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Report

Testing of novel net cleaning technologies for finfish aquaculture

Results from WP 2 of the NOTVASK project

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ABSTRACT

To avoid negative impacts on fish production caused by biofouling development, aquaculture nets around the world are periodically cleaning using high-pressure washers. Net cleaning is labour-intense and costly, can damage antifouling coatings on nets, and poses contamination as well as fish health and welfare risks. To support environmental sustainability of the growing aquaculture sector, novel net cleaning methods are needed. This study examined low-pressure-, cavitation-, and suction-based cleaning technologies as alternatives to conventional high-pressure cleaning. Using field experiments, cleaning efficacy, cleaning waste generation, and the impact of cleaning on coating integrity and net strength were evaluated. Cavitation and high-pressure cleaning achieved considerably higher cleaning efficacy than low-pressure and suction cleaning. However, a single high-pressure treatment caused up to 53% coating degradation, compared to 2% for cavitation. All cleaning technologies produced similar cleaning waste and neither reduced net strength significantly. This study identifies cavitation cleaning as promising technology for biofouling control on aquaculture nets.

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APPENDICES

1 Introduction

The growth of biofouling such as algae, hydroids, and mussels on production nets and other submerged infrastructure is a serious challenge in finfish aquaculture (Fitridge et al. 2012). If not controlled, biofouling can have a variety of negative impacts on both the fish and the infrastructure, including reduction of water quality, cage volume and stability, increased disease risk due to associated pathogens, and impacts on behaviour of cleaner fish used as biological sea-lice control agents (Eliasen et al. 2018, Fitridge, et al. 2012, Imsland et al. 2015, Kvenseth 1996).

In the salmon industry, biofouling is mainly controlled by frequent in-situ net cleaning using high-pressure washing rigs. The rigs are equipped with rotating disks, each having three to four nozzles from which water is expelled. The water is supplied with up to 350 bar pressure from on-board pumps on an adjacent support vessel. Water velocity at the net is essential for the cleaning efficacy and varies based on number of nozzles, nozzle diameter, hose length, and hose diameter. While moving along the inside of the net, the cleaner removes biofouling organisms from the net and releases them and their fragments as cleaning waste into the water (Carl et al. 2011).

Cleaning rigs are commonly attached to a crane or remotely operated vehicle, or feature inherent propulsion. Usually, a support boat and crew of two people are needed to deploy and steer the unit. In Norway, net cleaning is commonly conducted pre-scheduled every two weeks (Bloecher et al. 2015) and during peak biofouling season sometimes every five days. The main driver for this high cleaning frequency is the use of cleaner fish (Ballan wrasse and lumpsucker), employed as biological control agents against salmon lice (*Lepeophtheirus salmonis*), the biggest health challenge in farming of Atlantic salmon (*Salmo salar*) (Hjeltnes et al. 2019). While cleaner fish do feed on salmon lice, their natural diet also includes biofouling organisms (Imsland, et al. 2015, Kvenseth 1996). This led to the widely accepted assumption throughout the industry that nets need to be free of biofouling to ensure optimal cleaner fish performance, despite recent scientific evidence against this correlation (Eliasen, et al. 2018, Leclercq et al. 2018).

In addition to net cleaning, Scotland and especially Norway often impregnate nets with antifouling coatings containing copper to delay the onset of biofouling (Edwards et al. 2014, Floerl et al. 2016) and thus reduce the number of cleaning operations needed during a grow-out phase. However, after cleaning a coated net for the first time, farmers report that biofouling occurrence intensifies, necessitating cleaning with a frequency equal to uncoated nets.

Besides being labour-intense and costly in terms of money and energy consumption, net cleaning also poses several risks to the fish, the infrastructure, and the environment (reviewed in detail in Floerl, et al. 2016). These include impacts on fish health through contact with released biofouling particles, resulting in gill damage (Baxter et al. 2012, Bloecher et al. 2018) and the increased risk for infections with pathogens associated with biofouling organisms (Hellebø et al. 2016, Pietrak et al. 2012). Furthermore, farmers frequently report incidents where net cleaning led to damage of the net. A recent study showed that the cause for this damage is either incorrect use and insufficient maintenance of net cleaning equipment, or the presence of other cage elements (eg ropes) that increase the friction of the net cleaner's rotating discs on the net (Moe Føre and Gaarder 2018). It is thought that 85% of antifouling coatings applied to production nets are released into the sea due to leaching and abrasion in connection with net cleaning (caused by water jets and contact with the cleaner) (Skarbøvik et al. 2017). This contributes to environmental pollution and endangers non-target organisms (Fitridge, et al. 2012, Guardiola et al. 2012). As a result, high-pressure cleaning of copper coated nets is prohibited in many countries (Floerl, et al. 2016) as well as for all sites certified under the Aquaculture Stewardship Council (ASC) salmon standard (Aquaculture Stewardship Council 2017).

As an alternative to high-pressure cleaning, low-pressure cleaning is employed at some farms. Here, water pressure at the topside water pump is reduced to as low as 50 bar, while water flow can simultaneously be increased. A true definition or distinction from high-pressure cleaning, as well as an independent assessment of this technology are currently lacking.

Aquaculture is a growing global industry (Food and Agriculture Organization of the United Nations 2018) and Norway plans to increase production to an annual five million tons by 2050 (Olafsen et al. 2012). There is an expectation that growth in production will be paralleled by increased environmental sustainability both for the Norwegian and international industry (ASC standard; Aquaculture Stewardship Council 2017). This necessitates better solutions for biofouling control. One avenue for this is the development of novel net cleaning equipment that is at least as efficient as high-pressure cleaning but reduces impacts on fish health, antifouling coatings and net integrity. This study compared three emerging cleaning technologies - low-pressure cleaning, cavitation-based cleaning and suction-based cleaning - to high-pressure cleaning (the current *status quo*). Low-pressure cleaning, if able to remove biofouling effectively, might reduce premature degradation of antifouling coatings. Cavitation cleaning is already employed successfully for the cleaning of solid surfaces such as boat hulls (Albitar et al. 2016, Morrisey and Woods 2015) and has the potential to reduce the energy consumption needed for biofouling removal from pen nets. Suction cleaning would have the advantage of collecting the released cleaning waste, eliminating many of the disadvantages of high-pressure cleaning. The comparison was conducted using uncoated nets and nets coated with two different antifouling coatings to examine cleaning efficacy, cleaning waste composition, and impacts on net strength and coating abrasion.

2 Materials and Methods

2.1 Cleaning technology and net material

High- and low-pressure cleaning rely on the velocity and volume of expelled water (drag forces) to remove biofouling organisms from the net. For the experiments, cleaning was conducted using a commercial cleaning rig with six disks in a single row spanning a width of 2.6 m. Each disk had a diameter of 39 cm and four jet nozzles with an opening of 0.9 mm in diameter. To avoid strips of uncleaned net between the disks, the rig was operated at a 29° angle (to the horizontal plane) to create slight overlap between the disks, leading to a cleaning result similar to rigs where disks are aligned in two offset rows. The associated 147 kW pump delivered a maximum pressure of 300 bar through a 30 m hose with an inner diameter of 1.9 mm. It was operated at 220 bar for high-pressure cleaning and at 80 bar for low-pressure cleaning, delivering an approximate water volume of 220 L min^{-1} and 140 L min^{-1}, respectively.

Cavitation cleaning relies on energy released from imploding air bubbles generated by high-pressure water jets to remove biofouling organisms from the net (Kalumuck et al. 1997). For the experiments, cleaning was conducted using a single-disk unit with two rotating nozzles (CaviDome 1222 unit, CaviDyne, modified by

PSO) operated with a 16 kW pump that delivered 46 L min^{-1} at 152 bar per nozzle. The unit had a diameter of 32 cm, resulting in an observed effective cleaning area of 90 cm in diameter.

Suction cleaning relies on the velocity and volume of the intake water (drag forces) to remove biofouling organisms from the net. For the experiments, cleaning was conducted using a prototype system developed by SINTEF. The system featured a cleaning 'box' with a 58 cm x 0.75 cm opening, connected to a suction pump with a capacity of 360 – 540 L min^{-1}.

Net cleaning was conducted vertically at a speed of approximately 0.3 m s^{-1} relative to the net. The four cleaning technologies were applied to uncoated nets, as well as nets coated with either of two different antifouling coatings. Nets were commercial Raschel-knitted nylon smolt nets with a half mesh of approximately 14 mm. The coatings included in the test were commercial antifouling coatings Notorius A and Notorius 3 (Brynsløkken AS). Notorius A is a classic copper-based coating while Notorius 3 in addition to copper contains the booster biocide copper pyrithione and is designed to require less abrasive cleaning (ie lower water pressure).

2.2 Experimental design

Net cleaning, using the four cleaning technologies, was conducted on custom-built frames featuring net panels to provide experimental net cage surfaces. For high- and low-pressure cleaning rig, a 5 m x 7 m steel frame was used (Fig. 1). The frame was suspended from a crane to enable deployment and retrieval. Heavy weights at the corners along with mooring ropes were used to stabilise the frame in the water. For the cavitation and suction cleaning experiments, a holding scaffold for the cleaning units was built (Fig. 2). A net was stretched across a holding frame (2 m x 0.7 m) that could be moved past the cleaning unit without direct physical contact. The scaffolding was fixed to a dock from where the pump systems were operated. For both frame systems, nets were attached using cable ties. Net tension was evaluated by aquaculture professionals to resemble cage nets. The performance of the cleaning units was evaluated in two experiments. Experiment 1 examined cleaning efficacy and cleaning waste; Experiment 2 examined the impact of cleaning on coating integrity and net breaking strength.

Experiment 1. Net samples (0.5 m x 0.5 m) were deployed at two commercial salmon farm sites (Espeneståren and Edøya; Mid-Norway) to develop biofouling. Samples with antifouling coating were deployed earlier to compensate for the delay in colonisation (Table 1). Biofouling growth was monitored by regular visual assessment of the samples. During the individual experiments conducted over the course of two years, samples were randomly allocated to treatments (see supplement Table S1 for details on replicate numbers).

Table 1: Overview of the deployment times of biofouling samples and the time plan for the respective experiments.

Cleaning method	Net material	Sample immersion	Experiment conducted	Sample age
High/Low pressure	Coated	05.07.2016	06.10.2016	13 weeks
	Uncoated	05.10.2016	18.11.2016	6 weeks
Cavitation/Suction	Coated	14.07.2017	10.10.2017	12 weeks
	Uncoated	21.08.2017	10.10.2017	7 weeks

Cleaning efficacy was assessed by measuring biofouling wet weight on nets before and after cleaning and calculating the percentage of removed biofouling. For the high- and low-pressure cleaning trials, fouled samples (n = 6) were fit into three 'windows' cut into the net within the experimental steel frames (Fig. 1). The cleaner was guided over each sample once (down and up). For the cavitation and suction tests, samples (n = 6) were fit into similar 'windows' within experimental net frames before they were passed before the cleaner once (down and up; Fig 2).

To collect the cleaning waste released during washing, a custom-made plankton net (0.5 m diameter, 1.5 m length, 150 µm mesh; Hydrobios, Germany) was fixed behind four of the six replicates (Fig. 1). In case of suction cleaning, the water passing through the suction pump was filtered through the plankton net. The collected cleaning waste particles were stored in seawater with 10% formalin. For analysis, samples were rinsed in freshwater to remove formalin before sorting them into three categories using a dissecting microscope:

(1) Colonies of intact hydroid polyps. These were further split into four categories according to polyp length (≤20 mm vs. >20 mm) and colony clump size (≤10 polyps vs. >10 polyps).
(2) Particles (entire biofouling organisms and fragments thereof) ≥2.4 mm, and
(3) particles <2.4 mm.

The abundance of particles belonging to the individual categories was counted for particles ≥2.4 mm, and estimated as percent proportion for particles <2.4 mm. Total dry weight was measured for all three groups by collecting the particles onto pre-weighed GF filters (Whatman) or into porcelain cups and drying them for 24 hrs at 60°C. In addition to biological material, the size and abundance of coating particles was recorded. Since it was not possible to evaluate the total capture rate of particles during net cleaning, cleaning waste composition is presented as proportion of collected material.

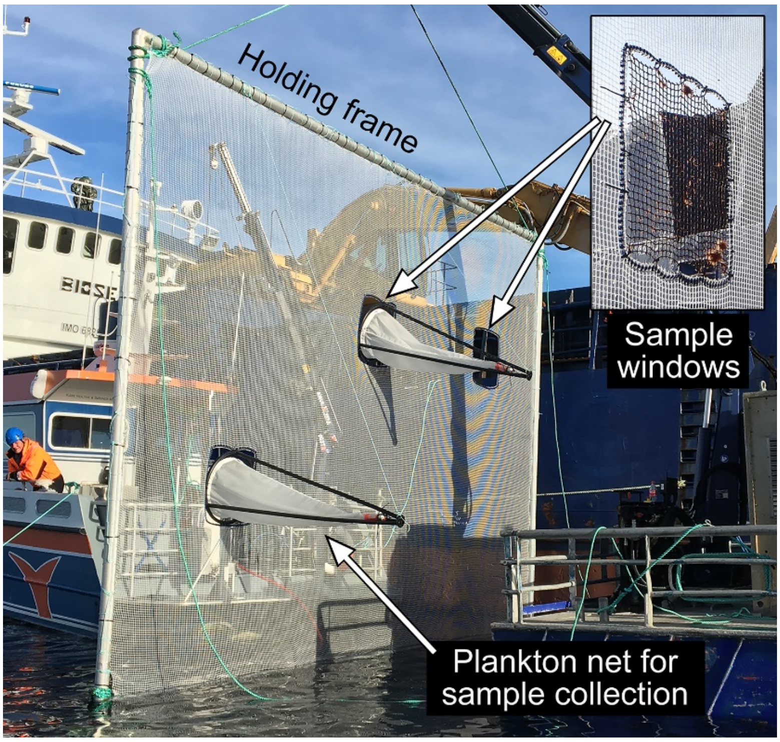

Figure 1: Experimental set-up for high- and low-pressure cleaning consisting of a steel frame holding a net sample. For testing of biofouled samples, smaller nets were attached in 50x50 cm 'windows' behind which plankton net cones could be secured to collect net cleaning waste.

Experiment 2. Coating integrity and net strength were assessed after nets were washed once (passed by the net cleaner on a downward and upward path) or 35 times (the maximum number of net cleaning events during a production cycle reported by fish farmers in a survey conducted prior to the experiments (SINTEF, unpubl. data)). Prior to the experiment, the coated nets were strung out on a rope and submerged at Bremvågen, Dolmøya, for four weeks to allow the coating to be thoroughly wetted yet not become fouled. The uncoated nets were immersed for 24 hrs before the experiments.

For high- and low-pressure washing, three replicate nets (6 m x 7 m) per coating type (Notorius A, Notorius 3, Uncoated) were spanned across the steel frame (Fig. 1). Overhanging net material was cut off and served as an unwashed control sample. Each net was divided into four areas that were then cleaned either once or 35 times using high or low pressure. For cavitation and suction cleaning, three replicate nets (1.2 x 0.6 m) per coating type (Notorius A, Notorius 3, Uncoated) and cleaning frequency (1x or 35x) were examined. Before cleaning took place, a sample was taken from each net piece as an unwashed control (see supplement Table S1 for details on replicate numbers)

After washing, four samples of 8 x 17 mesh openings were cut out of the path of the net cleaner and from the unwashed control net. Samples were labelled, air dried, and cut into two quadratic samples (8 x 8 mesh openings), before they were stored individually in plastic bags. One sample was used for analysis of net strength and the other for the analysis of coating integrity.

To analyse net strength, the mesh breaking force (N) of each sample was measured in five individual mesh openings of the wet net sample in accordance with ISO 1806 (International Organization for Standardization (ISO) 2002) with grips placed at two opposing net joints. The five measurements were averaged to calculate the average mesh breaking force for each of the four samples collected from each of the three net replicates. These values were then compared to the respective unwashed control samples. Samples washed only once, or with low-pressure, were not included in this analysis since data from previous experiments showed no effect of intense high-pressure net cleaning on net strength (Moe Føre and Gaarder 2018). This also indicated that low-intensity treatments were unlikely to lead to damage. Samples from the two treatments were stored in case initial examination of high-pressure cleaned samples contradicted the earlier study.

To analyse coating integrity, the washed side of every sample was photographed against a black background using a Nikon D800E 36 MP camera equipped with a 105 mm Sigma lens with crossed polariser and a polarised front illumination/flash. The RAW images were corrected for uniformity, distortion, and white balance in Adobe Lightroom and converted to JPEG before the final analysis was conducted using a LabVIEW-programme. After identifying the total net area, the programme calculated a score for the amount of intact red coating per net surface area based on a threshold of the ratio of blue and red information in the image. By comparing the scores to a baseline of unwashed fully coated nets and uncoated white nets, an approximation of the area (%) of intact coating with a corresponding area of damaged coating (flaked or entirely removed) could be calculated for each sample. These values were normalised to the respective unwashed control samples.

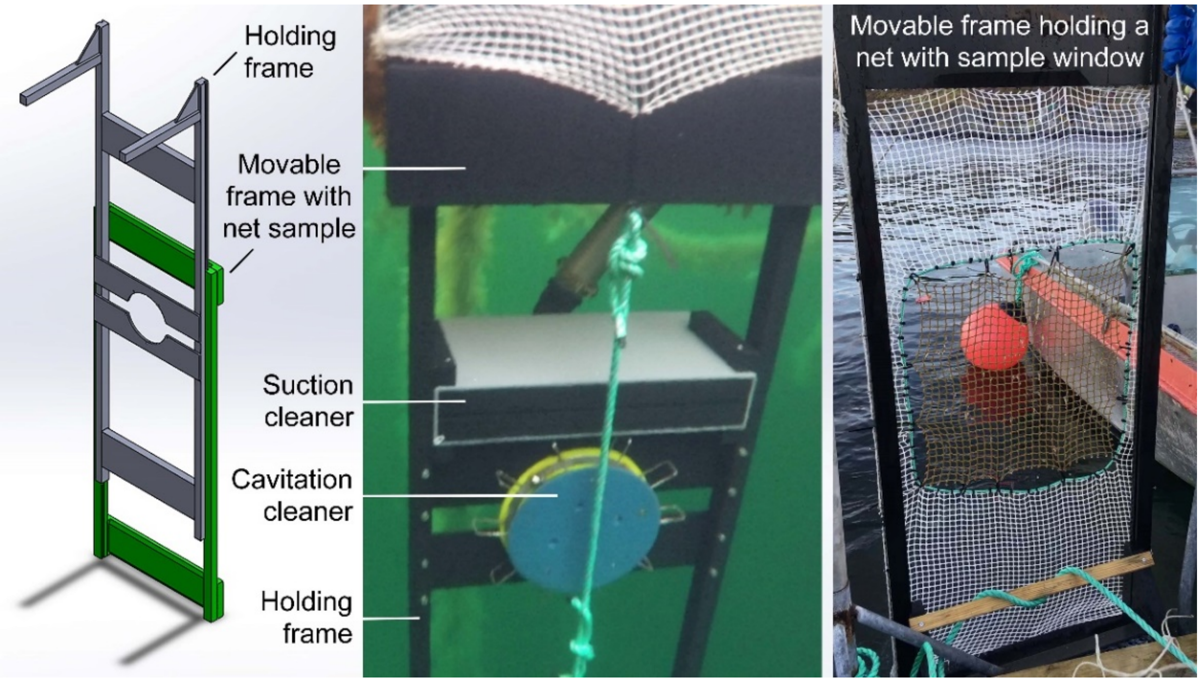

Figure 2: Experimental set-up for cavitation and suction cleaning consisting of a holding frame to which either of the two cleaning units could be attached, and a movable frame to hold a net sample (with or without sample window for biofouled samples), which could be moved past the cleaning unit.

2.3 Statistical analyses

The effects of cleaning and coating on cleaning efficacy, coating particles, net strength, and coating integrity were analysed using permutational analysis of variance (PERMANOVA, Primer v.7). The univariate analyses with the factors listed in Table 2 were conducted using Euclidean distance based on 9,999 unrestricted permutations of residuals under a reduced model with a significance level of 5%. Where the number of unique permutations was <100, the Monte-Carlo asymptotic pMC-value was consulted. If not indicated otherwise, values are presented as average ±1 Standard Error (SE). (Detailed statistical results can be found in the supplements)

Table 2: Overview of the factors considered in the permutational analysis of variance for the individual experiments

Experiment	Factors	Levels	
Cleaning efficacy	Cleaning technology	4 (High pressure, Low pressure, Cavitation, Suction)	Fixed
	Coating	3 (Notorius A, Notorius 3, Uncoated)	Fixed
Coating particles	Cleaning technology	4 (High pressure, Low pressure, Cavitation, Suction)	Fixed
	Coating	3 (Notorius A, Notorius 3, Uncoated)	Fixed
	- Contrast 1	- Coated vs. Uncoated nets	
Net strength (High pressure)	Cleaning	2 (High pressure, No cleaning)	Fixed
	Coating	3 (Notorius A, Notorius 3, Uncoated)	Fixed
	Net (Coating)	3*	Random, nested
Net strength (Cav/Suc)	Cleaning	3 (Cavitation, Suction, No cleaning)	Fixed
	- Contrast 1	- Cavitation vs. Unwashed control	
	- Contrast 2	- Suction vs. Unwashed control	
	Coating	3 (Notorius A, Notorius 3, Uncoated)	Fixed
	Net (Coating)	3	Random, nested
Coating integrity	Cleaning technology	4 (High pressure, Low pressure, Cavitation, Suction)	Fixed
	Coating	2 (Notorius A, Notorius 3)	Fixed
	Frequency	2 (1x, 35x)	Fixed
	Net (Coating)	3	Random, nested

*High-pressure cleaning of uncoated nets was conducted for two replicates

3 Results

3.1 Cleaning efficacy

Biofouling community composition was similar on all samples (coated and uncoated) and consisted mainly of the hydroid *Ectopleura larynx*. Average biofouling accumulation varied considerably between samples used in the high- and low-pressure tests (mean = 207 g) and the cavitation and suction tests (647 g), as well as between coating types (uncoated: 564 g, Notorius A: 448 g, Notorius 3: 269 g; supplement Fig. S1).

Cleaning efficacy differed significantly between cleaning technologies and with coating type (Cleaning technology x Coating: $F_{6,60}$= 12.71, p<0.001). On uncoated nets, high-pressure cleaning performed best, removing on average 77% of the biofouling (Fig. 3), followed by cavitation cleaning (47%). On nets coated with Notorius 3, the order was reversed, with cavitation removing most biofouling (81%), followed by high-pressure cleaning (61%). On nets coated with Notorius A, high-pressure and cavitation cleaning had similar efficacy (58% and 65%, respectively; Fig. 3). Low-pressure cleaning performed significantly poorer on all three net types with a maximum efficacy of 39%. Suction cleaning had the weakest performance on all coating types with a maximum efficacy of 13% (Fig. 3; pairwise comparison, p<0.05).

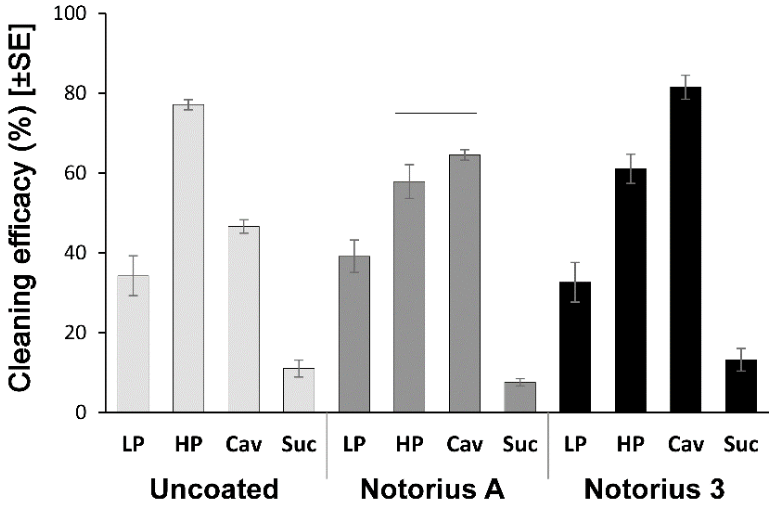

Figure 3: Cleaning efficacy (± SE) of low pressure (LP), high pressure (HP), cavitation (Cav), and suction (Suc) cleaning on uncoated nets and nets coated with Notorius A and Notorius 3. Pairwise tests (conducted within 'Coating') identified significant differences between all pairs, except HP vs. Cav on Notorius A (indicated by a horizontal bar).

3.2 Cleaning waste

Cleaning waste consisted on average of 88% hydroids, dominated by *E. larynx* colonies. The size distribution of the collected waste was similar for low- and high-pressure cleaning, with the smallest particles (<2.4 mm) and the hydroid colonies taking up approximately equal proportions while particles ≥2.4 mm were slightly less abundant (Fig 4a).

Cavitation cleaning produced a larger variation in particle size distribution where fewer intact hydroid colonies were washed off uncoated nets, and most off nets coated with Notorius 3. The other two particle categories were represented at approximately equal proportions (Fig 4a). Cleaning waste collected during suction cleaning consisted mainly of particles <2.4 mm and contained very few intact hydroid colonies. Colonies were collected from uncoated samples and samples coated with Notorius 3, yet not from samples coated with Notorius A (Fig. 4a). In general, more intact hydroid colonies were washed off coated nets than off uncoated nets. In contrast, washing uncoated nets released more particles ≥2.4 mm. When comparing removal of intact hydroid colonies (Fig. 4b), cavitation had the highest rate of removal of colonies consisting of large polyps. While high-pressure cleaning was able to remove such colonies, low-pressure and suction could only remove hydroid colonies with smaller polyps.

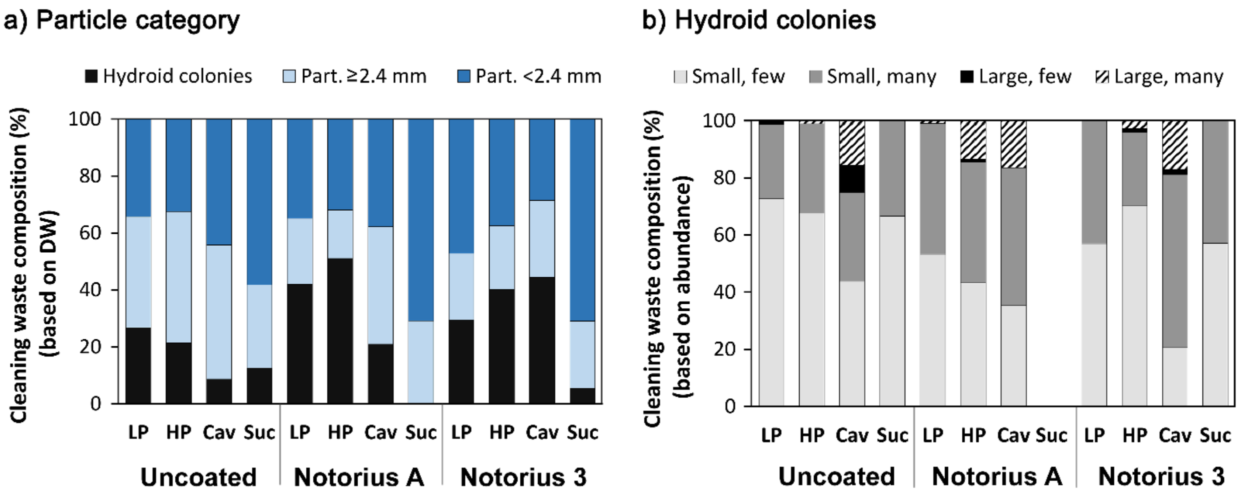

Figure 4: Overview of collected cleaning waste for the four tested cleaning technologies low pressure (LP), high pressure (HP), cavitation (Cav), and suction (Suc), for uncoated nets and nets coated with Notorius A or Notorius 3. Samples were analysed with regard to (a) composition based on dry weight (DW) for three categories: 'hydroid colonies' of *Ectopleura larynx*, particles ≥2.4 mm, and particles <2.4 mm; and (b) abundance of collected hydroid (*E. larynx*) colonies categorised based on polyp length (≤20 mm vs. >20 mm) and colony clump size (≤10 polyps vs. >10 polyps). Cleaning waste collected during suction cleaning of nets coated with Notorius A did not contain hydroid colonies. (For details on the species composition of the cleaning waste other than hydroid, please see Figures S2 and S3 in the supplements.)

The cleaning waste material contained coating particles of a size of 0.05 to 2 mm. Particle abundance differed significantly between cleaning technologies and coatings (Cleaning technology x Coating: $F_{6,36}$=4.45, p=0.001), although distribution was very patchy (Fig. 5). Most particles were found after high-pressure cleaning of coated nets (up to 51.5 particles per g DW; pairwise comparison, p<0.05). In contrast, coating particle abundance did not significantly differ between the other three cleaning technologies (pairwise comparison, p>0.05, Fig. 5). While cleaning of coated nets led to the collection of significantly more coating particles (contrast: Coated vs. Uncoated nets: $F_{3,36}$=4.28 p=0.011), they were also identified in cleaning waste washed off uncoated nets (up to 8.4 particles per g DW, Fig. 5).

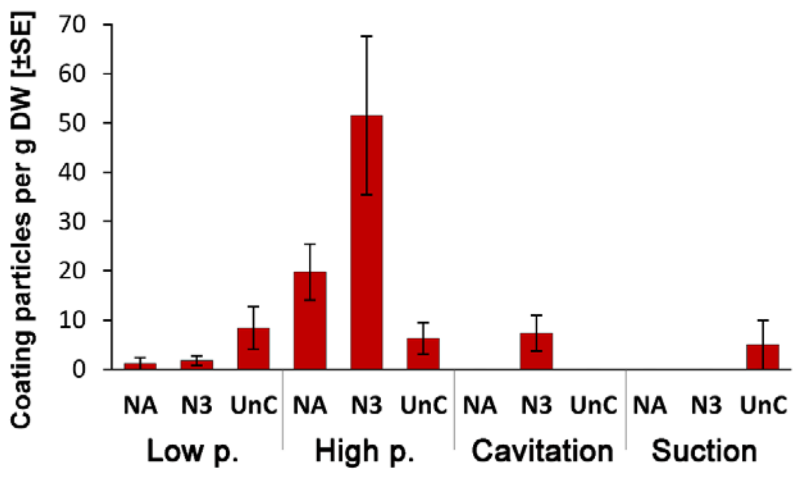

Figure 5: Number of coating particles per g dry weight of cleaning waste collected from samples coated with Notorius A (NA), Notorious 3 (N3), or without coating (UnC), washed with low pressure (Low p.), high pressure (High p.), cavitation, and suction.

3.3 Net strength

The mesh breaking force of unwashed nets was on average 20% and 28% lower in coated samples than in uncoated samples for the high-pressure and cavitation/suction experiments, respectively (High-pressure: Uncoated: 883 N, Notorius A: 705 N, Notorius 3: 707 N; Cavi/Suc: Uncoated: 942 N, Notorius A: 674 N, Notorius 3: 677 N). Average mesh breaking force of nets washed 35 times deviated from unwashed control nets by -0.3% to 4.9% (Fig. 6). High-pressure cleaning significantly increased average mesh breaking force compared to unwashed control nets, though not uniformly for all coatings and nets (NetCleaning x Net(Coating) $F_{5,48}$= 3.60, p= 0.007; Fig. 6). Also suction cleaning significantly altered mesh breaking force (contrast: Suction vs. Control x Net(Coating) $F_{6,81}$= 3.25, p= 0.004, Fig 6), yet led to both lower and higher average mesh breaking force, depending on the coating type and net. In contrast, cavitation cleaning did not significantly alter mesh breaking force (contrast: Cavitation vs. Control x Net(Coating), $F_{6,81}$= 0.53, p= 0.796, Fig. 6).

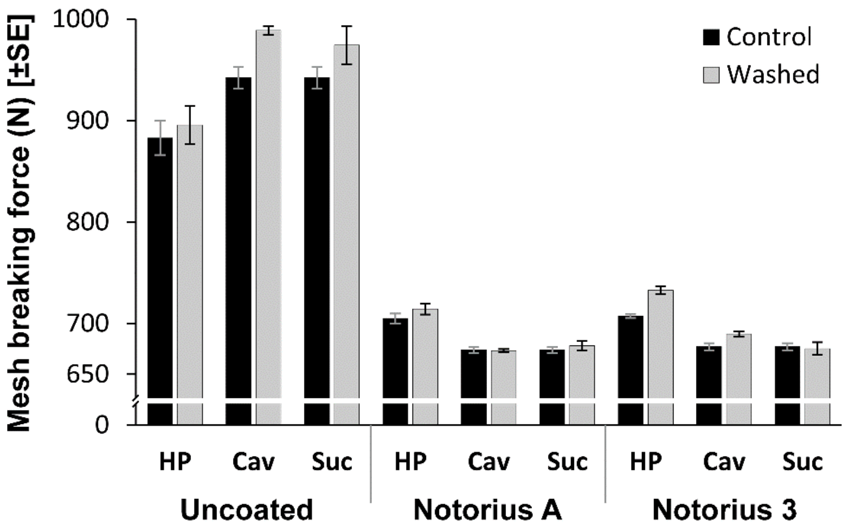

Figure 6: Average mesh breaking force (±SE) of nets (uncoated or coated with Notorius A or Notorius 3) washed 35 times using high-pressure (HP), cavitation (Cav), or suction (Suc) compared to corresponding unwashed control nets.

3.4 Coating integrity

Damage to the coating differed significantly between cleaning technologies, coatings, and frequencies, and was not consistent between replicate nets (Net(Coating) x Cleaning technology x Frequency: $F_{12,144}$= 5.01, p<0.001). High-pressure cleaning was most abrasive, damaging on average 21% and 31% (and maximum of 53%) of the washed surface area of Notorius A and Notorius 3 coatings, respectively, in a single cleaning event. After 35 cleaning events, on average 82% and 90% of the Notorius A and Notorius 3 coating, respectively, were damaged (Fig. 7). Low-pressure cleaning damaged on average up to 9% after a single cleaning event and up to 46% after 35 cleaning events. In contrast, a single cavitation cleaning event had no measurable effect on the coatings (average damage 0%, maximum 2%). After 35 cavitation cleaning events, on average 2% and 9% of the Notorius A and Notorius 3 coatings, respectively, were damaged. Suction cleaning did not damage the net coatings at all (average damage 0%).

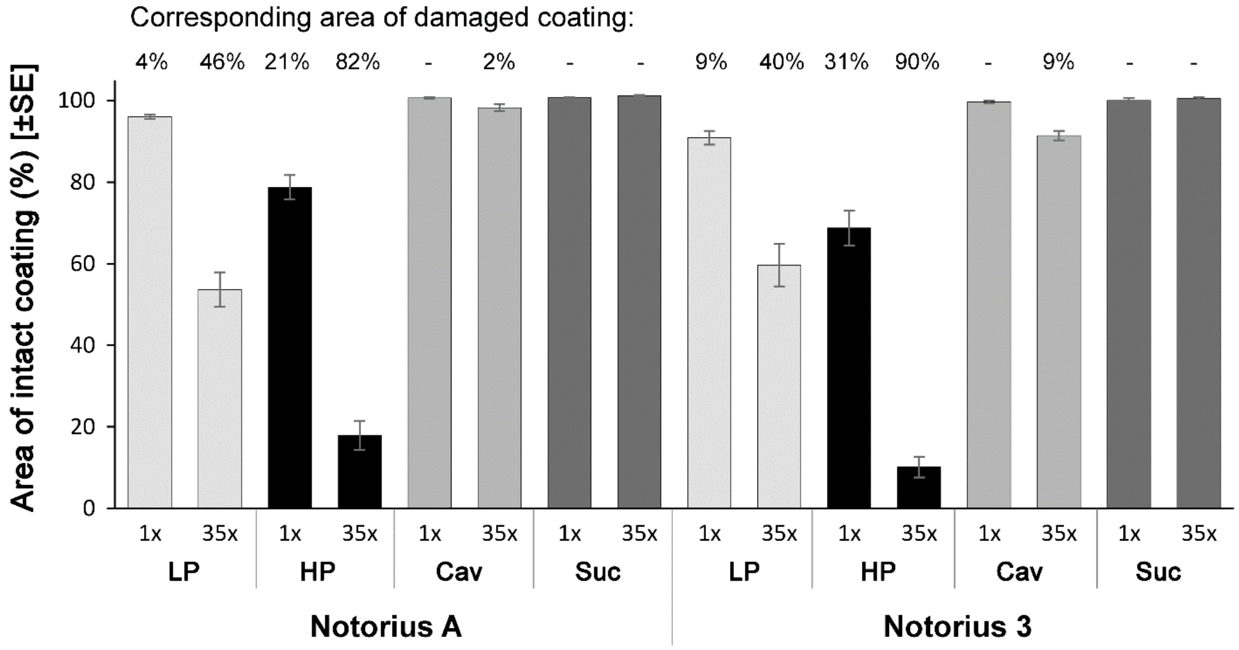

Figure 7: Coating integrity (measured as % area of intact coating ± SE) of nets coated with Notorius A and Notorius 3 after washing once or 35 times using low pressure (LP), high pressure (HP), cavitation (Cav), or suction (Suc), standardised to unwashed control nets. Above the graph, the corresponding average % area of damaged coating is listed.

4 Discussion

The challenges related to the prevention and control of biofouling accumulation on pen nets using antifouling coatings and in-water cleaning are shared by a large proportion, if not the majority, of global salmon farms. While the industry has over time developed strategies and routines to tackle these issues, recent studies (Fitridge et al 2012; Floerl et al 2016) identified considerable potential for how advances in science and technology development could provide better outcomes with regard to efficacy, fish welfare and health, and environmental contamination.

This study represented (to our knowledge) the first comprehensive attempt at comparing the efficacy of a range of established and developing cleaning technologies for pen nets, and the interaction of these methods with different types of antifouling coatings. We were constrained to examining only a single 'model' of cleaning tool from each of the four broader types of tools, precluding a generalisation of our findings. However, the results from the experiments provides valuable information on the comparative characteristics and potential merits of different types of cleaning tools, and thereby a starting point for technology development and more comprehensive evaluations.

4.1 Cleaning efficacy

High-pressure cleaning and cavitation cleaning were the most efficient cleaning technologies, while low-pressure cleaning and especially suction cleaning had a much lower cleaning efficacy.

On uncoated nets, high-pressure cleaning performed better than cavitation, while cavitation had an increased cleaning efficacy on nets coated with Notorius 3, the coating designed for use with low-intensity cleaning. There were no differences in performance on Notorius A coated nets.

However, in this study neither of the two methods was able to remove all biofouling. This contrasts with observations from the field, where high-pressure cleaning often has good efficacy and is able to remove almost all biofouling. A possible reason is that many of the samples used in the study featured relatively large amounts of biofouling despite efforts to grow representative biofouling abundances. In comparison, the frequent cleaning operations used on many farms prevent the build-up of considerable amounts of biofouling on commercial cages (SINTEF, unpubl. data). However, the biofouling intensities used in this study were within the realistic operational range. Based on data from the survey conducted prior to the study, repeated cleaning of net areas with high biofouling similar to the ones used in this study is sometimes necessary.

Low-pressure cleaning was unable to achieve the same cleaning efficacy as high-pressure or cavitation cleaning. Low-pressure cleaning conducted in this study does not exactly match the technology used by some farmers that combine low pressure cleaning with higher water volumes. Further testing is required before definite conclusions can be reached and should also include attempts at removing less well-developed fouling assemblages that have not yet attached as firmly as the mature communities in this study.

Suction cleaning technology was barely able to remove any biofouling growth from the nets, indicating that the design of the cleaner used for this study needs to be improved to increase efficacy. One potential avenue might be a reduction of the opening to increase water velocity and thus suction efficacy. However, for suction cleaning to be as effective as, for example, high-pressure cleaning, the water velocity affecting the biofouling organisms has to be of similar magnitude. This is harder to achieve when water is sucked in from the general surrounding area compared to being expelled from a single point source as during high-pressure cleaning.

Due to circumstances that could not be changed or controlled, the samples used in the cavitation and suction cleaning experiments had higher biofouling abundances than those used in the high- and low-pressure cleaner trials. This may have affected the results, as more mature biofouling is harder to remove (Tribou and Swain 2015). It is possible this may have underestimated the cleaning efficacy of the cavitation and suction cleaners used in this study, relative to high- and low-pressure cleaning.

4.2 Cleaning waste

The biofouling on the net and, consequently, the cleaning waste was dominated by the hydroid *Ectopleura larynx*, which is one of the most common biofouling organisms on salmon net in Norway (Bloecher et al. 2013, Carl, et al. 2011, Guenther et al. 2010). The presence of antifouling coating facilitated the removal of entire hydroid colonies consisting of multiple polyps with a connected root network. Possible explanations are that uncoated knitted nets have a structure that many biofouling organisms, including hydroids, use to their advantage when adhering to the net (Carl, et al. 2011). In contrast, the presence of a coating generates a smoother surface that facilitates removal (Baum et al. 2017, Swain and Shinjo 2014). In addition, as the colonies on the uncoated nets were more abundant and thus growing denser, their root network may have been interwoven to a higher degree, further facilitating adherence.

Cavitation resulted in the removal of the highest percentage of large hydroid colonies, indicating that this technology was either better suited to removing large organisms, or that other technologies such as high-pressure cleaning were more destructive, separating or damaging large colonies during removal. Suction cleaning waste did not contain any large particles, presumably because this technology lacked the strength for effective removal of biofouling, as described above. It is furthermore possible that larger particles fractioned during pump transport through the cleaner.

However, since only a small proportion of the released cleaning waste could be collected in the experiments, the collection efficacy needs to be improved before more detailed conclusions can be drawn. Had all samples been collected in the same year, and thus consisted of similar communities, an analysis of species composition in the cleaning waste may have given additional insight into removal efficacy of specific organisms. As it is, the analysis was restricted to particle size and ever-present hydroids.

Coating particles found in the cleaning waste were collected at highest abundance during high-pressure cleaning, indicating it as the most abrasive treatment and supporting the results of the coating abrasion tests. However, few coating particles were also found in cleaning waste collected from uncoated nets. A possible source for these coating particles could be the farm site where the nets were incubated. During cleaning of the copper coated farm nets, the biofouling on the incubating samples could have trapped the released coating particles.

4.3 Net strength

None of the cleaning technologies evaluated led to a significant reduction in average mesh breaking force after intensive use. This is in agreement with earlier research on high-pressure net cleaning (Moe Føre and Gaarder 2018). Anecdotal evidence indicating net cleaning operations as the cause for net breakage have been shown to be largely due to incorrect use and insufficient maintenance of net cleaning equipment, or the presence of other cage elements (eg ropes) that increase the friction of the net cleaner's rotating discs on the net (Moe Føre and Gaarder 2018). Since intensive net cleaning did not lead to a reduction in mesh breaking force, the breaking force of samples cleaned only a single time (all technologies) and samples cleaned via low-pressure were not analysed.

The increase in mesh breaking force seen after cleaning of coated nets is a common phenomenon associated with the removal of the coating (Moe et al. 2007). The impact of the coating on net strength could be seen when comparing the mesh breaking force of unwashed uncoated nets to unwashed coated nets, where both coatings led to an average reduction of mesh breaking force of 20% and 28% in the high-pressure and the cavitation/suction experiments, respectively. The mechanisms causing this phenomenon are still unexplained.

4.4 Coating integrity

The cleaning technologies examined differed strongly in their abrasiveness towards copper coatings, with high-pressure cleaning being clearly the most damaging approach. In an industry survey conducted leading up to this study, farmers reported observing clouds of particles in the water at first cleaning, and that biofouling growth rate and abundance on the nets increased significantly thereafter, indicating a loss of antifouling performance of the net (SINTEF, unpubl. data). This is consistent with the observed average coating damage of 21% and 31% (depending on the coating) on the washed side of the net, with up to 53% damage in individual measurements after a single cleaning event. The almost complete removal of the coating after frequent washing (up to 90%) is in accordance with estimates by the Norwegian Environment Agency of 85% of the copper coatings being lost at sea (Skarbøvik, et al. 2017). Similarly, also the ASC Salmon Standard assumes that copper coatings are washed off the net during one grow-out season (Aquaculture Stewardship Council 2017).

While cleaning with lower water pressure was significantly less abrasive, frequent cleaning did lead to considerable damage of the coating. In contrast, cavitation cleaning caused almost no damage to the coating despite having a cleaning efficacy similar to high-pressure cleaning – despite operating on samples with higher biofouling intensity.

Suction cleaning had no impact on the coating. However, as this coincided with a very low cleaning efficacy, comparative measurements would have to be repeated with a more efficient suction cleaner.

4.5 Conclusion and outlook

This study identifies cavitation-based cleaning as a promising technology for biofouling control on fish farm nets that should be investigated further. While having similar (and at times higher) efficacy as high-pressure cleaning, cavitation cleaning reduced the damage to the antifouling coating to a maximum of 10% - a nine-fold improvement over high-pressure cleaning. Thus, this technology has the potential to provide efficient net cleaning while considerably reducing the environmental contamination. Based on Norway's annual use of 1250 t copper for fish farming (Skarbøvik, et al. 2017), the transition to cavitation cleaning could reduce the copper pollution by up to 88%, from currently 1088 t to as little as 128 t annually. As cavitation-based cleaning is considerably less abrasive towards copper coatings than even low-pressure cleaning, this method should also be allowed at ASC certified sites where only 'light' cleaning is permitted (Aquaculture Stewardship Council 2017), increasing the number of biofouling management strategies available to ASC certified sites.

The increased cleaning efficacy on samples coated with Notorius 3, a coating designed to work well with non-abrasive cleaning, compared to the 'regular' copper coating Notorius A, indicates that the combination of cleaning technologies with a dedicated coating has the potential to further improve the performance of cavitation-based cleaning.

In addition, cavitation-based cleaning has the potential for better energy efficiency compared to high-pressure cleaning as the cleaning area of a cavitation unit is approximately double the size of a high-pressure unit. With similar efficiency of the technologies, fewer units would be needed to clean the same surface area. The resulting reduction in energy consumption and associated reduction in CO_2 emissions during net cleaning operation could considerably improve sustainability of aquaculture and salmon farming in particular. Thus, in a next step, a larger prototype of a cavitation cleaner should be built to enable testing of the equipment in the field and validate the finding of this study in full-scale.

However, as cavitation cleaning is unlikely to mitigate the gill health risk associated with the release of cleaning waste during net cleaning operations (Floerl, et al. 2016), other technologies should be explored too. While the efficacy of the suction cleaning prototype tested in this study was insufficient, the technology itself should be re-evaluated for options of improvement that prevent the release of cleaning waste. For example, several types of cleaning rigs used to remove biofouling from ships' hulls incorporate both cleaning systems (eg water jets or rotating brushes) and waste collection systems (suction, filtration and containment units) (Morrisey and Woods 2015). Similar combinations could be feasible for application in aquaculture. In addition to novel cleaning technologies, also innovations targeting the biofouling management strategy could offer improvement. Shifting from scheduled (eg annual) 'heavy' cleaning to weekly 'light' grooming has shown to significantly improve biofouling mitigation on boat hulls (Hunsucker et al. 2019, Tribou and Swain 2015). The frequent brushing of the hull prevents the build-up of mature fouling communities and pre-empts the release of larger cleaning waste particles. A similar strategy is targeted by several Norwegian companies that aim to develop cleaning units that can groom the net on a daily basis, preventing the build-up and thus release of biofouling particles (eg 'HALO Net Maintenance System' by AquaRobotics, 'Netrobot' by Mørenot). This is an interesting avenue and the efficacy and potential impacts of these novel systems should be assessed scientifically as soon as possible.

The development of optimised biofouling management technologies for finfish aquaculture should remain an important goal for this industry as it has the potential to achieve considerable benefits relating to farming operations, fish health and welfare, and environmental sustainability.

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Supplement 1

Background to statistical tests

Table S1: Overview of the data that was analysed and the number of replicates in the individual tests.

Experiment	Cleaning technology	Cleaning frequency	Net coating	Number of replicate nets	Samples per replicate	Tests per sample
Cleaning efficacy	High pressure Low pressure Cavitation Suction	1x	Uncoated Notorius A Notorius 3	6	1	1 (wet weight)
Cleaning waste	High pressure Low pressure Cavitation Suction	1x	Uncoated Notorius A Notorius 3	4	1	1 (Particle composition and dry weight)
Net strength	High pressure Cavitation Suction	35x	Uncoated Notorius A Notorius 3	3*	4	5, averaged (mesh breaking force)
Coating integrity	High pressure Low pressure Cavitation Suction	1x, 35x	Notorius A Notorius 3	3	4	1 (coated surface area)

* High-pressure cleaning of uncoated samples was conducted for two replicates.

Statistical results from PERMANOVA analyses

Cleaning efficacy

Permanova table of results

Source	df	SS	MS	Pseudo-F	P(perm)
Cleaning technology	3	3,6967	1,2322	195,8	0,0001
Coating	2	0,035158	0,017579	2,7933	0,0724
Cleaning technology x Coating	6	0,47979	0,079964	12,706	0,0001
Residuals	60	0,3776	0,006293		
Total	71	4,5892			

PAIR-WISE TESTS

Term 'Cleaning technology x Coating' for pairs of levels of factor 'Coating'

Within level 'Low pressure' of factor 'Cleaning technology'

Groups	t	P(MC)
Uncoated, Notorius A	0,72027	0,4901
Uncoated, Notorius 3	0,28565	0,7778
Notorius A, Notorius 3	1,0372	0,3163

Within level High pressure' of factor 'Cleaning technology'

Groups	t	P(MC)
Uncoated, Notorius A	4,3262	0,0017
Uncoated, Notorius 3	4,1338	0,0022
Notorius A, Notorius 3	0,53651	0,6052

Within level 'Cavitation' of factor 'Cleaning technology'

Groups	t	P(MC)
Uncoated, Notorius A	8,3623	0,0001
Uncoated, Notorius 3	10,304	0,0001
Notorius A, Notorius 3	5,1315	0,0007

Within level 'Suction' of factor 'Cleaning technology'

Groups	t	P(MC)
Uncoated, Notorius A	1,4286	0,1769
Uncoated, Notorius 3	0,62131	0,5468
Notorius A, Notorius 3	1,8535	0,0936

PAIR-WISE TESTS

Term 'Cleaning technology x Coating' for pairs of levels of factor 'Cleaning technology'

Within level 'Uncoated' of factor 'Coating'

Groups	t	P(MC)
Low pressure, High pressure	8,2938	0,0001
Low pressure, Cavitation	2,3203	0,0445
Low pressure, Suction	4,3147	0,0009
High pressure, Cavitation	14,492	0,0001
High pressure, Suction	26,514	0,0001
Cavitation, Suction	13,37	0,0001

Within level 'Notorius A' of factor 'Coating'

Groups	t	P(MC)
Low pressure, High pressure	3,2146	0,0087
Low pressure, Cavitation	5,8322	0,0001
Low pressure, Suction	7,3491	0,0002
High pressure, Cavitation	1,4614	0,1733
High pressure, Suction	11,595	0,0001
Cavitation, Suction	32,662	0,0001

Within level 'Notorius 3' of factor 'Coating'

Groups	t	P(MC)
Low pressure, High pressure	4,6723	0,0018
Low pressure, Cavitation	8,5356	0,0001
Low pressure, Suction	3,3915	0,0078
High pressure, Cavitation	4,3112	0,0012
High pressure, Suction	10,382	0,0001
Cavitation, Suction	16,762	0,0001

Coating particles

Permanova table of results

Source	df	SS	MS	Pseudo-F	P(perm)
Cleaning technology	3	4880,2	1626,7	12,176	0,0001
Coating	2	1081,2	540,58	4,0464	0,0165
Cleaning technology x Coating	6	3564,8	594,14	4,4472	0,0009
Residuals	36	4809,5	133,6		
Total	47	14336			

PAIR-WISE TESTS

Term 'Cleaning technology x Coating' for pairs of levels of factor 'Coating'

Within level 'Notorius 3' of factor 'Coating'

Groups	t	P(MC)
High pressure, Low pressure	3,0825	0,0195
High pressure, Cavitation	2,5052	0,0457
High pressure, Suction	3,1975	0,0181
Low pressure, Cavitation	0,75107	0,469
Low pressure, Suction	1,6977	0,1417
Cavitation, Suction	1	0,3471

Within level 'Notorius A' of factor 'Coating'

Groups	t	P(MC)
High pressure, Low pressure	3,144	0,0187
High pressure, Cavitation	3,4348	0,0124
High pressure, Suction	3,4348	0,0166
Low pressure, Cavitation	1	0,347
Low pressure, Suction	1	0,3539
Cavitation, Suction	Denominator is 0	

Within level 'Uncoated' of factor 'Coating'

Groups	t	P(MC)
High pressure, Low pressure	0,37712	0,7132
High pressure, Cavitation	1,9703	0,0983
High pressure, Suction	0,2111	0,8409
Low pressure, Cavitation	1,9412	0,1028
Low pressure, Suction	0,49526	0,6303
Cavitation, Suction	1	0,3573

PAIR-WISE TESTS

Term 'Cleaning technology x Coating' for pairs of levels of factor 'Cleaning technology'

Within level 'High pressure' of factor 'Cleaning technology'

Groups	t	P(MC)
Notorius 3, Notorius A	1,8565	0,1149
Notorius 3, Uncoated	2,7565	0,0334
Notorius A, Uncoated	2,0557	0,0876

Within level 'Low pressure' of factor 'Cleaning technology'

Groups	t	P(MC)
Notorius 3, Notorius A	0,30861	0,7716
Notorius 3, Uncoated	1,4863	0,1879
Notorius A, Uncoated	1,5801	0,1646

Within level 'Cavitation' of factor 'Cleaning technology'

Groups	t	P(MC)
Notorius 3, Notorius A	1	0,3523
Notorius 3, Uncoated	1	0,3568
Notorius A, Uncoated	Denominator is 0	

Within level 'Suction' of factor 'Cleaning technology'

Groups		t	P(MC)
Notorius 3, Notorius A	Denominator is 0		
Notorius 3, Uncoated		1	0,3598
Notorius A, Uncoated		1	0,3606

Net strength

➔ High pressure cleaning

Permanova table of results

Source	df	SS	MS	Pseudo-F	P(perm)
Cleaning technology	1	3861,1	3861,1	8,565	0,0326
Coating	2	3,66E+05	1,83E+05	42,311	0,0112
Net(Coating)	5	21642	4328,5	34,598	0,0001
Cleaning technology x Coating	2	885,63	442,82	0,9823	0,4299
Cleaning technology x Net(Coating)	5	2254	450,8	3,6032	0,0066
Residuals	48	6005,2	125,11		
Total	63	4,01E+05			

➔ Cavitation and Suction cleaning

Permanova table of results

Source	df	SS	MS	Pseudo-F	P(perm)
Cleaning technology	2	6883,8	3441,9	3,6675	0,0586
* Cavitation	1	6805,6	6805,6	23,553	0,0039
* Suction	1	2392	2392	1,4842	0,2734
Coating	2	2,03E+06	1,01E+06	1539,7	0,0075
Net(Coating)	6	3953,3	658,88	1,3559	0,245
Cleaning technology x Coating	4	8435,6	2108,9	2,2471	0,1235
* Cavitation x Coating	2	7189,5	3594,8	12,441	0,0069
* Suction x Coating	2	4000,9	2000,4	1,2413	0,3632
Cleaning technology x Net(Coating)	12	11262	938,49	1,9313	0,0366
* Cavitation x Net(Coating)	6	1733,7	288,94	0,53238	0,7962
* Suction x Net(Coating)	6	9669,7	1611,6	3,2566	0,0039
Residuals	81	39360	485,93		
Total	107	2,10E+06			

**contrast analysis (washed samples vs. unwashed control)*

Coating integrity

Permanova table of results

Source	df	SS	MS	Pseudo-F	P(perm)
Coating	1	526,69	526,69	0,61602	0,4975
Cleaning technology	3	98636	32879	108,84	0,0001
Frequency	1	30654	30654	276,99	0,0017
Net(Coating)	4	3419,9	854,98	33,401	0,0001
Coating x Cleaning technology	3	620,1	206,7	0,68427	0,5743
Coating x Frequency	1	36,75	36,75	0,33208	0,5962
Cleaning technology x Frequency	3	28699	9566,3	74,616	0,0001
Net(Coating) x Cleaning technology	12	3624,9	302,08	11,801	0,0001
Net(Coating) x frequency	4	442,67	110,67	4,3234	0,0017
Coating x Cleaning technology x Frequency	3	467,79	155,93	1,2162	0,3423
Net(Coating) x Cleaning technology x Frequency	12	1538,5	128,21	5,0087	0,0001
Residuals	144	3686	25,597		
Total	191	1,72E+05			

Biofouling growth on experimental net panels

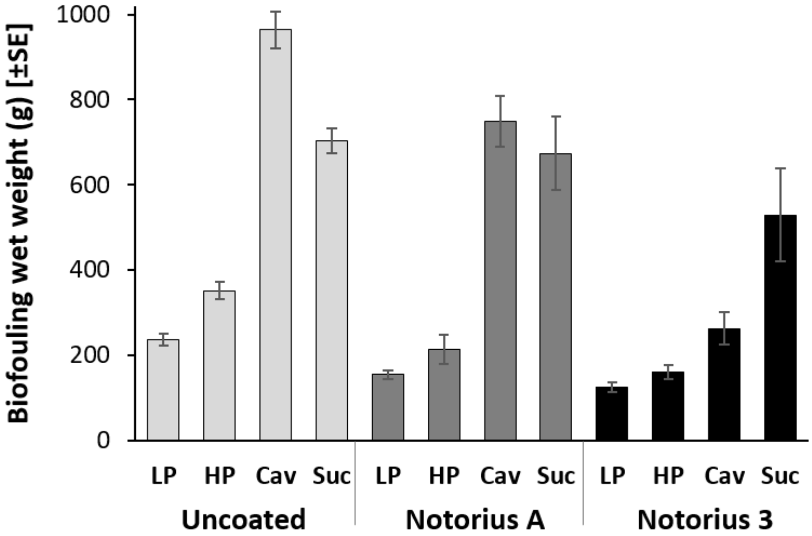

Figure S1: Average biofouling wet weight (g, ± standard error) on samples before cleaning using low pressure (LP), high-pressure (HP), cavitation (Cavitation) or suction (Suction) to determine cleaning efficacy.

Species composition of the cleaning waste collected during washing of biofouled nets

All particles collected as cleaning waste were identified to broad taxonomic levels. Particles of the hydroid *Ectopleura larynx* were further classified into four main body parts (entire polyp, hydranth, hydrocaulus and hydrorhiza, gonophores).

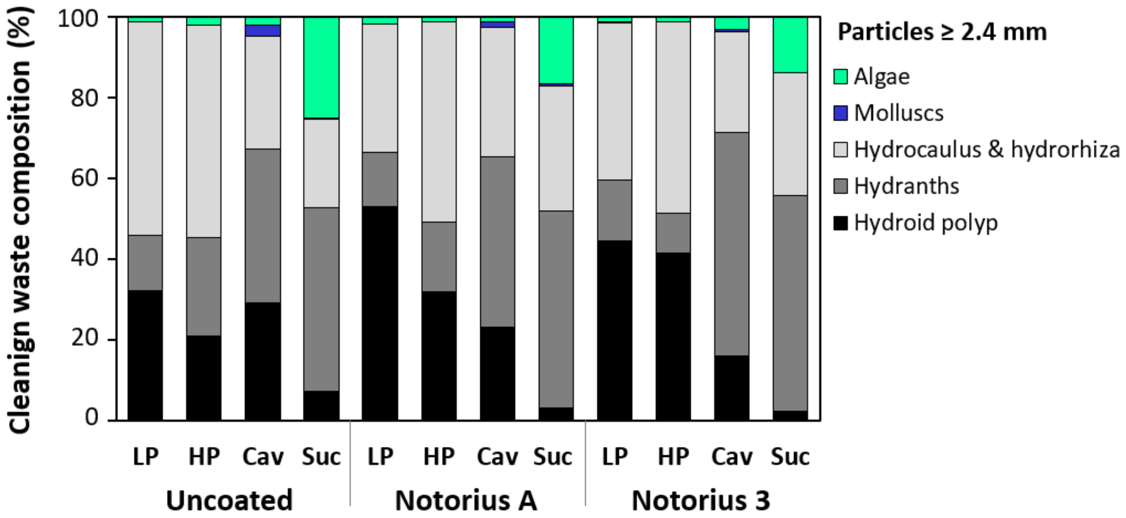

Figure S2: Composition of cleaning waste particles ≥2.4 mm (except hydroid colonies) based on abundance, containing algae and molluscs, as well as individual hydroid polyps and fragments thereof (hydranths, hydrocaulus and hydrorhiza).

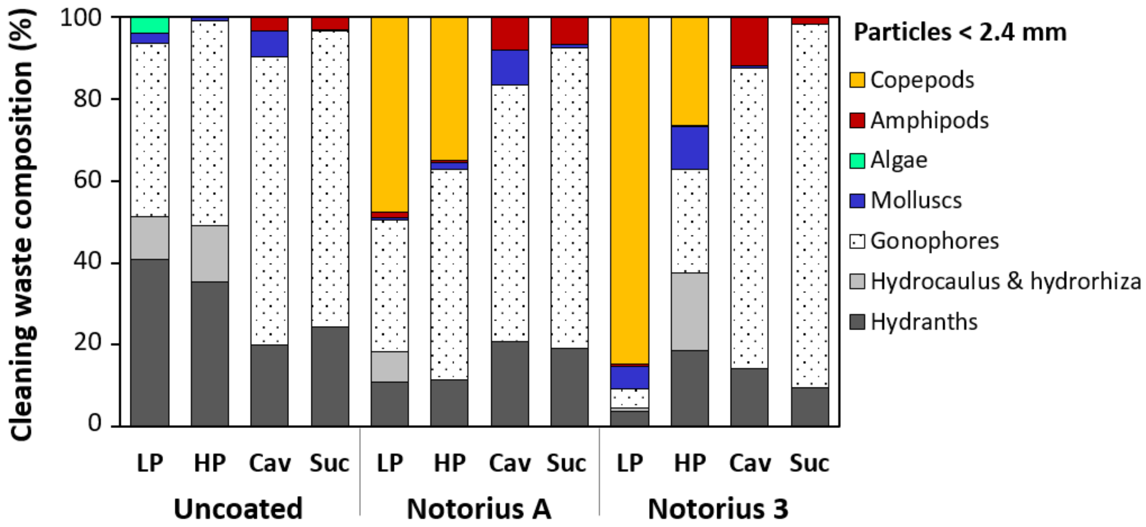

Figure S3: Composition of cleaning waste particles <2.4 mm based on abundance, containing copepods (planktonic), amphipods (associated with the biofouling on the net), algae, and molluscs, as well as hydroid fragments (hydranths, hydrocaulus and hydrorhiza) and hydroid gonophores.