMALL}) size fractions, did not meet the assumptions required for parametric statistical analysis. This was primarily due to the limited sample size (n=3 per material), which compromised the robustness of normality (Shapiro-Wilk test) and homogeneity of variance (Fligner-Killeen test) assessments. To address these limitations, differences in MP release among net materials were evaluated using a univariate permutational multivariate analysis of variance (PERMANOVA), conducted in PRIMER v.7. The analysis was based on Euclidean distances, using 9,999 unrestricted permutations of the raw data and a significance level of 5%. This non-parametric method was selected for its suitability in handling small sample sizes and data that deviate from parametric assumptions.

Microscope analysis of net and coating integrity

For the new, coated net samples, the integrity of both the net material and its coating was assessed post-abrasion using a dissection microscope. The analysis was conducted by examining 360 points on the abraded side of each net sample. For nylon nets, points were selected near the knots (four strands per knot) and midway between knots (three strands), as shown in Figure 6. For UHMWPE nets, assessment focused on three strands that were part of the knot structure (Figure 6). In nylon samples, damage was categorized as either (i) minor damage, affecting only some fibres, or (ii) major damage, involving clearly severed fibres across larger portions of the net strand. For UHMWPE, damage was assessed on a binary scale (present/absent) due to the subtle nature of the fibre damage, which was difficult to distinguish from coating damage. Differences between treatments were analysed using PERMANOVA (n=3; PRIMER v.7), based on Euclidean distances and 9,999 unrestricted permutations of the raw data, with a significance level of 5%. In cases where the number of unique permutations was fewer than 100, the Monte Carlo asymptotic pMC-value was used for interpretation.[15]

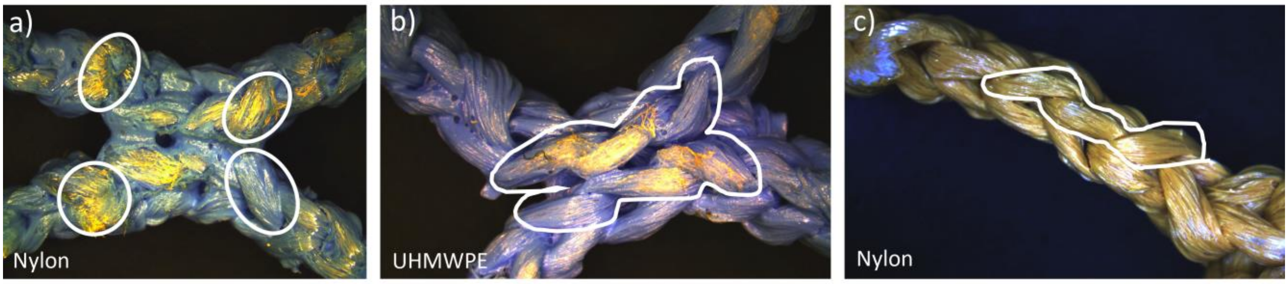


Figure 6: Net strands chosen for assessment of fibre and coating integrity, located as part of the knot (a, b) or between knots (c).

3.1.2 Effects of cleaning technology (accelerated net cleaning experiment)

To assess the impact of different net cleaning technologies on MP release, standard pressure cleaning was compared with two alternative methods: cavitation-based cleaning and autonomous underwater vehicle (AUV)-based brushing. The pressure and cavitation-based systems are reactive technologies, typically used weekly or biweekly to remove established biofouling. In contrast, AUV brushing is a preventative method, designed for daily use to inhibit biofouling settlement. To simulate 10 months of sea-based cleaning in an accelerated test, 35 cleaning events were assumed for both the pressure and cavitation-based methods. Each event consisted of two passes (e.g., downward and upward) of the cleaner over the net, resulting in a total of 70 passes. For AUV brushing, 150 cleaning events were estimated over the same period, amounting to 300 total passes.

To enable testing under conditions as close to real-life as possible, a 60 × 10 m test net was constructed, consisting of six 10 × 10 m nylon panels (Figure 7). Three of the panels were made from new nylon netting coated with Brynsløkken premium coating, while the remaining three were cut from a used nylon net. The used net had been deployed at sea for one season and subsequently stored for ten years. Originally coated with copper, panels for the test were harvested from sections located 5 metres below the waterline. The panels were sewn together in an alternating pattern (new/used) and mounted on an empty 159-metre plastic ring at Scale AQ’s assembly and decommissioning site in Nordhammervika, Frøya. The net was installed on 30.8.2024. Pressure cleaning was conducted on 2.9.2024, followed by cavitation cleaning a day later on 3.9.2024. AUV brushing was performed a week later, on 9.9.2024 and 10.9.2024.

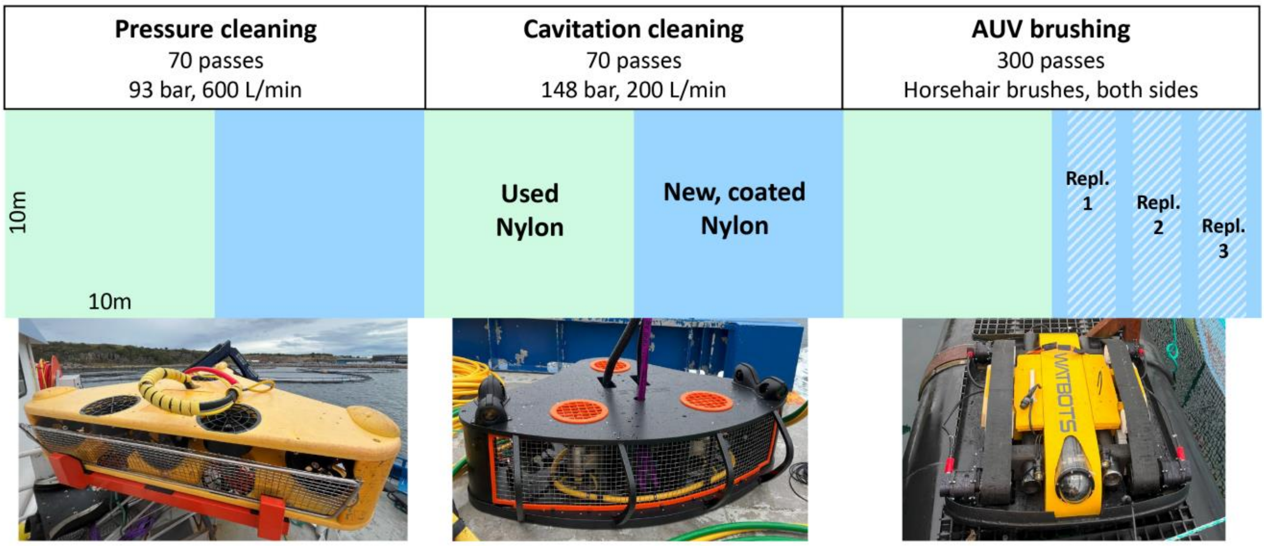


Figure 7: Schematised experimental set-up to simulate 10 months of net cleaning at sea testing three technologies on two net materials.

Pressure cleaning was performed using a stealth cleaner (Ocein AS), operating at a pump pressure of 130 bar and delivering 93 bar at the net, with a water flow rate of approximately 600 L/min. Cleaning a single replicate net strip took around 20 minutes. **Cavitation cleaning** was carried out using a *Meox* cleaner (Meox AS), operating at 175 bar pump pressure and 148 bar at the net, with a water flow rate of approximately 200 L/min. Cleaning one replicate net strip took approximately 20–25 minutes. **AUV brushing** was conducted using a *Watbots* AUV cleaning unit (Watbots AS), composed of two magnetic modules equipped with horsehair brushes on their undersides. These modules were attached to the inner and outer sides of the net, brushing both surfaces simultaneously with overlapping brushes. The AUV cleaner operated at a speed of approximately 15 m/s, requiring about one hour to clean a replicate net strip. Due to its slower speed and the higher number of required passes, the AUV only covered about half the 10-meter depth of the net panel. However, since MP release was measured as concentration per unit volume at a fixed sampling point (rather than as total mass released), no correction was made for the reduced cleaned area. Due to insufficient net tension, all cleaning devices experienced some difficulty maintaining their designated cleaning paths. In particular, the used net panel allocated to the AUV could not be cleaned due to the low tension of that specific panel. As a workaround, the same used net panel previously cleaned with the pressure system was reused for the AUV trial.

Samples were collected by positioning the hose connected to the filtration unit downstream of the washed net strip, at a depth of approximately 3 metres, where a majority of the emitted particles would expect to be found in a plume. Current direction and speed were monitored using a current meter and visual tracers (milk). Depending on the setup, the hose was either threaded through the walkway on the outside of the pen or suspended from a floater inside the pen, maintaining a distance of <1 metre from net surface being cleaned. Water sampling was carried out for the entire duration of each cleaning event. For pressure and cavitation cleaning trials, an additional five minutes of sampling were conducted after each replicate to increase the total sample volume.

A blank control sample was collected in the morning prior to washing the three replicates of the coated net. This involved 30 minutes of sampling without any cleaning activity, resulting in approximately 300 L of water. Another control sample was taken in the afternoon before switching to the cleaning of the used net. AUV brushing was carried out over two days. On the first day, two replicates of each net material were cleaned, with a control sample taken prior to each. On the second day, one replicate of each material was cleaned, again preceded by a control sample. To account for potential airborne contamination, air blank samples were collected by exposing a filter in a petri dish to ambient conditions throughout the sampling period. These samples are not presented as they did not show any relevant contamination (max. 4 MP particles per sample). All water samples were collected using the NORCE filtration unit described previously. Subsequent sample analysis was conducted at the microplastics laboratory at NORCE, Stavanger.

Each sample collected on the stainless-steel filters was first incubated overnight at room temperature in a 5% sodium dodecyl sulphate (SDS) solution to aid in particle detachment. This was followed by sonication to further dislodge particles from the filter surface. The resulting suspension was then filtered through a 47 mm stainless steel filter with a 10 µm mesh size. The retained material was incubated with 30% hydrogen peroxide (H_2O_2) for 6 hours at 50°C to digest any organic matter. Following digestion, density separation was performed using a potassium bromide (KBr) solution with a density of 1.7 g/cm³. The floating material was collected, filtered, and resuspended in a 5 mL mixture of ultrapure water and ethanol (50:50 v/v). Aliquots of approximately 500 µL were then filtered onto 13 mm unframed Anodisc membranes (0.2 µm pore size), which are compatible with infrared (IR) analysis.

Particles retained on the membranes were analysed using a ThermoScientific FTIR imaging microscope. Due to technical limitations of the instrument, only particles larger than 20 µm were characterised. The dried Anodisc filters were mounted on the IR reader plate and scanned in transmission mode. The entire filter area (active diameter: 10 mm; active area: 78.5 mm²) was scanned over an IR spectral range of 1200 to 3750 cm^{-1}. The following instrument parameters were used: 64 × 64 MCT-A linear array detector, 16 co-added scans per sample tile, and 120 co-added scans for the background tile. Each scan took approximately 4 hours. Particle size, location, and polymer classification were determined using automated image processing. Data were processed with siMPle software (v1.0.0; simple-plastics.eu), and spectral identification was performed by comparison with polymer reference libraries from Aalborg University and NORCE.

Differences between cleaning technologies and control samples were assessed using PERMANOVA (PRIMER v.7), based on Euclidean distances with 9,999 unrestricted permutations of residuals under a reduced model and a significance level of 5%. The analysis included two fixed factors: Technology (four levels: Pressure washing, Cavitation, AUV, Control) and Coating (three levels: Coated, Used, Control). Data are presented as the average of three replicate samples per treatment. For AUV brushing, control samples collected on days 1 and 2 were averaged to obtain a representative control value.

Assessment of coating integrity

As with the laboratory abrasion samples, the integrity of the coating on new, coated nylon nets was assessed using a dissection microscope. For this analysis, three subsamples (50 × 50 cm) were cut from the net at a depth of 3 metres, two days after the final cleaning event (Figure 8). Between 816 and 836 points were examined across both the front and back sides of the net, including areas within and between knots (Figure 9). Each observation point was classified into one of three categories (Figure 8):

1. **Intact coating:** Individual net fibres are not visible beneath the coating layer.
2. **Thinned coating:** Individual nylon fibres are visible, and while some may no longer be fully covered, the net strand remains structurally intact. No obvious edge to the coating is visible.
3. **Broken coating:** Coating is visibly damaged with a distinct edge; white fibres are exposed and, in some cases, no longer held together. This category included a range of expressions that varied depending on the cleaning technology used.

Differences between cleaning technologies were assessed within each category using PERMANOVA (n=3; PRIMER v.7), based on Euclidean distances with 9,999 unrestricted permutations of raw data and a significance level of 5%.

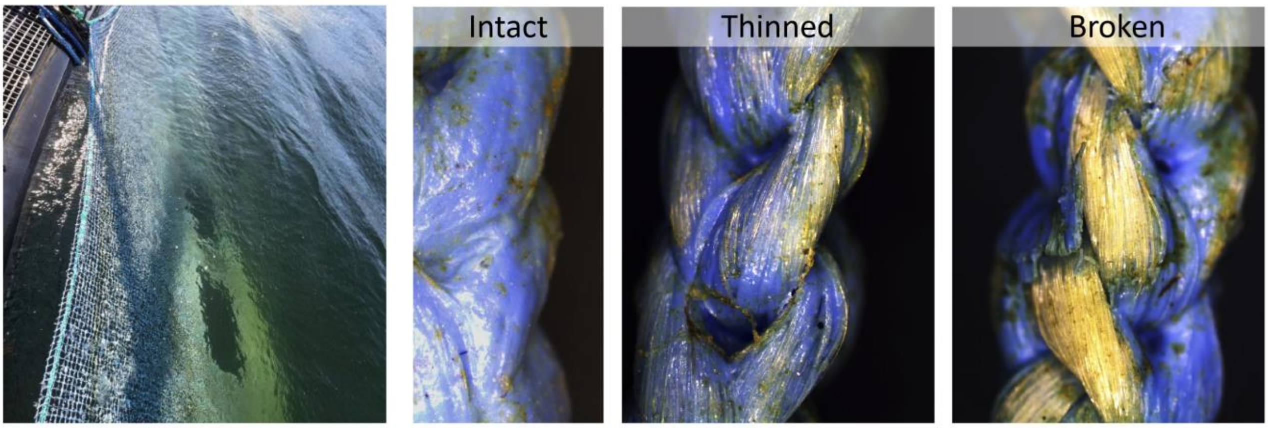


Figure 8: Coating integrity after net cleaning was analysed for samples taken at 3 m depth (left) based on three coating status categories.

Figure 9: Net strands chosen for assessment of coating integrity located on front and back side of the knot, as well as between knots.

3.1.3 Field sampling

Samples from an active net cleaning operation at a commercial salmon farm were collected on 6.4.2025. Control samples were taken the previous day to assess background MP concentrations prior to cleaning. The site consisted of five circular plastic pens, each with a circumference of 159 meters. Four pens contained nylon nets coated with a non-biocidal coating and were equipped with 6-metre-long permeable lice skirts; one pen was empty. Three control water samples were collected from a depth of approximately 1 metre, 5 metres outside the perimeter of the net pen. Each sample contained between 62 and 86 L of water. Additionally, an air blank sample was taken by exposing a filter to ambient conditions for the duration of the sampling event.

Net cleaning was performed using two *Manta* units (Mainstay AS) operating simultaneously—one starting from the top of the net and the other from the bottom, working toward each other. This approach allowed the cleaning of a single pen to be completed in approximately one hour. The cleaners operated at 140 bar pump pressure, delivering 80 bar at the net, with a water flow rate of approximately 500 L per minute. Sampling began about 20 minutes after cleaning commenced to allow time for particle generation and continued until the service crew initiated their final task: cleaning the top of the net with a smaller cleaning unit. Water samples were collected on the downstream side of the pen by feeding the sampling hose through the walkway to a depth of 3 meters. Sampling was conducted using the NORCE filtration unit described previously.

Sampling during net cleaning operations was conducted at three cages:

- **Cage 3:** The net had been replaced with a larger-meshed version at the end of January 2025 and had not yet been washed. Sampling lasted only 15 minutes (195 L of water) as the cleaning process was aborted early.
- **Cage 4:** A smolt net that had been deployed since July 2024 and had undergone eight cleaning events so far this season. The most recent cleaning occurred 21 days prior. Sampling lasted 53 minutes and collected 222 L of water.
- **Cage 5:** A smolt net, in the water since July 2024, with ten cleaning events so far this season. The last cleaning was 21 days prior. The lice skirt had been lifted in preparation for a delousing operation scheduled later in the week. Sampling lasted 40 minutes, with 247 L of water collected.

Specific information on the age of the individual nets was not available, except that none were in their first season at sea.

In addition to water samples, two air filter samples were acquired by keeping a filter exposed to the ambient air conditions during both the acquisition of control samples and during sampling at the cages to monitor airborne contamination. These two filters were processed alongside the water samples and served as procedural blanks in the laboratory to account for potential contamination introduced during sample handling and analysis.

As described in earlier sections, material collected on the filters was rinsed and resuspended in a 30% ethanol and Milli-Q water solution to facilitate downstream separation and analysis. Due to the generally low quantity of material retained on the 300 µm filter, both the large and small particle fractions were combined during the rinsing phase. The suspended samples were filtered and concentrated directly using 10 µm stainless steel filters (diameter ~4.5 cm, Sartorius, Germany), followed by oxidative treatment with 30% hydrogen peroxide (H_2O_2) for 24 hours at 40 °C. This step facilitated sample purification by removing biogenic material. After purification, the material retained on the filter was resuspended in a solution of 30% ethanol and Milli-Q water, then filtered through 0.2 µm Anodisc membranes. The resulting samples were subjected to automated imaging Fourier Transform Infrared (FTIR) spectroscopic analysis.

FTIR spectroscopy was performed using an Agilent Cary 620 microscope coupled with an Agilent Cary 670 spectrometer (Agilent Technologies). The FTIR microscope was equipped with a 128 × 128 focal-plane array (FPA) detector and a 15× IR objective lens, yielding a final magnification of 150×. To analyse the entire surface area of the Anodisc filters, mosaics of micro-FTIR images were acquired in transmission mode over the wavenumber range of 3600–1200 cm^{-1}, with a spectral resolution of 8 cm^{-1} and 6 co-added scans. To reduce data volume, 16 pixels (4 × 4) were binned together, resulting in an effective image resolution of 32 × 32 pixels and a pixel size of 22 µm. A background spectrum was obtained from a clean, unused Anodisc filter. Identification of MP particles within the mosaic images was performed using a custom-developed Python script.

Prior to statistical analyses, all MP concentration values were blank-corrected by subtracting the particle count detected in air-procedural blanks, ensuring that only sample-derived MP particles were included in the comparison. As the data did not satisfy the assumptions for parametric statistics, statistical differences between total MP and only polyamide (also potentially including nylon) concentrations in water samples collected during the net cleaning and control samples were assessed using univariate PERMANOVA, based on Euclidean distances with 9,999 unrestricted permutations of residuals under a reduced model. Additionally, differences in the polymeric composition between control and net washing samples were assessed using multivariate PERMANOVA based on Bray-Curtis similarities of standardised data with 9,999 unrestricted permutations of residuals under a reduced model. The analyses were performed with PRIMER v.7 and the significance level was set at a 5%.

3.1.4 Service site as potential source for MP

As part of the project, two aquaculture service sites were visited. At **Site 1**, the drum washer operates with a closed water recycling system. Used water is progressively replaced with fresh water, and the removed water is incorporated into concrete, eliminating the potential for MP release into the environment. In contrast, **Site 2** discharges water back into the sea after multiple filtration stages. Here, a portion of the system water is reused, while the rest is replaced with fresh seawater. Additionally, rainwater from the facility grounds enters the system through roof gutters. Alongside a drum washer for nets, the facility also includes a washer for cleaner fish shelters, both integrated into the water and filtration cycle. Due to its potential for environmental MP release, this site was selected for sampling. In addition to sampling at Site 2, personnel at both service sites were interviewed regarding their experiences with net wear. These interviews also included information from internal testing conducted at the respective facilities.

Sampling was conducted at four time points and three locations:

1. **Initial reservoir sample:** Taken from the water reservoir that stores recycled water and feeds the drum washer, sampled at the beginning of the wash cycle during drum filling.
2. **Reservoir sample post-seawater addition:** Taken from the same reservoir after the introduction of fresh seawater, which may have resuspended previously sedimented particles in the reservoir tank.
3. **Intermediate filter stage:** Collected partway through the washing process from one of the later filtration stages.
4. **Post-filtration discharge tank:** Taken at the end of the final washing cycle from the tank that holds water (post-ozonation) ready for sea discharge.

As described in the previous section, one air blank was acquired in addition to water samples by keeping a filter exposed to air during the sample acquisition to monitor airborne contamination. This blank was processed alongside water samples and served as procedural blank in the laboratory to account for potential contamination introduced during sample handling and analysis.

The drum washer has a capacity of 50 m³ and is filled and partially emptied multiple times (typically 3 or more) during the washing process, depending on the degree of net fouling, which is classified as light, medium, or heavy. Washing is conducted exclusively with seawater, while disinfection occurs separately in a dedicated tank at the end of the process. The net cleaned during sampling was a nylon net with a non-biocidal coating, after its second season at sea. It measured 160 m in circumference and 35 m in length (20 m straight walls). It was classified as medium fouled. The net washed prior to this (and potentially a residual source of particles in the system) was a Dyneema net, also 160 m in circumference but 32 m in length, with 17 m of straight walls. It had completed its third season and was classified as heavily fouled. The site's filtration system consists of mechanical filters and sedimentation tanks, supported by chemical flocculation, followed by ozonation as the final treatment step before water is either released back to the sea or recirculated into the reservoir tank. An air blank was collected by exposing a wetted filter to ambient conditions during sampling. All water sampling was carried out using the NORCE filtration unit, as described previously.

As previously described, the material collected on the 500 µm and 10 µm filters was rinsed and resuspended in a solution of 30% ethanol and Milli-Q water to facilitate downstream separation and analysis. The suspended samples were then filtered and concentrated using a 300 µm nylon membrane filter (diameter ~4.5 cm, PLASTOK, UK) for the MP_{LARGE} fraction, and a 10 µm stainless steel filter (diameter ~4.5 cm) for the MP_{SMALL} fraction. The material retained on each 300 µm filter (MP_{LARGE}) was visually inspected under a stereomicroscope (SMZ745T, Nikon). Particles were manipulated using stainless steel tweezers during the identification process, which excluded non-plastic materials such as glass, sand, minerals, and shell fragments. Particles displaying clear cellular structures were excluded as organic matter. Particles visually identified as potential plastics were characterised based on shape, colour, and size (measured at the largest cross-section), and were photographed using a stereomicroscope equipped with a DeltaPix camera. These particles were then isolated and subjected to point-based FTIR spectroscopy to determine their polymer composition.

MP_{LARGE} particles were manually transferred from the nylon filters onto a barium fluoride (BaF_2) slide (25 mm diameter, 1 mm thickness) using stainless steel tweezers under a stereomicroscope. Micro-FTIR images were collected in transmission mode over the wavenumber range of 3600–900 cm^{-1}, with a step size of 4 cm^{-1} and 16 co-added scans. A background spectrum was recorded from a particle-free area of the BaF_2 slide. An in-house Python script was used to extract FTIR absorption spectra from the micro-FTIR images. Spectral interpretation was conducted using the *KnowItAll Informatics System* (2018), where similarities in wavenumber positions and the relative intensities of absorption bands were compared against a reference library (Bio-Rad Sadtler, Bio-Rad Laboratories) to determine polymer composition. Polymer identification was completed for four particles with representative physical characteristics. For an additional 13 particles exhibiting identical visual features, the same polymer composition was inferred. Cumulative polymer assignments—both directly analysed and inferred—are presented in the Results section. Material retained on the 10 µm filter (MP_{SMALL}) was resuspended in a solution of 30% ethanol and Milli-Q water, then filtered through 0.2 µm Anodisc filters (Whatman) for automated imaging FTIR analysis (Agilent system), as described in the previous section.

3.2 MP release from ropes

3.2.1 Effects of rope material and age (laboratory experiments)

To assess the effect of rope material and age (unused vs. used) on MP release, laboratory abrasion tests similar to those described in Section 3.1.1 (nets) were conducted on ropes commonly used in aquaculture. Abrasion testing was performed using the same abrasion machine described previously. The test included five rope materials: HDPE, UHMWPE, and three types of polyolefin ropes—two standard polyolefin variants (referred to as polyolefin1 and polyolefin2), and one rope composed of 50% recycled material (Figure 10). All five materials were tested in their new, unused state. In addition, samples of used UHMWPE and polyolefin1 were tested. The used polyolefin1 sample originated from a net pen where it had been in service for up to 21 months (likely less).

The ropes were physically characterised through inspection and manual measurements using vernier callipers and a micrometre. Each rope was deconstructed, and the strands and fibres were measured and counted. A 1.0 m long sample was cut from each rope and weighed on a calibrated lab scale. Ropes were dry at the time of measuring the weight. The ropes were also photographed using a DSLR camera with a macro lens. Data from the measurements are shown in Figure 10.

SINTEF

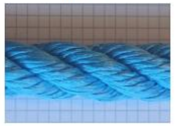
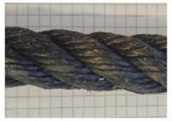
marking	20mm HDPE	26mm polyolefin1	Used polyolefin1	20mm polyolefin2	22mm 50% recycled polyolefin	10mm UHMWPE	Used UHMWPE
color	bright orange	deep blue	blue , worn	light blue	black	light yellow	tan / brown
photo rope							
photo strands							
measured diameter	20mm	26mm	25mm	21mm	24mm	oval 13x9mm	oval 18.5x14mm
Strands x Yarn x Fiber	3x20x35	3x29x18	3x?x5	4x11x10	4x17x13	12x ca 2500	12x8x ca 400
comment			~30 strands (difficult to count)	4 strands + 2mm core		12 non-twisted braided strands with multifilaments	12 braided strands, each consisiting of 8 braided budles of filament
perceived relative bending stiffness	very stiff	stiff	very stiff	stiff	stiff	soft	very soft
main strand twist	right twist	right twist	right twist	right twist	right twist	braided	braided
twists per meter	16	15	14		12.5	6.66 (braiding patterns)	
strand diameter	10mm	11.5mm	11.5mm	9.5mm	9.5mm	5x2mm	5mm
strand twist	left twist	left twist	left twist	left twist	left twist		left twist
twists per meter	15-16	10-11	low	low	10		
yarn diameter	2mm	1.8mm	2mm	2.5mm	2.5mm		
yarn twist	left twist	right twist	right twist	right twist	right twist	not twisted	not twisted
fiber diameter/thickness	0.33mm	0.42mm	0.4x1.7mm	0.4x1.5mm	ca 0.4x0.8mm	~0.02mm	~0.03mm
yarn properties	monofilaments	split fiber	split fiber	split fiber	split fiber	multifilament	multifilament
fibers per yarn	35	18	5	10	13	ca 2500	ca 400
fibers per rope	2100	1566	?	446	884	ca 30 000	ca 40 000
weight per meter	202 g/meter	260 g/meter	246 g/meter	192 g/meter	228 g/meter	55 g/meter	99g/meter
producer data 1 - strength	*4300 kg*	*9400 kg*	*9400 kg*	*6100 kg*	*6500 kg*	*9100 kg*	
producer data 2 - size/diameter	*20mm*	*26mm*	*26mm*	*20mm*	*22mm*	*10mm*	
producer data 3 - weight	*200 g/meter*	*319 g /meter*	*319 g /meter*				

Figure 10: Summary of rope data and characterisation parameters.

Characterisation of the ropes was performed using two different types of 3D scanner. The goal was to measure a virtual cross-sectional area of the rope and determine the dimensions of the rope more accurately than the manual measurements achieved with vernier callipers. The first scanner was a handheld CR-Scan Raptor scanner from Creality. It uses a hybrid blue laser and NIR and comes with software that claims to deliver very high accuracy. In practice, this scanner had problems mapping ropes of the sizes used in this project and appears better suited for scanning larger objects. Irrespective of the settings used, the software was unable to perform a complete 360 degree scan of the rope. When tested on a larger 50 mm rope (not used in the abrasion studies), the scanner was able to generate good results, as shown in Figure 11.

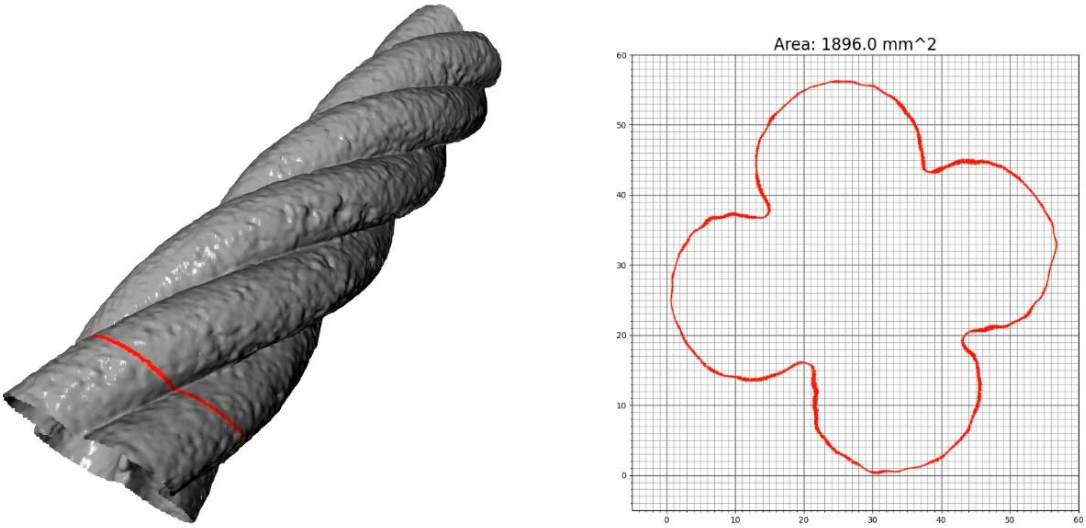


Figure 11: 3D scan and cross sectional area of a 50 mm rope using a Creality Raptor 3D-scanner.

A photogrammetry method was also tested on the rope samples used in the abrasion studies. This method works by reconstructing the rope in three dimensions from a structure-from-motion approach. The method was able to generate significantly higher quality images from the 25 mm diameter ropes but was found to be a more challenging method to use for accurate dimension measurements as it does not give correct scale-to-real world measurements, as well as having some measurement artifacts. Examples of the resulting 3D images from the photogrammetry analysis are shown in Figure 12.

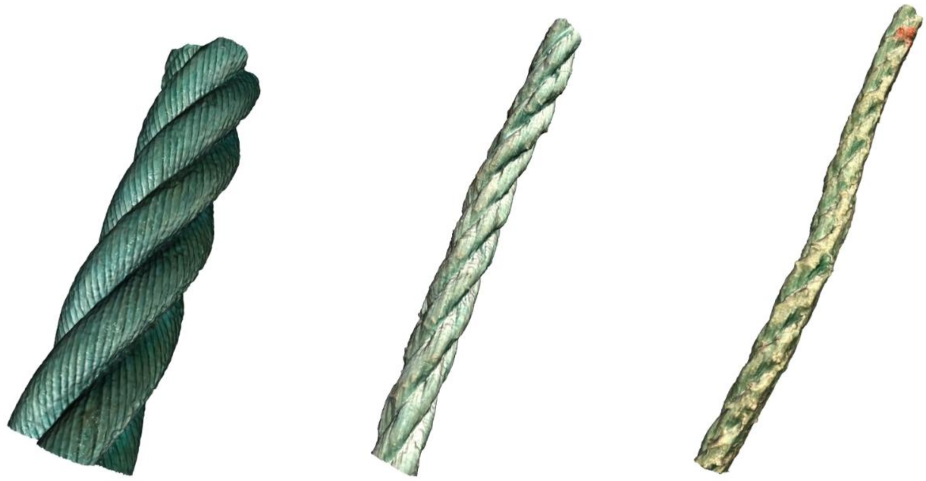


Figure 12: 3D images of ropes from photogrammetry experiments

The abrasion protocol followed was analogous to that described for the net samples. Briefly, prior to each abrasion trial, the tank and pump system were thoroughly cleaned by flushing with freshwater for approximately three minutes. A new abrasive cloth band (220 grit) was installed on the drum before each replicate test to ensure consistent mechanical wear conditions. The water tank was filled with tap water at room temperature, and a blank (reference) sample was collected by circulating the water through clean filters to account for any background contamination from the system or materials. Each rope sample was installed in the abrasion machine with a pre-tension of 10 kg, applied using weights at the free end (Figure 13). During each test, the drum completed 20 rotations, followed by a 1.5-minute washing and filtration phase. Particles generated during abrasion were captured on two filters per replicate: a 300 µm filter for larger particles (MP_{LARGE}) and a 10 µm filter for smaller particles (MP_{SMALL}). Three replicate abrasion and filtration tests were performed for each rope material. Sample preparation and gravimetric analysis for the quantification of MP_{LARGE} and MP_{SMALL} particles was performed as described for the nets (see section 3.1.1).

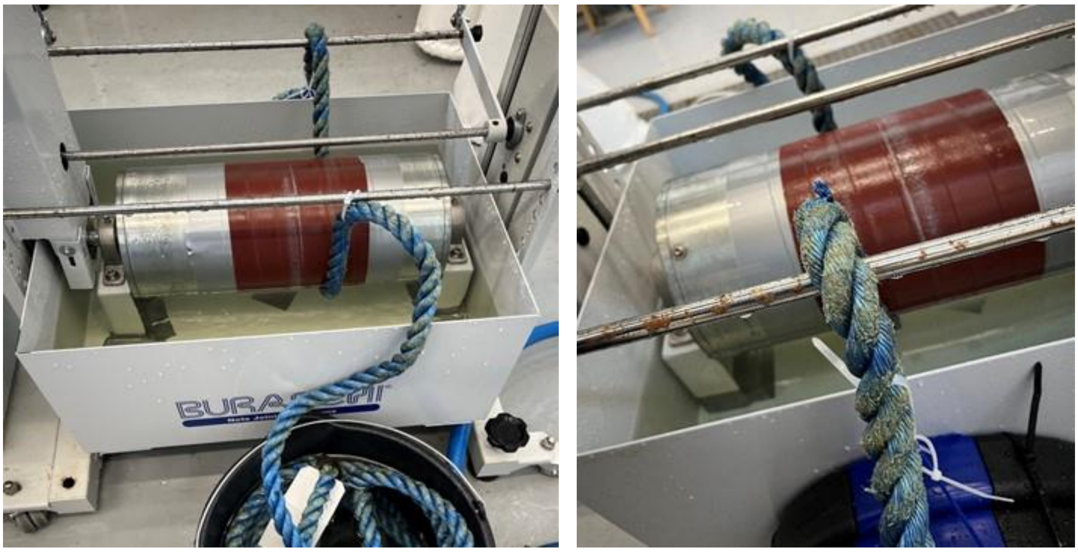


Figure 13: Set-up for rope abrasion test. The rope was fixed at one end (white cable tie in left picture), while two 5 kg weight discs were attached at the free end (right picture). In these pictures, the red abrasive band had been previously used, while for the presented result it was changed between each replicate test.

3.2.2 Effects of coating on rope material

To evaluate the potential influence of rope material and surface coating on MP release, four rope types—HDPE, UHMWPE, polyolefin2, and 50% recycled polyolefin2—were selected for experimental coating trials using both standard and premium coatings.

However, several methodological challenges arose during the coating process:

- The coatings did not adhere properly to the rope surfaces (Figure 14a, b).
- The coated ropes became excessively rigid, losing their functional flexibility and rendering them unsuitable for practical use in aquaculture applications.

Figure 14: Examples of unsuccessfully coated polyolefin2 (A) and recycled polyolefin2 (B) with standard coating.

Due to the abovementioned coating issues, it was concluded that applying coatings to ropes is not a viable strategy for reducing MP emissions from ropes. As a result, no experimental data on coated ropes are included in the Results section.

4 Findings, discussion and conclusion

4.1 MP release from nets

4.1.1 Effects of net material, coating, and age (laboratory experiments)

Release of MP

The comparison of net materials revealed that nylon nets released nearly five times more MP on average (94 ± 19 mg MP, mean ± standard error) than the three polyethylene-based (PE) net materials (based on mass), which showed MP releases ranging from 7 ± 0.5 to 19 ± 5 mg (Figure 15). When coatings were applied, MP release from nylon nets more than doubled with the premium coating (223 ± 39 mg), while the increase with the standard coating was less pronounced (121 ± 23 mg). In contrast, neither coating type led to an increase in MP release from UHMWPE nets (Figure 15). Although statistical significance was not achieved due to the limited number of replicates (n=3) and relatively high variability, consistent trends across materials were observed. These trends suggest meaningful differences in MP release that warrant further investigation. Visible wear was observed over a length of approximately 25 cm for the netting test panels, and over the whole width of about 35 cm.

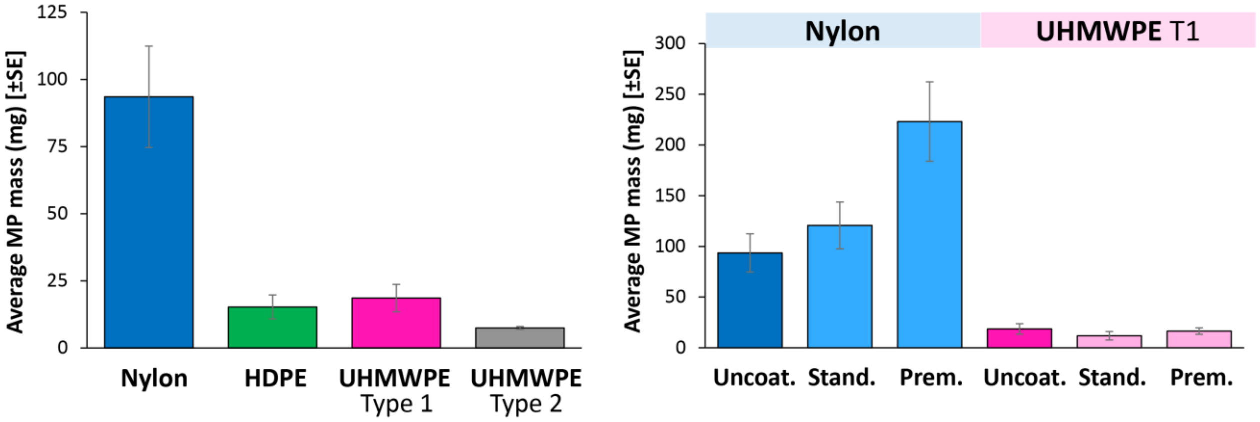


Figure 15: Average (n=3) MP release per net from four different new net materials (left), as well as from new nylon and UHMWPE type 1 nets (n=3) coated with Brynsløkken standard or premium coating (right).

Nylon netting appears to be less abrasion-resistant than the PE materials (HDPE and UHMWPE) tested in this study. While HDPE, UHMWPE, and nylon are generally known for their good abrasion resistance compared to other plastics, UHMWPE has consistently been shown to outperform nylon in many applications. Previous tests comparing nylon with PE nets (both HDPE and UHMWPE) have demonstrated that nylon experiences a greater reduction in strength under similar abrasive conditions and exhibits more visible signs of wear.[14] For HDPE nets, the increased abrasion resistance may also be attributed to the use of significantly thicker monofilament fibres, in contrast to the much finer nylon multifilaments typically used in conventional netting.

Clear differences were observed in how the coatings interact with nylon and UHMWPE net materials. For UHMWPE, average MP emissions were similar across the uncoated, standard-coated, and premium-coated samples. This suggests that the coatings adhere well to UHMWPE, providing effective protection against abrasion due to both good adhesion and the inherent resistance of the coating material. This is supported by the fact that the UHMWPE net had a higher coating uptake than nylon (see Section 3.1.1). In contrast, the lowest MP emissions for nylon were recorded in the uncoated samples. While the standard-coated nylon net showed a moderate increase in MP release (not statistically significant), the premium-coated nylon net exhibited the highest emissions. These findings suggest that the coatings adhere less effectively to nylon than to UHMWPE, with the premium coating possibly showing the poorest adhesion, or simply providing more material to abrade off due to the thicker coating application. Alternatively, it may be that the coating penetrates more deeply into the strands of the UHMWPE net compared to nylon nets, where it adheres more superficially and was thus easier removed. It is important to note that the total MP measured for each sample includes contributions from both the coating and the net material.

For nylon nets, a trend was observed indicating increased MP emissions from used nets (Figure 16). A similar, though less pronounced, pattern was also seen for the UHMWPE net. However, it is important to note that the UHMWPE net had been coated during its final season at sea, and some of the collected particles may have originated from the coating rather than the net material itself. Despite this uncertainty, both materials showed a consistent trend, where areas identified by service site personnel as being most prone to abrasion—such as sections just below the surface and at the bottom of the pen (see Section 4.1.4)—tended to have higher MP emissions compared to samples taken from the middle of the net.

A similar trend of higher emissions from areas below the surface and at the bottom compared to the middle was also observed for the used HDPE nets. However, overall MP emissions from the used HDPE nets did not differ significantly from those of the new HDPE nets. One possible explanation for the absence of a clear trend for HDPE nets may be the age of the used net. While the nylon net samples came from an end-of-life net that was considered unfit for further use due to factors such as loss of strength, the HDPE net had not yet reached the end of its service life. Its likely better functional condition may have influenced the emission results and limited the ability to assess the impact of net age on MP release for HDPE.

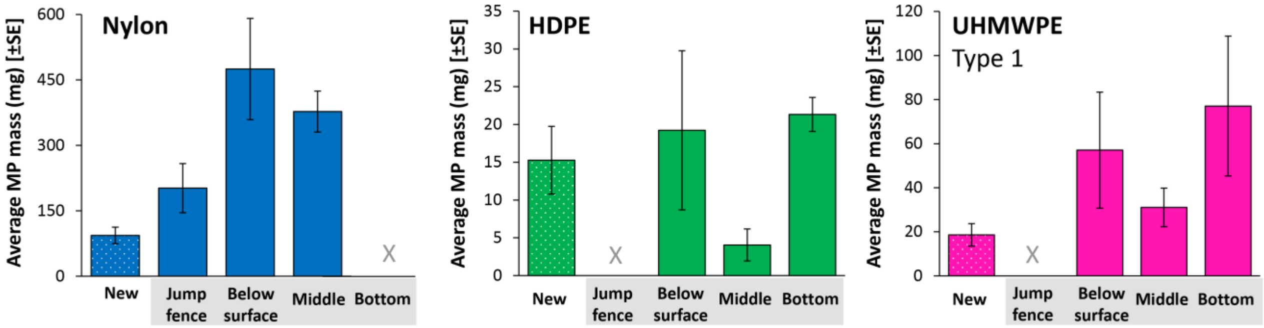


Figure 16: MP release per net from different regions of three different used net materials (grey underlay) in comparison to the same material when new (n=3). Three areas out of four possible spots in the used pen net were sampled for each material. (Note the different axis scales).

Microscope analysis of coating abrasion

The assessment of fibre and coating damage revealed no significant difference between the two coating types for nylon nets (Figure 17). On average, 72% of the surface of the nylon net with standard coating exhibited fibre damage, with major damage accounting for almost half (45%) of the assessed strands. For the premium-coated nylon net, 76% of the assessed strands showed damage, with major damage making up 40% (Figure 18). In contrast, UHMWPE nets did not show obvious fibre damage, but exhibited a difference between coatings. On average, the premium-coated UHMWPE nets showed greater coating damage (66%; Figure 18) compared to those with the standard coating (48%) ($F_{1,5}$ = 9.23; pMC = 0.04). It is unclear why the microscopic results do not align with the MP release measurements. It must also be noted that the assessment was limited to three replicates, and so interpretation of statistical results should be done with care.

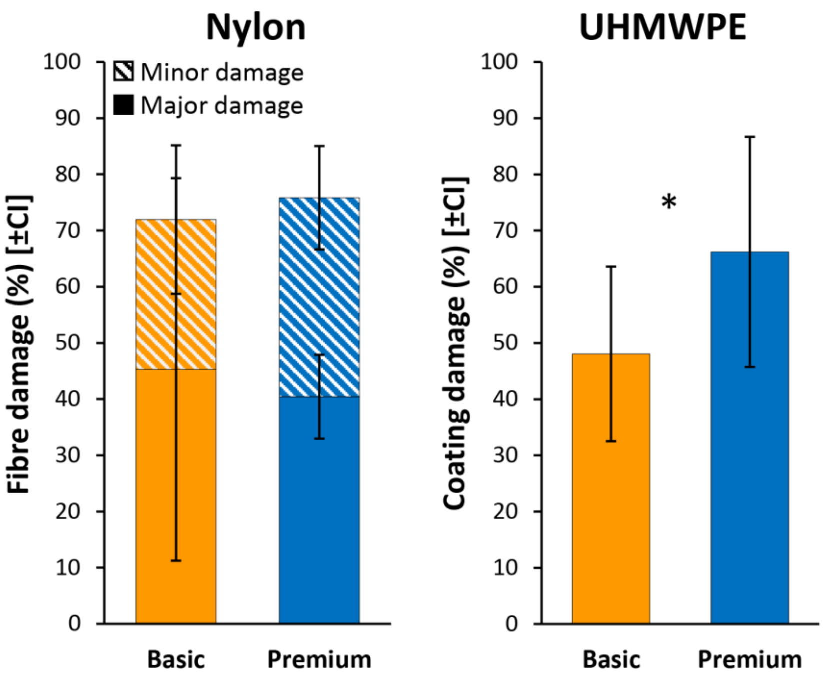


Figure 17: Assessment of coating and fibre damage for nylon and UHMWPE type 1samples from the laboratory abrasion test (n=3). Significant differences in damage between materials are indicated by an asterisk.

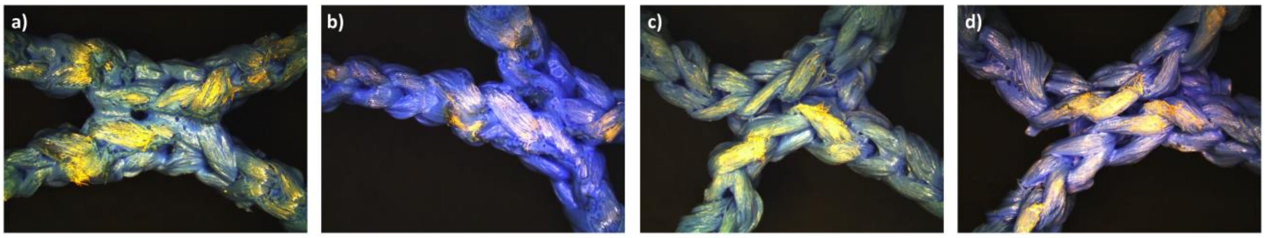


Figure 18: Examples of nylon (a + b) and UHMWPE (c + d) nets with premium coating showing signs of abrasion.

4.1.2 Effects of cleaning technology (accelerated net cleaning experiment)

Release of MP

No differences were observed in MP particle abundance between cleaning samples and control samples collected prior to cleaning, nor between the different cleaning technologies. In many cases, control samples showed higher total MP particle counts than the average values determined for the cleaning samples, with concentrations reaching up to 1.2 MP particles L^{-1} (Figure 19). The collected particles were classified into 17 different material types, indicating a wide range of different polymer type MP particles were present in the collected water samples. The polymer composition of the net and coating material were known and represented just two polymer types; the results indicate that the water samples contain a diverse loading of MP that come from other sources. Interestingly, neither the nylon nor the coating material stood out as being dominant compared to the other types of polymer present.

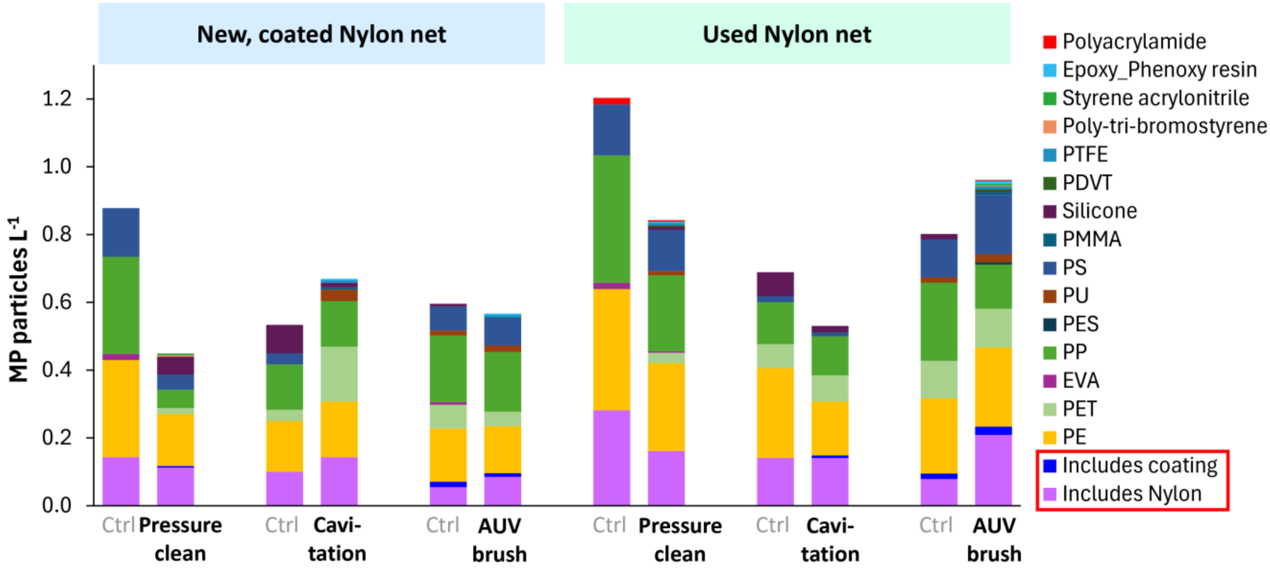


Figure 19: MP particles per Liter collected during the accelerated cleaning experiment.

Of these, two categories were relevant for identifying particles originating from the nylon net or the coating. For both categories, MP abundance did not differ notably between the different cleaning technologies or the control (PERMANOVA for factors Technology and Coating, $p>0.05$), ranging from 0.02 to 0.25 MP particles L^{-1}. In fact, the greatest variation was found among individual replicates of the same sample, rather than between different cleaning treatments. Focusing on the category that included nylon particles (Figure 20a), only one case showed consistently higher particle counts in the cleaning samples compared to the control: AUV brushing of the used nylon net. However, this result should be interpreted with caution, as pressure cleaning had previously been performed on this same net. When focusing on particles potentially originating from the coating (Figure 20b), only a few samples from coated net cleaning contained particles identified as coating-derived (3 out of 9 samples). For the used nylon net, this number was slightly higher (5 out of 9 samples), but concentrations remained very low—fewer than 3 particles per 100 L.

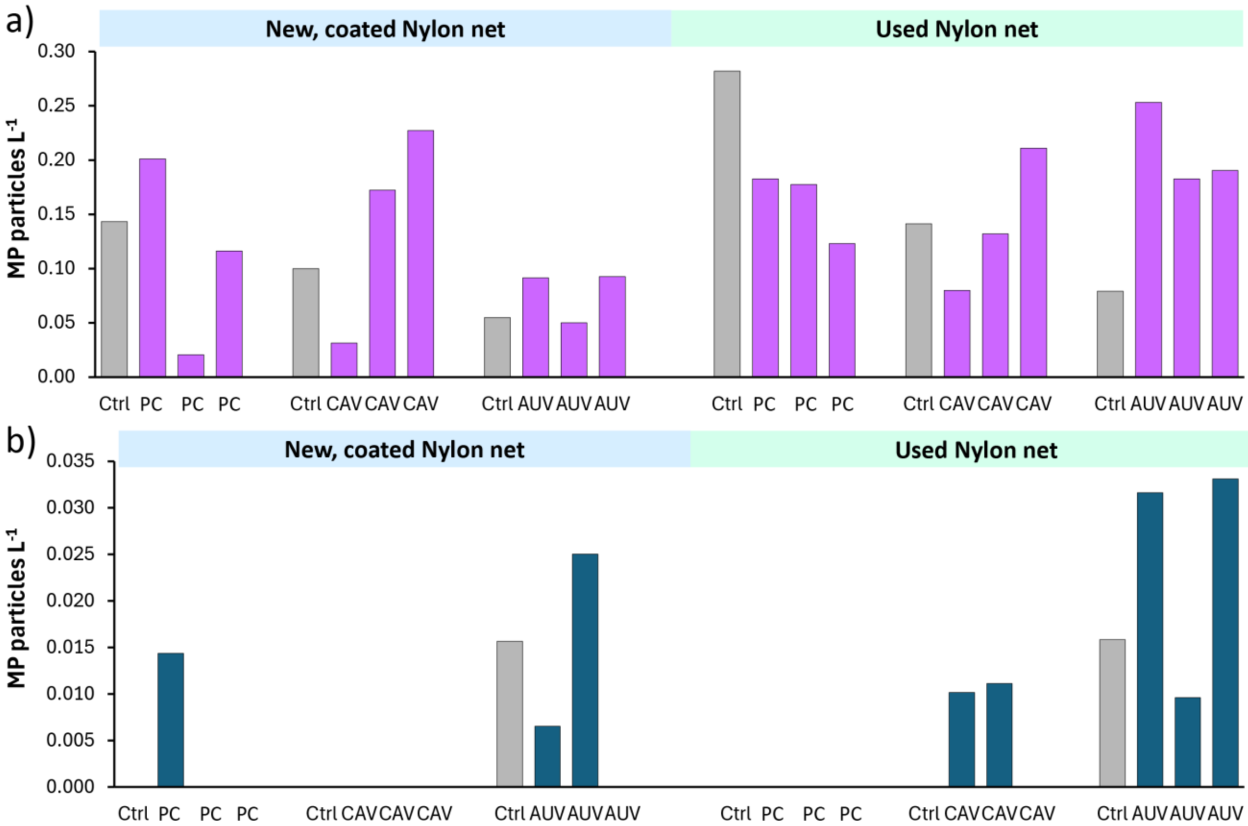


Figure 20: MP particles per Liter, belonging to the category that includes a) nylon nets and b) net coating; one control sample followed by three samples taken during net cleaning using three technologies (pressure cleaning (PC), cavitation cleaning (CAV) and AUV brushing (AUV)) on two net materials.

In conclusion, the results support our initial concern that sampling MP particles released during net cleaning is highly challenging. In addition to the low number of particles likely released from the washed nets, a number of other particles were detected. This suggests the presence of multiple potential MP sources in the immediate vicinity (e.g., several harbours with a range of vessel activity, assembly and decommission site for net pens), reducing the ability to confidently attribute collected particles to the net or coating materials. Furthermore, shifting currents, tides, and wind-driven surface movement likely contributed to the difficulty in capturing representative samples, despite our best efforts to account for this. These dynamic conditions hindered the ability to predict the drift path of released particles, making it uncertain whether sampling was conducted at the correct locations or in sufficient volumes to detect MP emissions accurately. However, the net cleaning may not have released sufficiently large amounts of material that it became distinguishable from background levels of MP.

Microscopic analysis of coating abrasion

In contrast to the challenges of collecting MP particles, the assessment of coating abrasion provided a clearer and more conclusive picture (Figure 21). While the total affected surface area did not differ significantly between cleaning technologies, with all three showing damage on 83–92% of the coated surface, differences emerged when the extent of damage was considered. Pressure and cavitation cleaning resulted in significantly higher proportions of broken coating (57% and 59%, respectively) compared to AUV brushing (29%) ($F_{2,8} = 6.18$; $p = 0.04$). Conversely, thinned coating was more prevalent following AUV brushing (55%)

than after pressure and cavitation cleaning (26% and 33%, respectively), with this inverse relationship also being statistically significant ($F_{2,8}$ = 22.46; p = 0.03).

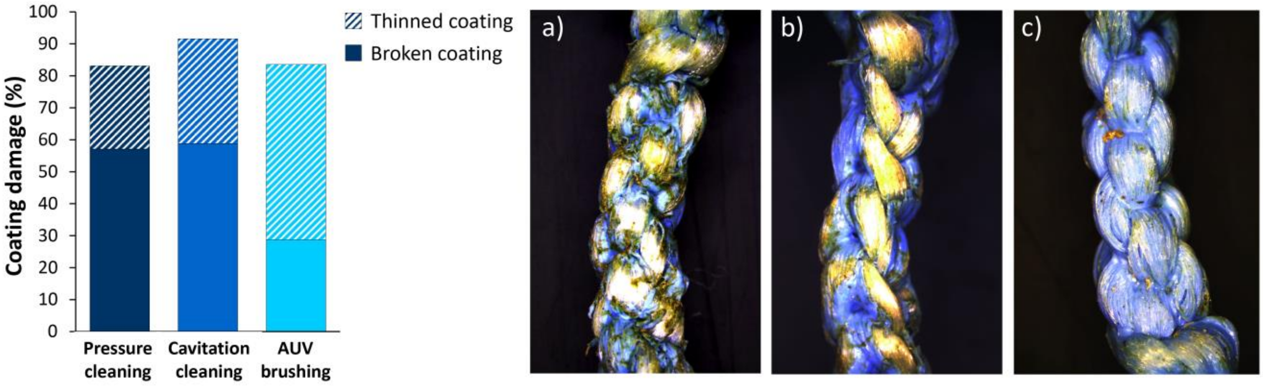


Figure 21: Results from microscopic assessment of coating integrity of new, coated nylon nets (n=3) after accelerated net cleaning using three different cleaning technologies, with examples of worst-case damage from: a) pressure cleaning; b) cavitation cleaning and c) AUV brushing.

While conclusions based on only three replicates should be drawn with caution, clear differences in coating damage were evident under the microscope. AUV brushing appeared to remove the coating more uniformly across the surface (Figure 21c). Although coating integrity was still compromised in some areas, exposing the underlying nylon strands, the damage from pressure and cavitation cleaning was more severe, often resulting in sharp-edged breaks in the remaining coating (Figure 21a, b). However, how these differences translate into MP release remains uncertain based on the current data. One possibility is that AUV brushing generates smaller particles, whereas the other two technologies may cause the coating to splinter off in larger pieces. The implications of particle size for total MP release, as well as subsequent environmental transport and potential uptake by organisms require further investigation. Future studies should also consider that nets have distinct 'sides', with knots protruding on one side. In this experiment, pressure cleaning was conducted on the backside of the net (with protruding knots), cavitation cleaning on the front side, and AUV brushing operated on both sides. Although microscopic assessment included both sides—since damage was observed even on the 'unwashed' side—the influence of cleaning direction or side preference on the results cannot be determined from this study alone and require further investigation.

Finally, it should be noted that the results described are specific to the three technologies tested in this study. While it is generally assumed that pressure cleaning is relatively similar between technology providers, there may be differences between technologies and their effect on net materials (depending on e.g., water volume and pressure used, nozzle shape, as well as operator style and skill). This is likely most relevant for cavitation and AUV brushing as these are emerging technologies.

4.1.3 Field sampling

The results presented in Figure 22 indicate variability in MP concentrations (MP particles L^{-1}) and polymer compositions across the water samples collected during high pressure washing of three aquaculture cages and three control samples (Control 1 to 3) collected at the same site prior to net cleaning. The water sample collected during cleaning of Cage 5 had the highest total MP particle number with 36.1 particles L^{-1} (Figure 22). In contrast, Cages 3 and 4 had lower concentrations of MP particles (10.8 and 2.9 MP particles L^{-1}, respectively). Control samples reached a similar range of concentrations with values between 1.3 and 31.1 particles L^{-1}.

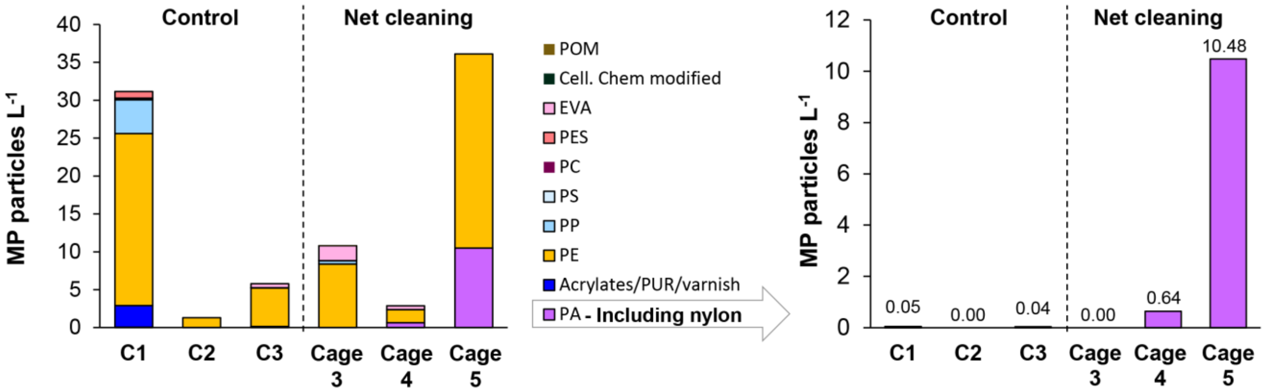


Figure 22: The number MP particles per Liter in water samples collected during an in-situ net cleaning operation using conventional pressure washing (Cage 3-5) and in control samples (C1-3) collected the day before. In addition, data for the fraction that may contain nylon particles is presented individually (on the right).

The reason for the increased MP release measured at Cage 5 may be the lack of lice skirt. Lice skirts have been shown to retain particles inside the skirt volume compared to below,[16] indicating a delayed release and lack of distribution through the skirt walls. Without the presence of a lice skirt in Cage 5, it is suggested that MP were able to disperse more quickly and more widely around the cage during cleaning, increasing concentrations also around the sample intake point. In comparison, the sample collection point for Cages 3 and 4 was approx. 3 m above the lice skirt edge. In these cages, the MP particles may have taken longer to disperse higher up in the water column or, for negatively buoyant polymer particles, may not have reached the sample intake point at all.

The overall MP composition of both control and cleaning samples was dominated by PE. In contrast to the control, the MP particles identified as polyamide (PA) in the samples collected during cleaning were found in high abundance at Cage 5 (10.5 particles L^{-1}). The PA MP particles are the fraction most likely to include nylon particles derived directly from the nets. Cage 4 also had a proportionally high fraction of PA particles (0.6 particles L^{-1}) compared to other polymer types and the control samples, while no PA particles were detected in the sample taken at Cage 3. The three control samples all had very low concentrations of MP particles identified as PA (0.0 – 0.05 particles L^{-1}).

The FTIR spectra for PE is dominated by responses from the CH_2 bonds present in the polymer. These CH_2 bonds may also be common to the coating material used on the nets at this aquaculture facility, for example if a wax-based coating has been used. Unfortunately, the specific coating composition on the nets was unknown and so it is not possible to fully attribute the high amount of particles identified as PE particles as being coating particles or actual PE from other sources. Given that the coating is expected to be the component of the net that undergoes the most abrasion during cleaning, it could be expected to see an increase in coating particles in the samples taken during net cleaning relative to the controls.

As with the total MP concentration values, it is hypothesised that the primary reason for the comparatively high number of PA particles found at Cage 5 may have been the lack of lice skirt. Moreover, while the large variation between samples may reflect variability in the sampling technique and the prevailing environmental conditions at the time of sampling (e.g., current direction), the comparatively young age of the coating and the fact that the net had not yet been washed after having been exchanged earlier the same year (more protection provided to the underlying net material by the coating), may also have contributed to the lack of PA particles collected from Cage 3. In comparison, Cages 4 and 5 had nets that had already undergone 8 and 10 cleaning events, respectively. Additionally, Cage 3 was washed for a much shorter period of time than Cages 4 and 5 due to conditions at the time of sample collection, thus reducing the chance of particles being released from the net and subsequently captured.

Overall, these results suggest that pressure washing may contribute episodically to MP emissions, with particles identified as being PE and PA (likely including nylon particles) being prominent in samples collected from Cages 4 and 5 during cleaning. However, it is important to note that the large variation in total MP numbers and polymer type distribution between the limited number of samples that could be collected means that no statistically significant differences in general MP particle composition or PA content were observed between the control samples and the samples collected during cleaning. Operational factors such as the influence of recent net changes or the presence/absence of a lice skirt on individual cages highlights the need to consider site-specific conditions while attempting to assess the risk of MP release during aquaculture net cleaning. Furthermore, detailed knowledge of the coating composition used on specific nets is necessary, ideally with dedicated spectroscopic composition verification for fingerprinting, to ensure that MP polymer type and identification in water samples is robust. Considering the limitations and uncertainties associated with the study performed within SMARTER, these results should be considered as being indicative but would need more detailed assessment for any statistically significant trends to be elucidated.

4.1.4 Service site as potential source for MP

Analysis of the water collected from the filtration unit revealed substantial variation between the four samples. The water in the reservoir supplying the drum washer had a very low particle concentration prior to the addition of fresh seawater (0.08 MP particles L^{-1}; Figure 23). However, following the addition of fresh seawater, the total particle concentration increased significantly to 1.45 MP particles L^{-1}. This rise in MP concentration could be attributed to MP already present in the incoming seawater. Alternatively, the influx of water may have disturbed particles previously settled in the reservoir tank. Since no sample of the fresh seawater was taken for comparison, it is not currently possible to determine the exact cause of the increase in MP.

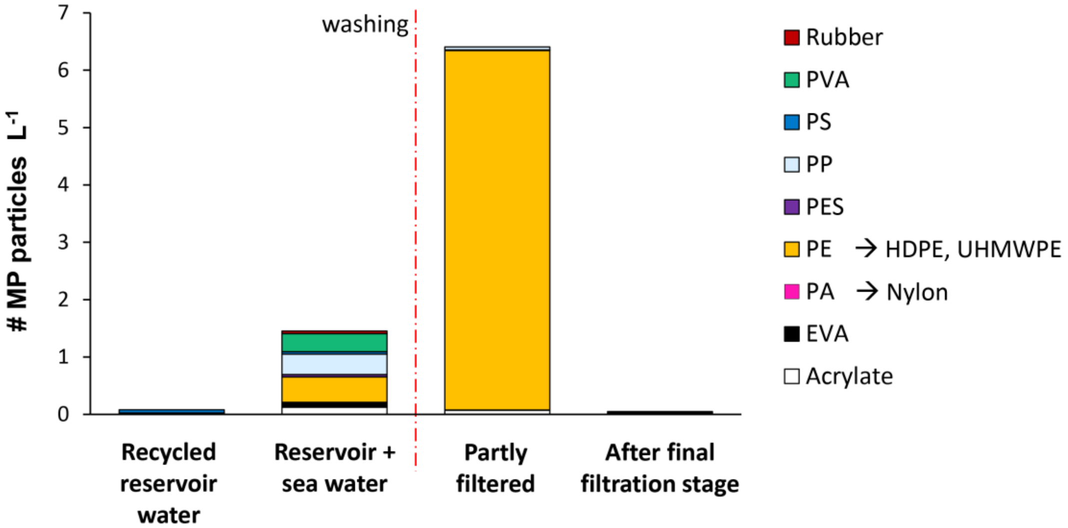


Figure 23: MP particles collected from different stages of the filtration unit associated with the drum washer. Presented data were subjected to blank correction by subtracting the particle count detected in the air-procedural blank.

After net cleaning began, the sample taken from the partially filtered water showed a high concentration of PE particles. However, the net being washed at the time was made of nylon, suggesting that the detected particles likely originated either from the previously washed UHMWPE net or from a cleaner fish shelter being washed in an adjacent unit connected to the same filtration system. The final sample, taken from the filtration unit just before the water was treated with ozone and either recirculated to the reservoir tank or released into the sea, had the lowest measured MP particle concentration—0.05 MP particles L^{-1} (5 particles in a 101 L sample). Given that control samples collected at sea showed average concentrations as high as 18.4 ± 8.6 MP particles L^{-1}, this can be considered a low MP concentration. Although this conclusion is based on a single sample, the filtration system appears to be effective at removing the majority of MP particles ≥10 µm in size.

Information from interviews with service site personnel

Service site personnel consistently reported that net wear is most pronounced just below the waterline and around the bottom of the net. In the upper sections, potential sources of abrasion include contact with the net pen collar, lice skirts, ropes, and chains. Additionally, this part of the net is often subject to heavy biofouling, which necessitates more frequent and intensive cleaning. UV exposure near the surface may also contribute to material degradation. In contrast, wear at the bottom of the net is primarily caused by contact with equipment such as the gyro and the dead fish lift system. If sewn-in equipment is included during drum washing, it may further exacerbate abrasion in all sections of the net.

There is general agreement that the drum washer generates abrasion, although distinct abrasion patterns are difficult to observe. In the absence of detergents, cleaning is achieved by the mechanical action of the net rubbing against itself and the internal structure of the rotating drum. This process removes fouling and coating material and may also affect the underlying net fibres. The degree of abrasion can vary depending on the type of biofouling present. For example, fouling that includes calcifying organisms may increase the abrasive effect. Additionally, copper-based coatings appear to detach more readily during drum washing compared to biocide-free coatings.

4.2 MP release from ropes

The amount of MP released during abrasion testing varied among the rope materials tested (Figure 24). The commonly used polyolefin ropes, as well as the new HDPE and UHMWPE ropes, showed similar and relatively low levels of MP release. In contrast, the rope made with 50% recycled polyolefin released a higher quantity of MP (average 61 ± 13 mg MP). For the polyolefin-based ropes, no significant differences were observed between new and used samples. However, the used UHMWPE rope released more than three times the amount of MP (122 ± 36 mg MP) compared to the new UHMWPE rope (25 ± 3 mg MP) and other rope materials tested. It is important to note that the used UHMWPE rope originated from a coated net in its final season at sea. Visible wear was observed over a length of approximately 35 cm of the tested rope samples.

It must be noted that the recycled rope appeared to be quite brittle, an issue that has been common for early batches of recyclables. Developments in plastic recycling have been progressing very rapidly recently, and even during the months after this rope was produced, the quality of recycled ropes has improved greatly. Such ongoing advances indicate that high quality recycled rope materials can be expected in the near future, with comparable MP release levels to those of 100% virgin polymer materials.

During handling of the used UHMWPE rope, it was found to release a lot of particles that resembled copper coating residuals. Therefore, it is probable that a high proportion of the particles collected originate from the coating rather than the rope material itself. The used UHMWPE rope was also thicker and possibly softer than the new rope, which may also have led to increased abrasion and MP production. Thus, release of MP from the used UHMWPE rope material itself (without coating) cannot be directly compared to MP from new rope, and there is no evidence that the UHMWPE MP release is increasing with use (or the opposite).

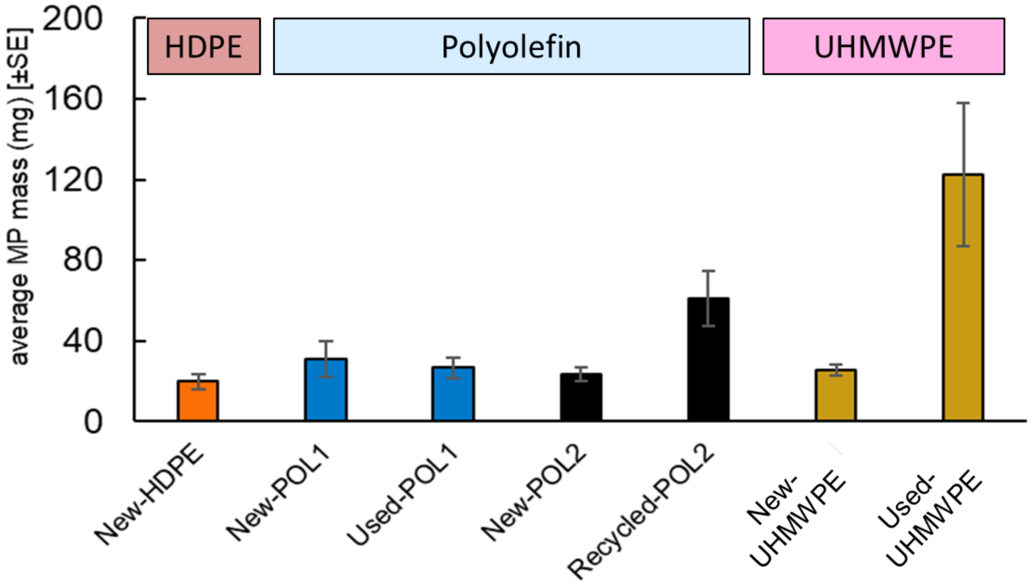


Figure 24: MP release per rope from 5 different new rope materials (including 50% recycled polyolefin), as well as from used polyolefin and UHMWPE ropes.

The tested ropes were primarily standard 'off-the-shelf' ropes, with the exception of the recycled rope that represented an example of a sustainable product entering the market. The ropes used in the study all had different structures, including the lay of the rope, rope thickness and mass per length, fibre geometries and raw material (Figure 10). With such a high number of varying parameters across the different ropes tested, it is impossible to evaluate the effect of specific parameters on MP release. For example, comparing the HDPE rope with the polyolefin1 rope, we see that the HDPE rope is thinner, has thicker fibres, and a lower strength. The results in Figure 24 suggest that the HDPE rope has a slightly lower MP release than many of the other ropes, but it is not possible to point to the parameters(s) that may have caused this. It could be related to the different raw materials, the different rope and fibre thickness, or combination of these factors. To study the effect of the lay of rope or rope thickness, for example, specific tests focusing on varying the selected parameter alone must be performed. Thus, this test conducted in the current study should be considered as a comparison of specific ropes and not rope properties.

Although the project aimed to study a suite of ropes with similar breaking strength, this proved challenging and the final selection of ropes had a strength ranging between 4-9 tons, where the used UHMWPE rope probably exceeded that. In tensile testing of ropes, it is common to add a pretension equal to a small fraction of the breaking load. If this principle were to be followed in the abrasion testing in the current project, the pretension used should have been varied according to the specific rope. As the effect of pretension in abrasion testing is not fully known, however, a pretension of 10 kg was used for all ropes.

Due to the limited number of experimental replicates and the substantial variability within the data, statistical significance could not be established for the results of this study. Nonetheless, the observed trends suggest the presence of discernible patterns in MP release as a function of both rope material composition and rope age (including contributions from coatings). These preliminary findings are valuable as they highlight potential relationships that warrant further investigation. They also provide an important foundation for future research aimed at more rigorous and detailed assessments of MP release dynamics under varying rope characteristics.

Interview service station:

As ropes constitute an integral part of cage nets and are frequently sewn directly into the net bag, they are subject to physical abrasion in spatially similar regions to those identified for the net itself, namely in both the uppermost and lowermost sections of the net. This spatial overlap in exposure suggests that ropes and net materials likely experience comparable mechanical stresses during regular usage and handling. During the net washing stage, there is a procedural distinction made between 'external' ropes and those that are sewn into the net structure. Specifically, ropes that are attached externally to the net are systematically removed prior to the washing process; this practice is implemented to prevent the formation of tangles, which could otherwise complicate or impede the effective cleaning of the net. In contrast, ropes that are permanently sewn into the net cannot be easily detached and therefore remain affixed to the net during the washing procedure. Therefore, these sewn-in ropes are subjected to additional mechanical abrasion caused by the agitation and friction inherent to the washing process, over and above the abrasion they experience during normal use. This differential exposure to abrasive forces is likely to result in a higher degree of physical degradation for the sewn-in ropes compared to their externally attached counterparts. Such findings are significant, as they may influence both the rate and extent of MP release from various net components, as well as the overall structural integrity and functional lifespan of the net. These observations underscore the importance of considering both the placement and method of attachment of ropes when assessing abrasion-related wear and the potential environmental impacts associated with MP emissions from gear.

4.3 Scenarios of MP release

Three qualitative scenarios of MP release from Norwegian aquaculture, each defined by a specific combination of net material, coating strategy, and cleaning regime were made (Table 2). These scenarios are derived from the data and knowledge generated experimentally within SMARTER through the laboratory abrasion tests, accelerated cleaning simulations, and targeted field sampling. Case 1 represents the 'industry standard' scenario with a non-biocidal coated nylon net that is cleaned on a weekly basis by pressure washing. This acts as a reference point for the two other scenarios presented, with differing material choices or cleaning approaches. It is important to note the qualitive nature of these scenarios and that they are derived from data that has varying degrees of uncertainty associated with it. As such, the scenarios should be viewed and interpreted accordingly.

Table 2. Scenario summary.

#	*Polymer (net)*	*Coating*	*Cleaning regime*	*Expected MP-release level**	*Key input from SMARTER*
1	Nylon	Non-biocidal (standard)	Weekly/bi-weekly pressure washing	High	• Nylon released ≈5 × more MP than PE nets • Coating increased MP release • Pressure washing produced the most severe coating damage
2	UHMWPE	None	Weekly/bi-weekly pressure washing	Low	• Uncoated UHMWPE emitted 5x less MP than nylon • Pressure washing did not measurably increase MP concentrations above background values in field trials
3	HDPE	None	Daily AUV brushing	Very low	• HDPE showed the same low MP emission as UHMWPE in lab trials • AUV brushing caused the least coating damage and MP counts in water never exceeded controls.

* The expected release is a qualified estimate based on the SMARTER experiment results

Case 1 – Current industry standard (reference)

Nylon net | non-biocidal coating | weekly pressure washing

In 2022, nylon multifilament nets comprised approximately 67% of new aquaculture nets sold in Norway.[6] Nylon nets remains widely used due to practical and economic advantages. As such, this study retains nylon nets as the reference scenario. Laboratory trials showed that nylon nets released nearly five times more MP particles than polyethylene alternatives. Interviews with service site personnel identified the main areas wear of a net at the net bottom and just below the waterline due to friction from lice skirts, collars, and dead-fish lifts. Weekly high-pressure washing further contributes to material degradation by abrading protective coatings and nylon fibres. Accelerated cleaning tests (70 washer passes, simulating 10 months of wear) showed coating damage on 57% of inspected areas. However, in-situ field sampling rarely detected nylon MP particles above background levels, likely due to existing coastal plastic pollution.

Key insight: nylon offers operational convenience but may yield a higher MP footprint. Unless combined with less abrasive cleaning methods, nylon nets are likely to remain the baseline for MP emissions in open-sea salmon farming.

Case 2 – Stronger netting

UHMWPE net | no coating | weekly pressure washing

UHMWPE offers higher tensile strength and abrasion resistance than nylon, enabling the production of netting and ropes with significantly higher abrasion resistance. In SMARTER's laboratory abrasion trials, uncoated UHMWPE nets released only a fraction of the MP value recorded for uncoated nylon, and the difference was even larger for coated nets. Emissions remained consistently low even with standard or premium coatings, indicating strong coating adhesion and intrinsic fibre durability. However, widespread adoption of UHMWPE is limited by e.g., higher cost as the nets are more expensive than nylon alternatives.

Case 2 represents a material substitution only: no changes to the cleaning or service cycle are needed, yet microplastic emissions are likely reduced compared to Case 1.

Key insight: material choice alone may significantly reduce MP emissions—even before cleaning technologies improve. Nonetheless, broader market uptake will depend on procurement budgets.

Case 3 – New net material and cleaning technology

HDPE net | uncoated | daily AUV brushing

HDPE nets show high abrasion resistance, using thick monofilaments (~1 mm) that probably reduce MP release. Laboratory tests showed MP release similar to UHMWPE and less than nylon. This scenario also involves an innovative cleaning method: autonomous underwater vehicles (AUVs) with soft horsehair brushes provide continuous, low-impact grooming. In accelerated cleaning trials (300 brush passes simulating 10 months of use), microscopy showed minimal fibre damage on HDPE. Water sampling also detected low MP values close to background levels.

Key insight: HDPE nets paired with gentle, frequent cleaning may support a practical pathway for future aquaculture with reduced MP emission. Case 3 illustrates what a next-generation system could achieve as HDPE and AUV technologies are implemented at scale.

4.4 General discussion and conclusions

This study provides key insights into MP release from aquaculture infrastructure, with a primary focus on nets and ropes under laboratory and service-site conditions. Several key patterns emerged from the results, highlighting the influence of material type, coating, age, and operational procedures on MP emissions. The type of net material had a major influence on MP release, with nylon nets emitting significantly more MP than polyethylene-based alternatives (HDPE and UHMWPE). The likely explanation lies in nylon's finer multifilament structure, which is more prone to mechanical wear than the thicker monofilaments in HDPE nets. This confirms existing literature on the superior abrasion resistance of UHMWPE,[17] and underscores the importance of material selection when designing or procuring nets with reduced environmental impact in mind.

Net coatings were also found to interact differently with the base materials, significantly increasing MP emissions from nylon nets, especially with premium coatings. The results suggest poor adhesion of coatings to nylon, likely leading to coating flaking and higher total MP release. In contrast, UHMWPE type 1 nets showed consistent MP emissions regardless of coating, indicating better adhesion and abrasion resistance of the coating on this material. It is also possible that the coating penetrates more deeply into the strands of the UHMWPE net compared to nylon nets, reducing abrasion of the coating. These findings suggest that the efficacy of coatings is not universal and must be evaluated in the context of specific material pairings.

The effect of net age was also apparent. Used nylon and UHMWPE type 1 nets tended to release more MP than their new counterparts, particularly in sections identified as abrasion-prone by service personnel (e.g., just below the surface and at the net bottom). While HDPE nets did not show a significant increase in emissions after use, this may reflect the limited use duration of the sampled nets rather than a generalizable trend. The association between operational wear and MP release highlights the importance of monitoring net condition over time.

In terms of cleaning technology, while particle counts in the water during cleaning were low and often indistinguishable from environmental background levels, microscopy revealed clear differences in coating damage. Pressure and cavitation cleaning caused more severe, localised coating damage, while AUV brushing led to more uniform thinning. These patterns suggest AUV brushing may be less aggressive and could potentially produce smaller MP particles, although this hypothesis requires further validation. Challenges in MP particle sampling in dynamic field conditions—such as background contamination, shifting currents, and uncertain particle drift—further emphasize the need for complementary microscopic and lab-based assessments.

Regarding rope materials, results again showed variability in MP emissions based on material type and usage history. The 50% recycled polyolefin rope released significantly more MP than virgin material ropes and used UHMWPE ropes showed more than triple the emissions of their new counterparts. However, uncertainty remains due to potential coating residues and the limited sample size. Moreover, interviews with service site personnel revealed that sewn-in ropes are exposed to additional mechanical abrasion during net washing compared to externally attached ropes, further exacerbating wear and MP release. This distinction is important for both gear design and operational practices.

Finally, service-site-based MP sampling revealed additional complexities. High MP concentrations were sampled during the filtration process, indicating that cleaning in drum washers indeed leads to the release of MP. As these abundances are impossible to quantify with current sampling techniques, it remains impossible to identify how much MP is released from a net during land-based washing compared to its time at sea. However, sampling further showed that filtration was successful in removing the majority of MP particles before the release of wash water to the sea. Thus, land-based washing is unlikely to directly contribute to MP found at sea.

In summary, this study demonstrates that MP release from aquaculture gear is influenced by a complex interplay of material properties, coating interactions, usage duration, and operational procedures (such as cleaning). While some findings remain preliminary due to sample size limitations, the observed trends provide a strong foundation for improving material selection, net and rope design, cleaning protocols, and monitoring practices in the aquaculture sector. Further research should aim to refine these insights under broader conditions and with standardized methods to support industry-wide strategies for MP emission reduction.

Despite the degree of uncertainty related to some of the studies performed within the SMARTER project, the outcomes have the potential to position the aquaculture industry to take immediate and informed action toward reducing MP emissions. The knowledge generated can be used to directly support producers in identifying optimal combinations of net materials, coatings, rope types, and cleaning technologies that minimise abrasion and MP release. Since the materials and technologies tested are already commercially available, adoption can begin immediately as part of routine investment and replacement cycles, enabling tangible short-term improvements in environmental performance. Over the long term, we hope that SMARTER's baseline emission data will serve as benchmarks for further, targeted knowledge generation, and the development and evaluation of future mitigation strategies and technologies.

4.5 Stakeholder views on knowledge gaps

As part of the SMARTER webinar hosted on 28th May 2025, a Mentimeter survey was conducted with online participants to gauge the current understanding of knowledge gaps related to plastic and MP emission and pollution linked to aquaculture. The survey comprised two main parts:

- Two open questions that aimed to generate opinions from the stakeholder participants
- A series of knowledge gaps proposed by the project team, where the participants were asked to state how much they agreed with each statement.

The two questions that were first posed to the participants were:

1. On microplastics emissions from ropes and nets: What knowledge gaps do you think should be addressed in further research?
2. What other plastic-related issues should be addressed in further research with aquaculture?

The responses to each of the questions are summarised in Table 3 below:

Table 3. Overview of responses to the questions posed to participants at the SMARTER webinar regarding current knowledge gaps.

Question	Participant responses
On microplastics emissions from ropes and nets: What knowledge gaps do you think should be addressed in further research?	Need comprehensive info for choosing nets etc. Including cost benefit
	Better data on actual release of MP from nets and ropes in sea
	The impact of microplastics on the environment
	Origin of the fibres in rope, netting, production process, and quality of the product before it is put into use
	Toxicity/uptake in target organisms, as well as better safety on the amount of emissions
	What about new versus old equipment with regard to MP emissions?
	Methods appear to be a limitation. The challenges of controls vs environmental samples
	Impacts of released microplastics (why does it matter)
	The current trend is towards nets with mixtures of different types of plastic. Is this the way to go in terms of recycling? How should the industry develop products in the future?
	Quantify the fate and transport of gear-derived microplastics in both water column and sediment near farms
	Is it possible to develop plastic-free coatings?
	Actual advice on what is the best net type when it comes to reduce MP
	Life cycle assessments that integrate microplastic emissions across gear production, use, and disposal
	Consequences of anti-fouling and coating also when it comes to chemical release, not only MP
What other plastic-related issues should be addressed in further research with aquaculture?	Reuse
	Recirculation and downstream opportunities on HDPE
	Transfer of aquaculture microplastic from plastic-gears and associated chemicals to the farmed fish
	Analyse the occurrence and risk of lost or "ghost" nets and ropes as macroplastics in production areas
	Effect on farmed fish. Gill health PFAS etc.
	Recycling of ropes, what are the plastic types that are best suited for recycling
	Exploring circular economy solutions for the collection, recycling and reuse of used aquaculture plastic
	Studying bacterial and fungal growth on various plastic materials

In the second part of the survey, the following statements about knowledge gaps were posed to the participants and they were asked to say how much they agreed or disagreed with each statement on a scale from 1 (strongly disagree) to 5 (strongly agree 5):

- A We do not know what the main sources of microplastic are along the production chain of aquaculture products
- B We do not understand how microplastic interacts with aquaculture species
- C We do not know what amounts of microplastic are present in consumer products
- D We have insufficient knowledge about the transfer of plastic additive chemicals from aquaculture infrastructure to fish and the wider environment.
- E We do not understand the risks associated with microplastic exposure and presence in aquaculture species
- F The general public are concerned about microplastic levels in wild caught seafoods
- G The general public are concerned about microplastic levels in farmed seafoods

The results of the survey are presented in Figure 25 below:

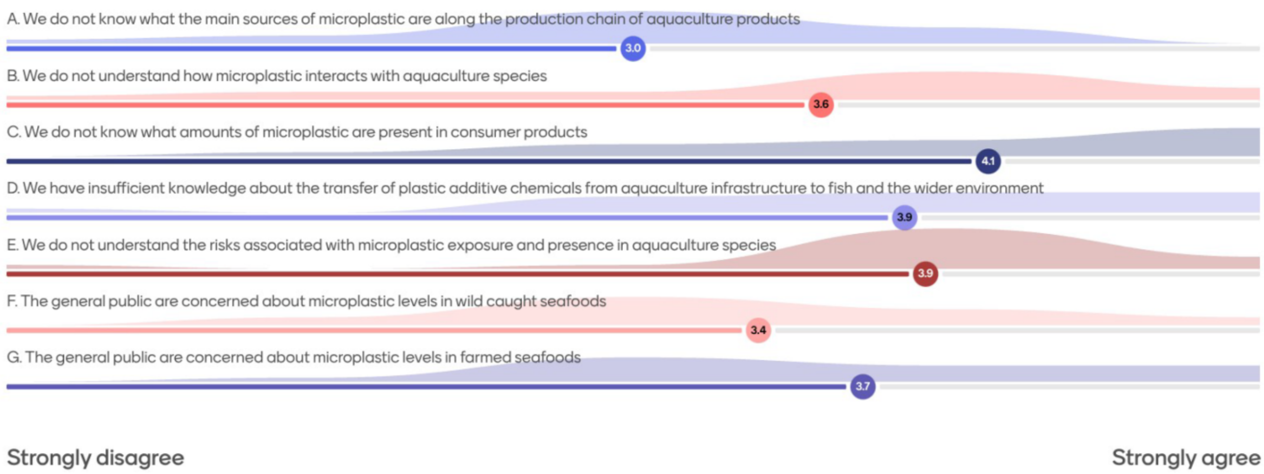


Figure 25. Summary of the responses from participants to knowledge gaps proposed by the project team.

The results showed a general trend where a majority of participants were in agreement with the statements. The specific statement that the participants most strongly agreed with was 'We do not know what amounts of microplastic are present in consumer products' (average score of 4.1/5). In contrast, the statement that the participants agree with the least was 'We do not know what the main sources of microplastic are along the production chain of aquaculture products' (average score of 3.0/5).

5 Main findings and recommendations (should be written in both Norwegian and English)

5.1 Project highlights (English)

- **Nylon nets subjected to regular pressure cleaning may release significantly more MP than polyethylene-based alternatives (HDPE and UHMWPE):** Laboratory abrasion tests showed that nylon nets released nearly five times more MP. Nylon was also more prone to wear, likely due to its thinner multifilament structure compared to the thicker monofilaments used in HDPE nets.
- **Coating Performance Differs Strongly Between Net Materials:** Coatings increased MP release from nylon nets, especially with premium coatings, potentially due to e.g. coating thickness, degree of adhesion, flaking, and/or level of coating absorption into the netting structure. In contrast, coatings on UHMWPE nets did not significantly affect MP release.
- **Alternative net cleaning technologies showed promise:** While high-pressure and cavitation cleaning caused more severe coating damage, AUV brushing resulted in less destructive, more uniform thinning of the coating. However, actual MP particle counts during cleaning with all three technologies were generally low and often indistinguishable from background MP levels.
- **Used nets generally released more MP than new ones:** Older nets may emit higher amounts of MP. Testing indicated that this may be most prevalent in areas prone to abrasion (e.g., just below the waterline and at the net bottom). This trend was especially distinct for nylon and UHMWPE materials. Coating residuals probably had a significant effect on MP amount.
- **Rope material and composition influenced MP release:** Recycled polyolefin ropes emitted more MP than virgin materials. Used UHMWPE ropes also showed higher MP emissions, which was affected by coating residual.

5.2 Recommendations (English)

- It is important for end users of the data generated within the SMARTER project to consider uncertainties associated with the datasets presented within this report. It is also important to note that the data are specific to the combinations of net/rope material and coating, and may differ for other combinations not included in the studies. Furthermore, the industry is diverse, meaning that the results from this work may differ for different anti-fouling strategies (i.e. cleaning and coating strategies).
- The data presented from this study can already be used as an indication for aquaculture facility design and product selection to reduce MP emissions but further testing of additional (and emerging) material and coating combinations, as well as more detailed assessment of cleaning technologies, will make such decision making more robust in the future.
- While SMARTER has provided some strong indications that MP emissions change with the age, degree of usage and degradation level of a net or rope, comprehensive studies are needed to fully understand this complex set of factors and further studies should include assessment of products and materials that are relatively new on the market at this point in time.
- Given the uncertainty with measuring MP emissions during cleaning procedures conducted in the field, combined with background levels of MP that complicate interpretation of the resulting data, it is recommended that dedicated mesoscale assessment is conducted under controlled laboratory conditions in facilities of a suitable size to assess the effect of different cleaning technologies.
- It is suggested that following the same net over a longer period of time (ideally over its usable working life) would provide the best opportunity for gaining an improved and more accurate understanding of general degradation and abrasion of nets and coatings. For example, taking a piece

of the net every time that it is sent for service would allow the evolution of these processes to be followed over relevant timescales.

- Conduct longitudinal studies in operational aquaculture sites to track MP release and concentrations in both water and sediments over multiple seasons and under varying environmental conditions (e.g., UV exposure, temperature, salinity, biofouling). This can help validate laboratory findings and inform emission models. Ideally, this should be done at new aquaculture locations where baseline mapping of MP sediment concentrations can be done before establishment so that changes in MP levels can be assessed during different phases (installation, operation, decommissioning).
- Microscopy is an important support when assessing coatings, as it allows characterisation of the coating abrasion, providing additional information on the kind of damage, including differentiation between coating and fibre damage.
- Integration of MP release data into comprehensive life cycle assessments (LCAs) of aquaculture nets/ropes, including comparison of traditional materials and coatings with innovative alternatives coming on to the market, will help to identify potential trade-offs between performance, durability, cost and environmental impact.
- Assess the economic implications of switching to aquaculture nets/ropes and cleaning technologies that can lower MP emission, including cost-benefit analyses for producers and potential market incentives.

5.3 Prosjekthøydepunkter (Norsk)

- **Nylonnøter som utsettes for regelmessig høytrykksspyling kan frigjøre betydelig mer MP enn polyetylenbaserte alternativer (HDPE og UHMWPE):** Slitasjetester utført i laboratoriet viste at nylon notlin frigjorde nesten fem ganger mer MP. Nylon var mer utsatt for slitasje, sannsynligvis fordi notlinet består av svært tynne fiber (multifilament), i motsetning til tykkere monofilamentene som brukes i HDPE-nett, og har lavere slitasjemotstand enn UHMWPE.
- **Coatingens funksjon varierer for forskjellige notlinmaterialer:** Coating førte til økt mengde MP fra nylon notlin, spesielt ved bruk av premium coating, potensielt på grunn av tykkelsen til påført coating, grad av vedheft, avflassing, og i hvilken grad coatingen absorberes i notlinet. I motsetning til dette påvirket ikke coating av UHMWPE-notlin mengden MP som ble frigjort.
- **Alternative gjøringsteknologier viste lovende resultater:** Mens høytrykks- og kavitasjonsrengjøring forårsaket betydelig skade på coatingen, var AUV-børsting mindre destruktiv og ga en mer jevn fortynning av belegget. Antall MP-partikler som ble samlet opp under rengjøring var imidlertid lavt og ofte umulig å skille fra bakgrunnsnivåer av MP.
- **Brukte nett slapp generelt ut mer MP enn nye:** Brukt notlin kan produsere høyere mengder MP. Testing indikerte at dette kan være mest utbredt i områder som er utsatt for slitasje (f.eks. rett under vannlinjen og i bunnen av nota). Denne trenden var spesielt tydelig i nylon- og UHMWPE-materialer, hvor også rester av coating eller impregnering ga betydelige bidrag til MP-nivåene.
- **Taumateriale og -sammensetning påvirket MP-utslipp:** Resirkulerte polyolefintau slapp ut mer MP enn jomfruelige materialer. Brukte UHMWPE-tau ga også høyere MP-utslipp, noe som var påvirket av partikler fra coating.

5.4 Anbefalinger (Norsk)

- Det er viktig at sluttbrukere av data som genereres i SMARTER-prosjektet vurderer usikkerheter knyttet til datasettene som presenteres i denne rapporten. Det er også viktig å merke seg at dataene er gyldige for testet notlin, taumateriale og coating, og resultatene kan variere for andre kombinasjoner som ikke er inkludert i studiene. Videre er bransjen mangfoldig, noe som betyr at resultatene fra dette arbeidet ikke nødvendigvis er gyldige for alle begroinshindrende tiltak (rengjøringsstrategier og coating/impregnering).

- Dataene som presenteres fra denne studien kan allerede brukes som en pekepinn for design av akvakulturanlegg og produktvalg for å redusere MP-utslipp, men ytterligere testing av andre (og nye) kombinasjoner av material og coating, samt mer omfattende vurdering av rengjøringsteknologier, vil gjøre slik beslutningstaking mer robust i fremtiden.

- Selv om SMARTER har gitt noen sterke indikasjoner på at MP-utslipp endres med alder, brukstid og aldringsgsnivå til et nett, er det behov for omfattende studier for å forstå dette komplekse settet med faktorer fullt ut, og ytterligere studier bør inkludere vurdering av produkter og materialer som er relativt nye på markedet på dette tidspunktet.

- Gitt usikkerheten knyttet til måling av MP-utslipp under utførte rengjøringoperasjoner i felt, kombinert med bakgrunnsnivåer av MP som kompliserer tolkningen av de resulterende dataene, anbefales det at dedikert mesoskalavurdering utføres under kontrollerte laboratorieforhold i anlegg av passende størrelse for å vurdere effekt av ulike rengjøringsteknologier.

- Den beste metoden for å få en forbedret og mer nøyaktig forståelse av generell nedbrytning og slitasje av notlin og coating kan være å følge den samme nota over en lengre periode (ideelt sett over hele dens levetid) . For eksempel vil det å ta en prøve av notlinet hver gang nota sendes til service gjøre det mulig å følge utviklingen av aktuelle prosesser over tid.
- Det bør gjennomføres studier i operative akvakulturanlegg for å spore MP-utslipp i både vannog sediment over flere sesonger, og under varierende miljøforhold (f.eks. temperatur, salinitet, biologisk begroing). Dette kan bidra til å validere laboratoriefunn og forbedre utslippsmodeller. Ideelt sett bør dette gjøres på nye akvakulturanlegg der kartlegging av MP-konsentrasjoner i sedimentene kan gjøres før etablering, slik at endringer i MP-nivåer kan vurderes i løpet av ulike faser (installasjon, drift, brakklegging/avvikling).

- Mikroskopi er et viktig hjelpemiddel ved vurdering av coating, ettersom det muliggjør karakterisering av coatingslitasje og gir ytterligere informasjon om type skade, inkludert differensiering mellom belegg- og fiberskade.

- Integrering av MP-utslippsdata i omfattende livssyklusanalyse (LCA) av notlin og tau, inkludert sammenligning av tradisjonelle materialer og coating med innovative alternativer som kommer på markedet, vil bidra til å identifisere potensielle avveininger mellom ytelse, holdbarhet, kostnad og miljøpåvirkning.

- Vurdere de økonomiske implikasjonene av å bytte til notlin, tau og rengjøringsteknologier som kan redusere MP-utslipp, inkludert kost-nytte-analyser for produsenter og potensielle markedsinsentiver.

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7 Deliverables

The following table contains a detailed overview of all deliverables in the project, including their status at the time the report was submitted.

D#	Date Due	Description	Status
D1	04.2023	Physical start-up meeting with the reference group and project staff (RG1)	Completed
D2	04.2023	Minutes from start-up and RG1 meeting, work plan for the first half of the project (M1-M12; See Gantt)	Completed
D3	06.2023	Media resource pack completed and distributed to project team members for use	Completed
D4	06.2023	Dedicated project webpage hosted on SINTEF or NCE Aquatech website online	Completed
D5	10.2023	Digital status and update meeting with reference group (RG2), short minutes provided afterwards	Completed
D6	10.2023	1st 6-monthly status report to FHF	Completed
D7	04.2024	Physical reference group meeting (RG3)	Completed
D8	04.2024	Minutes from RG3 meeting and work plan for the second half of the project (M13-M24; See Gantt)	Completed
D9	04.2024	2nd 6-monthly status report to FHF	Completed
D10	10.2024	Digital status and update meeting with reference group (RG4), short minutes provided afterwards	Completed
D11	10.2024	3rd 6-monthly status report to FHF	Completed
D12	05.2025	Stakeholder webinar event	Completed
D13	05.2025	Physical final meeting with the reference group and project staff (RG5), presentation of final report draft and feedback for revisions	Completed
D14	05.2025	Minutes from RG5 meeting and list of revisions to be made to the final report	Completed
D15	06.2025	Final report completed and submitted to FHF	Completed
D16	06.2025	Open access publication submitted to peer-review journal	To be completed
D17	06.2025	Administrative report completed and submitted to FHF (financial reporting)	To be completed
D18	06.2025	Popular science summary/fact sheet published on the SMARTER webpage	Completed