Facilitating greener education and cleaner shipping through the development of novel bespoke microtextured metals to combat biofouling in niche areas on vessels

By

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Facilitating greener education and cleaner shipping through the development of novel bespoke microtextured metals to combat biofouling in niche areas on vessels

By
Liverpool John Moores University

Contractor : Christian Matthews
Research Coordinator : Simone Dürr

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Theme 3: Greener and cleaner shipping

Liverpool John Moores University (Contractor)

And

Research Coordinator

Dr Simone Dürr

Associate Professor, Liverpool John Moores University, s.t.durr@ljmu.ac.uk

Research Partners

Dr Sheelagh Conlan

Senior Lecturer, Liverpool John Moores University

Dr Martin Sharp

Visiting Fellow, Liverpool John Moores University

Dr Eduardo Blanco-Davis

Reader, Liverpool John Moores University

Dr Tahsin Opoz

Reader, Liverpool John Moores University

Dr Hiren Kotadia

Reader, Liverpool John Moores University

Prof Bogdan Hnatiuc

Professor, Constanta Maritime University

Prof Cristina Dragomir

Professor, Constanta Maritime University

Prof Simona Ghita

Professor, Constanta Maritime University

Prof Mihaela Hnatiuc

Professor, Constanta Maritime University

Prof Yasin Arslanoglu

Professor, Istanbul Technical University

Prof Özkan Ugurlu

Professor, Ordu University

Prof Refik Özyurt

Professor, Constanta Maritime University

Prof Mani Jayaprakashvel

Professor, University Academy of Maritime Education and Training

Prof Radhakrishnan Muthezhilan

Professor, University Academy of Maritime Education and Training

Prof Vijayaraj Radha

Professor, University Academy of Maritime Education and Training

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Abstract Biofouling, the unwanted biological growth on ships, causes economic and environmentally penalties by, for example, increasing fuel costs, emissions, corrosion and transfers non-native invasive species. With updated international regulations not only were biofouling guidelines improved but training for maritime personal and students is a requirement. Current antifouling solutions are coatings such as self-polishing antifouling coatings containing biocides damaging the marine environment. More modern coatings use foul-release technology that requires the vessel to be in transit. These coatings are also costlier and less effective than traditional technologies. Recently, biocidal catalysts and boosters were introduced to these originally environmentally friendly coatings causing biocidal leaching into the environment. Consequently, a new environmentally friendly and sustainable approach is needed. The aim in the IAMU and Nippon Foundation funded project NOFOUL was to develop bespoke novel antifouling laser machined textures (in tandem with non-thermal plasma) on metals for diverse maritime environments (Irish Sea, Black Sea, Marmara Sea, Bay of Bengal) and niche vessel areas, for example where coatings cannot be reapplied. The four objectives were to: 1) fine-tune existing novel non-toxic antifouling textures; 2) demonstrate the antifouling efficacy of the final texture in diverse maritime environments and the potential synergistic effect texture/plasma; 3) exchange biofouling and antifouling training within the team = knowledge transfer and impactful dissemination of project outcomes (IAMU in/outside); 4) establish a professional IAMU Biofouling Network. The NOFOUL project partners were LJMU (project lead), CMU, ITU, ODU and AMET (Project website: https://www.ljmu.ac.uk/microsites/project-nofoul).

In pilot experiments by LJMU existing microtextures on 316L 2B stainless steel panels (50x50x0.9mm) were fine-tuned and their antifouling efficacy was tested in the Liverpool South Docks, UK. From these 15 textures three textures were selected for testing at the partner sites. In pilot experiments by CMU the GlidArc technology was evaluated and two technologies, Dielectric Barrier Discharge and Minitorch, were selected to treat the sample panels with non-thermal plasma causing an antifouling effect on the surface. Selected textures were produced on non-thermal plasma treated stainless steel panels (24 panels including controls, n=3) and sent to project partners to run their field experiments. Trained project partners were running their own field experiments (participatory research) in the spring 2025. All experiments were complete by the partners, assessed by LJMU and the best antifouling texture with non-thermal plasma and without was selected. All NOFOUL partners were received training in biofouling (workshop) and site-specific training in person by LJMU to be able to run the field antifouling test in order to achieve standardization of the experiment and thus, allowing comparisons between sites. Two types of textures demonstrated lowest biofilm percentage coverage at LJMU, AMET2 (2 sites), and CMU, ODU, respectively. The same textures but plus plasma treatment, demonstrated lowest biofilm percentage coverage at AMET2, and LJMU, CMU, respectively. Even as the selection of the best textures may appear the same with and without plasma treatment for these sites, nevertheless, the outcomes are not the same. AMET2 may benefit from one texture with and without plasma but LJMU may only benefit from this texture under non-plasma conditions and may benefits more from the other texture under plasma treatment, while CMU benefits from the texture with and without plasma treatment. The outcomes of different types of textures with and without plasma in their antifouling performance was better at some sites and worse at other sites. Biofilm in quality and quantity may not the same globally, rather it may vary between the NOFOUL sites at large and small scales. Thus, the changes in biofilm may lead to different antifouling solution requirements as NOFOUL demonstrated with the unique and novel environmentally friendly antifouling solution textures with plasma treatment.

Knowledge transfer and exchange of biofouling and antifouling between project partners (LJMU, CMU, ITU, ODU, AMET) were essential to achieve the project wide field experiment under standardized conditions. NOFOUL used research in the project as a tool for a case study demonstrating training and knowledge transfer in biofouling and antifouling. The first step was a 2-day workshop at LJMU during which LJMU used an interactive approach containing short lectures, discussions, laboratory visits and practical as well as a field trip to exchange knowledge between all partners. The second step was site specific training by LJMU at the partner sites. During the one to one training partners were able to prepare for their field experiment to a common standard in order to compare research results and interpret

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in the context within the project. The outcomes of the training and knowledge exchange between partners in biofouling and antifouling were evaluated and interpreted with a view of expanding the approach for the wider IAMU community. During NOFOUL the IAMU Biofouling Network was initiated and has a positive effect on IAMU members from webinar to webinar. During the webinars knowledge on biofouling was not just only transferred to participants but knowledge exchange is demonstrated in the question and answer sessions while developing into discussions. In the webinars, NOFOUL trained non-specialists disseminated the NOFOUL research and demonstrated their new knowledge and skills. The NOFOUL project's higher education initiative on biofouling by CMU demonstrated impressive success in engaging electrical engineering students with environmental marine sciences concepts. The strong interest levels reported by students, coupled with their openness to further learning and project participation, indicate effective educational content and delivery. The survey showed valuable insights about student preferences, highlighting engineering applications, pollution concerns, and environmental impacts as particularly resonant topics.

The NOFOUL project team achieved all aims and objectives. All deliverables are met and dissemination of the project is ongoing with two scientific articles and conference presentation. With trained non-specialists NOFOUL demonstrated the antifouling performance of the environmentally friendly antifouling solution, the microtextures in optional combination with non-thermal plasma treatment. Both do not leach microplastics nor biocides in the marine environment. The NOFOUL project developed training and knowledge exchange approaches and trained non-specialists for biofouling. Their training was evidenced with a 2-day workshop and a participatory research field experiment, and resulted in their knowledge transfer in a Biofouling Network with webinars and Higher Education teaching. Recommendations from NOFOUL are: 1) Increase the qualified personnel in biofouling and antifouling so students and mariners achieve their required skills in the field as in Resolution MEPC.377(80). Diversify teaching and training activities by mentoring, improving resource access, and their recognition and supported incentives. 2) Accessibility of real-world experimental approaches for maritime students and mariners by maritime institutes. 3) Encourage innovation in biofouling and antifouling solutions by expanding funding opportunities and facilitating start-ups within maritime institutes. 4) Grow the IAMU Biofouling Network to support MET and real-world experimental opportunities in the form of participatory research.

Overall, our novel antifouling solution demonstrated that our bespoke microtextures, tested in the field under a number of different marine environments by local trained NOFOUL non-specialists using the same experimental protocol, showed antifouling performance by reducing the percentage coverage of local marine biofilm. This established a loop between our research and our biofouling training within NOFOUL facilitated the transfer of the new knowledge by the trained NOFOUL non-specialists to other non-specialists in IAMU such as in education and in the IAMU Biofouling Network.

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1. Introduction

Any surface in seawater will get biofouled first by biofilm and then by algae and invertebrates [1, 2, 3]. These cause corrosion, material fatigue and increased drag, transfer of non-native invasive species, fuel consumption, emissions, thereby contributing to Global Climate Change [4]. Indeed, [5] estimated that the economic impact of biofouling just for the US DDG-51 fleet was $56M per year at the time. Recently, progress has been made with the updated and amended guidelines on the control and management of ship biofouling, Resolution MEPC.377(80) (International Maritime Organisation, 2023). This includes training and education for maritime personal on impacts of invasive aquatic species from ships' biofouling benefits to the ship of managing biofouling and biofouling management measures, and marine training organisations need to include these in their syllabuses as appropriate. Still, biofouling is neglected in maritime training and education. Reasons for this may be because of lack of knowledge and confidence on the biofouling topic, as well as the importance of the topic may not be accepted in the maritime organisations, industry and educational institutions.

The NOFOUL project developed a highly innovative, environmentally friendly and new solution using laser texturing in combination with non-thermal plasma treatment addressing biofouling. Our novel antifouling solution is bespoke designed for niche areas of vessels such as water in/outlets, sensors, ballast water pipes, sea chest and certain areas on the hull [6] where conventional coatings and cleaning may be insufficient but harbors biofouling and invasive species. Conventional counter-measures to biofouling are such as self-polishing antifouling coatings containing biocides. However, these damage the environment, and environmental legislation means they will be phased out in the future [7, 8, 9]. Most modern coatings use foul-release technology that requires the vessel to be in transit. They are also costlier and less effective than traditional technologies [10]. Recently, biocidal catalysts and boosters were introduced to these originally environmentally friendly coatings causing biocidal leaching into the environment [11]. Consequently, a new environmentally friendly and sustainable approach is needed. Altering the surface microtrexture is a novel approach to reducing biofouling [12]; surface roughness and other structural features such as pores, grooves and pits on the nano- and micrometre scale influence biofouling settlement patterns [13]. The reasons why surface texturing impacts upon biofouling can be found in the attachment point theory [14, 15]. The settlement on a roughened surface relates to the scale of the roughness in correlation to the organisms' size. Biofouling is also impacted by surface wettability and chemistry [16-19]. Wettability and surface roughness are also linked explained in the Cassie-Baxter and the Wenzel Models [20-25].
Experimental studies demonstrate that one can reduce settlement of marine invertebrates, algae and biofilm by altering surface texture e.g. [26]. However, the only commercially successful biomimetic microtexture was developed by [19] and patented in [27]. These textures were originally considered for antifouling but they were applied by photolithography and this restricted their use to medical devices. Using novel laser technology, the microtopography of a surface can be precisely designed on multiple levels, well-defined and reproducible. This facilitates an antifouling and/or foul-release effect based on roughness, wettability and chemistry [28-31]. Laser texturing of metals with a fibre laser can reduce biofilm formation by up to 90% [32, 33]. Wettability of a surface and therefore biofouling can be further changed by additional non-thermal plasma treatment. Using Glidarc plasma reactor technology surfaces can be efficiently cleaned off microorganisms and inhibits them [34, 35]. The treatment of metals with plasma is currently used to remove microbiological contamination or to short-term condition for subsequent treatment [36-39]. A pre-treatment prior to texturing may improve the wettability of the textured surface further synergistically. The combination of these technologies gives additional novelty to this project, they have not yet been tested together for synergistic effects. NOFOUL proposed to not only develop bespoke anti-biofilm textures but to determine for the best texture the effect of texture in tandem with plasma (prior to surface texturing) in the final field test.

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In the IAMU/Nippon Foundation funded project NOFOUL the research aim was to develop bespoke novel antifouling laser machined textures on metals for diverse maritime environments and niche vessel areas. This antifouling field testing at an international scale was used as a model training approach on biofouling and antifouling for non-specialist trainees, in this case engineers, and specialist trainers. The non-specialist trainees were the project partners from Constanta Maritime University (CMU, Romania), Istanbul Technical University (ITU, Turkey), Ordu University (ODU, Turkey) and the University Academy of Maritime Education and Training (AMET, India). The specialist trainers and facilitators were biofouling and antifouling researchers from the lead institution Liverpool John Moores University (LJMU, United Kingdom).

In NOFOUL, a number of teaching and learning tools were combined (training, knowledge transfer and exchange, coaching, participatory research, networks, Higher Education Teaching) and split into activities (2-day training workshop, site-specific training at the partners/trainees, training through coaching during the experiment, IAMU Biofouling Network organisation with webinar presentations, Higher Education maritime teaching on biofouling). Training as in training by demonstration and by doing while focussing on real-life experience. was used in the 2-day training workshop and site-specific visits. Coaching during the field experiment, the guidance of the trainee, was applied partly at site specific training as well. Knowledge transfer was introduced from the first activity onwards, the workshop, and the last activity, the webinar presentations and Higher Education maritime teaching. When the knowledge transfer was completed by the specialist trainers, the non-specialist trainees, changed into trained non-specialists and were able to train themselves non-specialists by contributing to webinars in the network (connections between people with shared interests), and Higher Education maritime teaching at their institutions. All partners participated in wide discussions and knowledge exchange in the subject, the two-way knowledge transfer, from the start of the project.

In NOFOUL participatory planned international research, network organisation and Higher Education Teaching by non-specialists were enabled by training, knowledge transfer and exchange, and coaching. Participatory research methodologies emphasize collaboration between researchers, practitioners, and end-users throughout all stages of the research process, from problem definition to solution implementation [40, 41]. Interdisciplinary, -sectoral, and -cultural participatory research is demonstrated by both opportunities, such as facilitating of the exchange of specialised technical knowledge, fostering cross-cultural innovation, and bridging global and local perspectives on subjects, and challenges, such as issues with power dynamics, communication barriers, and lack of understanding of technological solutions [42, 43]. Thus, careful coordination, mutual respect, and shared commitment to co-learning, supporting by an agreement, is needed to integrate expertise within participatory frameworks.

The importance and number of participatory research is risen in recent years [44, 45] such as the EU funded Collective Research on Aquaculture Biofouling (CRAB ID: 500536, 2004-2007; Factsheet https://cordis.europa.eu/project/id/500536) and projects by [46, 47].

The aim of the study was to develop bespoke novel antifouling laser machined textures (in tandem with non-thermal plasma) on metals for diverse maritime environments and niche vessel areas.

The objectives were to:
- fine-tune our existing novel non-toxic antifouling textures (Objective 1)
- demonstrate the antifouling efficacy of the final texture in diverse maritime environments and the potential synergistic effect texture/plasma (Objective 2)
- exchange biofouling and antifouling training within the team = knowledge transfer and impactful dissemination of project outcomes (IAMU in/outside) (Objective 3)
- establish a professional IAMU Biofouling Network (Objective 4)

The team addressed the question "Can we devise a novel environmentally friendly universal antifouling surface that works across diverse maritime regions?" This question and our objectives align with Theme

3 desirable goals: For objectives 1 and 2, we apply new and innovative methodologies with novel laser machined texture technologies (potentially enhanced by plasma treatment), with biological knowledge in a multidisciplinary team (engineering, biology, education) and real-time field experiments utilising full factorial experimental design, response surface, multivariate and image analysis methodologies. NOFOUL tested efficacy at six field sites in different regions: Irish Sea, Black Sea, Marmara Sea, Indian Ocean to demonstrate the antifouling properties of our technology in diverse maritime regions. Our approach is reducing shipping emissions and pollutants by decreasing biofouling and invasive species incidence without releasing pollutants (i.e. biocides, microplastics). We contribute to greener shipping, cleaner oceans and decelerating Global Climate Change while transferring our knowledge on best practice to the IAMU network and beyond via novel multi-level training in objectives 3 and 4.

Part 1 – Developing and testing of environmental friendly antifouling solutions at diverse maritime environments

2. Methodology

2.1 Fine-tuning of environmentally friendly antifouling solutions

2.1.1 Antifouling microtextures on metal surface

2.1.1.1 Production of textures

Material used was 316L 2B stainless steel in size 50x50x0.9mm. Stainless steels were obtained from Merseyside Metals Services Ltd (Liverpool, UK) and laser cut to size by Diamond Precision Engineering Ltd (Liverpool, UK).

Laser System
The laser system used was formed of an infrared fibre laser, an optical system and a three axes automatic table. The IR fibre laser model was a SPI Laser (UK) G3 20 W nanosecond pulsed fibre laser. The optical system consisted of a manual 1064 nm beam expander (Linos (Qioptiq) 2-8x), a scanning galvanometer (Nutfield Extreme-15-YAG) controlled using SAMLight v3.05 software (SCAPS Gmbh), a focal length of 100 mm (Linos Ronar F-Theta focal lens) and four silver mirrors (Thorlab). The three axes computer-controlled table was provided by Aerotech Limited (UK). The laser has a wavelength 1064 ± 5 nm, and a near TEM00 mode with beam quality factor $M^2 = 2.1$. The laser can work with several pulse lengths varying from 9 ns to 200 ns and at various Pulse Repetition Frequencies that range from 1 kHz to 500 kHz. The laser has a maximum average power of 22 W and maximum pulse energy of 880 µJ before the optical system. Maximum average power was measured after the beam expander with an Ophir laser power meter system, using a 30A-N-SH ROHS head and Nova II display software. The beam expander was set to give a raw laser beam diameter of 5.7 mm. Four mirrors guide the laser beam to the scanning galvanometer mirror head fitted with a f-theta focussing lens. This device handled the displacement of the laser beam on the sample surface and the scan rate of the laser beam across the surface can vary from 0.01 mm/s to 20,000 mm/s. The lens had a focal length of 100 mm. The automatic table speed ranged from 0.017 mm/s to 225 mm/s. The laser system operated with the full optical system. The laser beam was moved on the 50 mm x 50 mm samples via galvanometer scanning.

Texture Characterisation
The topography of the samples, each measuring 50 mm x 50 mm with an optical light profilometre (Bruker ContourGT optical profiler), operating with green light and in VSI or VXI mode. The optical light profilometre was used to measure the surface roughness of the samples.

Laser Parameters
The maximum scan speed of the galvanometer scanning was 20000 mm/s. The laser parameters to generate the single-layer textures on the 50 mm x 50 mm x 0.9mm 316L 2B stainless steel samples are summarised in Table 1. Five high density dimple textures (HD 1 to 5), seven ridge textures (R 1 to 7) and three low density textures (LD 1 to 3).

Table. 1. Laser parameters of the single layer textures for 316L 2B stainless steel

Pattern	SS (mm/s)	HHD (μm)	HHA (θ)	VHD (μm)	VHA (θ)	SN	PRF (kHz)	PL (ns)	PE (μJ)	d_o (μm)	Z (μm)
HD 1	3125	100	135	100	45	20	125	30	90	51	0
R 1	3125	50	135	50	45	20	125	30	90	51	0
HD 2	3125	150	65	20	140	5	125	30	90	51	0
HD 3	5000	80	135	80	45	10	125	30	90	51	0
HD 4	625	50	135	50	45	5	25	200	270	51	0
R 2	625	150	65	20	140	5	25	200	270	51	0
HD 5	800	50	135	50	45	5	25	200	440	51	0
R 3	1200	75	0	-	-	5	25	200	270	51	0
R 4	1200	100	0	-	-	5	25	200	270	51	0
R 5	1800	75	0	-	-	5	25	200	270	51	0
R 6	1800	100	0	-	-	5	25	200	270	51	0
R 7	3200	100	0	-	-	20	25	200	440	51	0
LD 1	8000	100	0	-	-	20	25	200	440	51	0
LD 2	8000	100	0	50	90	20	25	200	440	51	0
LD 3	6250	300	0	-	-	20	25	200	440	51	0

Nomenclature; SS, Scan speed. HHD; Horizontal hatch distance. HHD; Horizontal hatch angle. VHD; Vertical hatch distance. VHA; Vertical hatch angle. SN, Scan number. PRF, Pulse rate frequency. PL, Pulse length. PE,. Pulse energy. do, Laser beam diameter. Z, Distance to focal point.

2.1.1.2 Antifouling field testing of textures

Duration of the field experiments were variable in length adjusted to the amount of biofilm on the control. The field site for all the field experiments is the Liverpool South Docks, Royal Alber Dock, Liverpool, UK. The pontoon is owned by Canal River Trust and is gated with two larges permanently moored large barges. The general public and weekend watersports enthusiasts have no access. Field experiments are deployed from the pontoon, not visible for the people, facing away from the pontoon to avoid shading for optimal conditions for biofilm growth. Experiments are attached to frames and situated at 1m depth, under static conditions (Fig. 1.).

Fig. 1. Deployment of frame on pontoon, Royal Albert Dock.

Experimental Design

Textures (n=3) and controls are attached randomly to PVC carrier panels (20x20cm) with velcro (Fig. 2). Panels are attached to the frame with cable ties. Experiments were run between 24th July to 2nd August 2024.
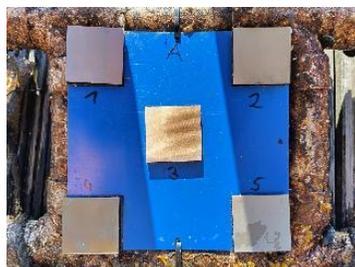

Fig. 2. Carrier panel with velcro attached textures on 316L stainless steel.

Imaging

All samples were imaged for biofilm using the Keyance 3D microscope at 500x magnification. Per sample ten subsamples were randomly imaged and saved as tif files.

Image Analysis of Biofilm

The images of 3 subsamples per sample (15 textures, 1 control with 3 replicates) were analysed for biofilm percentage coverage using ImageJ and the standardised random 100 dot method. One hundred dots are applied on the image by the software representing 100% in total by identifying biofilm under each dot. For 316L stainless steel 510 images were analysed for biofilm coverage.

Statistical Analysis

Basic statistical analysis was conducted to determine differences between controls and textures on biofilm coverage using one-way ANOVA and following post hoc test, Tukey HSB Test, after assumptions were tested for normality, Shapiro-Wilk Test, and homogeneity of variances, Leven's Test, [48]. Level of significance was 5%. Reduction of biofilm coverage relative to the control was calculated.

2.2.1 Development of non-thermal plasma treatment on metal surface

2.2.1.1 Preparation of non-thermal plasma treatment

We used 10 samples of A36 naval steel, dimensions 50 x 50 x 5 mm. Only 7 of them were prepared for analysis.

Their polishing until metallic luster was done in 2 stages:
Stage 1: In the laboratory, manually, for 80, 100, 120, 180, 400, 800 grit sandpaper and felt. It was ensured that the temperature during processing did not exceed 40 ºC and that the surface microcavities observed with the naked eye disappeared, see Fig. 3. The time required for manual treatment was approximately 2 hours for each sample. Solutions for automating the preparation of the samples were also tried to shorten the time, but they did not have the desired results, see Fig. 4.

Stage 2: Finally, after manual grinding, the samples were processed with a specific MINITECH 300SP1 machine, what is a manual grinder / polisher machine. In this case the total preparation time of all samples was about 10 hours. The process was helped by a specific tool machine made at 3D printer, see Fig. 5.

In Figs. 6 and 7 could be observed the surfaces of the one naval steel sample before the grinding with MINITECH 300 SP1 machine and after this operation.

Fig. 3. Photo of the conditioning treatments - microcavities present
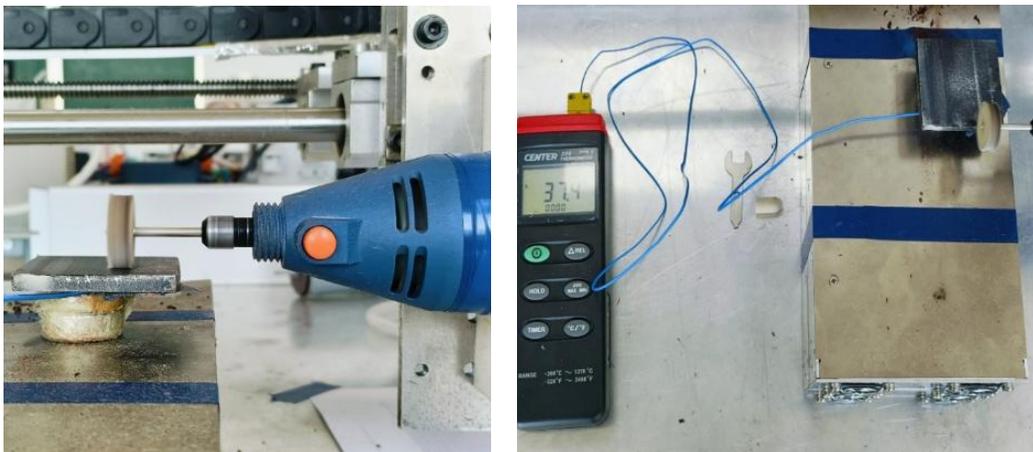
Fig. 4. Grinding on CNC with surface temperature check
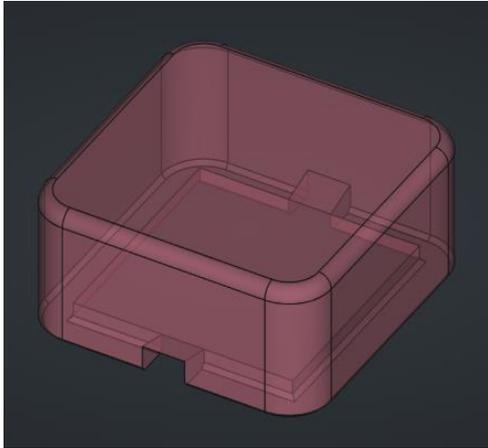
Fig. 5. Tool machine for grinding of samples
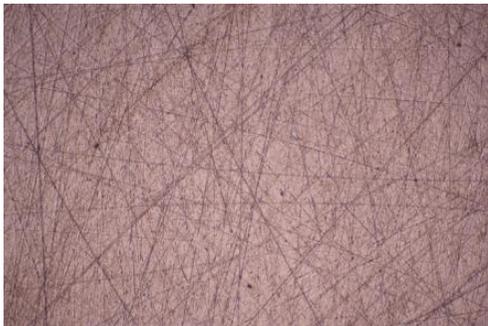
Fig. 6. Sample Before machine treatment
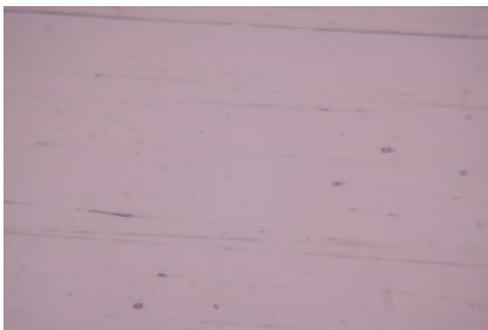
Fig. 7. Sample after machine treatment

2.2.1.2 Treatment of non-thermal plasma treatment

The purpose of the plasma treatment is to superficially modify the treated metal surface in order to increase the efficiency of the final treatment that will be applied later. For this purpose, it is considered to obtain:
1) a smoothing phenomenon by reducing the roughness,
2) increasing the forces at the atomic level,
3) concentrating some chemical species on the superficial surface of the samples against the rust.

All these must be obtained without thermal damage of the treated surface.

Three types of electrical discharges with non-thermal plasma were chosen to treat the samples: GlidArc (Fig. 8), Minitorch (Figure 9 and 10) and DBD (Fig. 11).
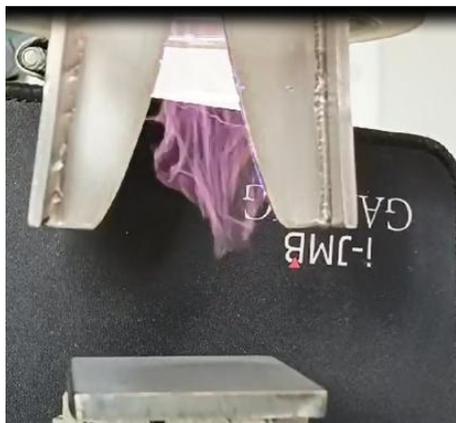
Fig. 8. – Non-thermal plasma treatment using GlidArc technology

Fig. 9. Minitorch with double beam
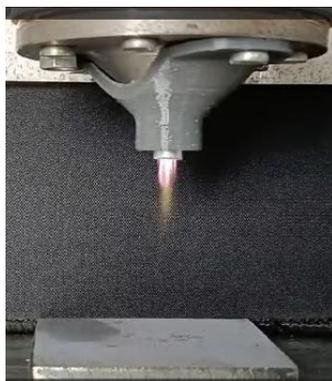
Fig. 10. Minitorch with single beam (final version)
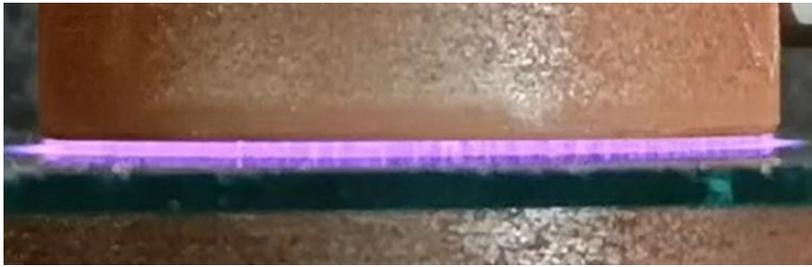
Fig. 11. Non-thermal plasma treatment using DBD technology (Power supply at 5 kV, 20 mA, 25 kHz, new version)

Six naval steel samples were treated, 2 for each type of non-thermal plasma, and sample number 7 was considered as a control.

After the plasma treatment, the samples were placed in plastic bags that were vacuumed using a food vacuum device, FoodSaver FFS016X-01 type. The samples were kept in these conditions until the analyses were performed.

Minitorch Treatment

The Minitorch is a technology derived from Gliding Arc technology. The geometry of the reactor is cylindrical. An electrode is placed along the axis of the cylinder, in the form of a rod pointed at the lower end. The second electrode has a tronconical shape, being placed at the lower end of the assembly, so that the minimum distance between the electrodes is near the exit from the reactor. An air flow is introduced through the upper side of the reactor, with the exit in the axial direction in its lower part, where a plasma jet is formed, as can be seen in Figure 10. The minitorch is placed on a machine with numerical control of CNC3D type, that allows the choose of the followed trajectory, see Figure 12, the adjustment of the travel speed and the distance to the treated sample. The samples had a fixed position, being placed on a magnetic table.
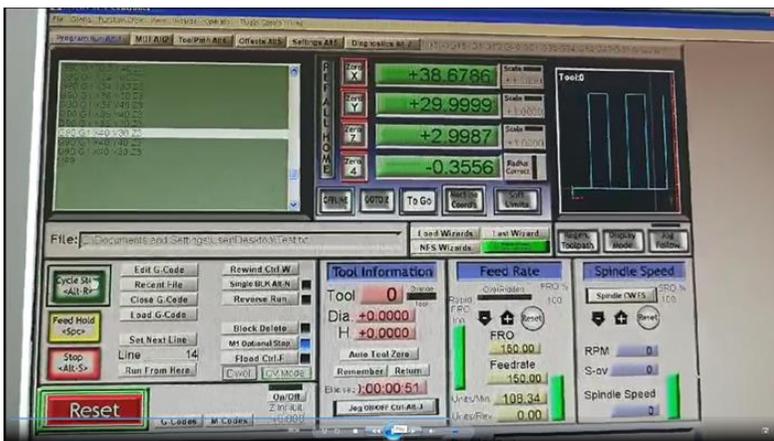
Fig. 12. Trajectory of the Minitorch on CNC3D machine on the top right corner

Sample 1 was treated using the minitorch. The treatment parameters were: treatment time 3 minutes, final temperature of 35 oC, gas flow rate 7 m3/h, distance between the nozzle and the sample of 4 cm. The power source used generates 5 kV, 100 mA at the industrial frequency of 50 Hz alternating current.

Sample 2 was treated using the minitorch as well. The treatment parameters were: treatment time 3 minutes, final temperature 32 oC, gas flow 7 m3/h, distance between the nozzle and the sample 3 cm. The power source used generates 10 kV, 50 mA at the industrial frequency of 50 Hz alternating current. The treatment time of 3 minutes corresponds in this case to two orthogonal passes of the minitorch over the treated sample, so the plasma is applied twice on the surface of the sample.

GlidArc Treatment

The GlidArc technology is based on a series of electric discharges initiated between two electrodes of divergent shape that are elongated due to a gas flow axial blown. They start from the area of the minimum distance between the electrodes and go out in the area of the maximum distance, at which point a new discharge is initiated in the area of the minimum distance. The power sources used for GlidArc were 10 kV / 50 mA, respectively 5 kV / 100 mA. Due to the high voltage of these sources, the electrons and photons (light particles) acquire a significant temperature and energy that they use to initiate specific reactions based on the active species created (radical OH, N2, O3, etc.). However, the ions (heavy particles) remain at a temperature close to the ambient temperature, which makes this type of plasma out of thermodynamic equilibrium. On the other hand, by limiting the electric current through discharges and due to the gas flow, the temperature of the plasma is low, which makes its non-thermal character.

The GlidArc technology allows obtaining a planar discharge or a volumetric discharge, depending on the geometry of the reactor. In the case of our tests, a plannar electrode geometry was used, and the samples were placed in a semi-open cylindrical enclosure. This enclosure had metal walls, and at the lower part where the samples were placed, there were two open windows in order to release the air from the reactor.

Two samples were treated with GlidArc technology considering the following conditions:
-        Sample 3 – time of treatment 3 minutes, gas flow at 1.5 m3 / h, minimum distance between the electrodes 2 mm, maximum temperature of the sample 36 oC, distance between the top of the electrodes and the sample 8.5 cm.
-        Sample 4 – time of treatment 3 minutes, gas flow at 1 m3 / h minimum distance between the electrodes 2 mm, maximum temperature of the sample 41 oC, distance between the top of the electrodes and the sample 8.5 cm.

DBD (Dielectric barrier discharge) treatment

The DBD technology consists in producing an electrical discharge through a space that contains at least one solid insulator between two conductive surfaces. In our case, one conductive surface was that of the treated sample, and the other was an identical surface, of an untreated sample. Between them, two layers of dielectric were used, one of which is air, with a distance of 2.5 mm, and one of glass with a thickness of 2 mm. A multitude of random arcs (hundreds or even thousands) are produced into the gap exceeding 1.5 mm between the two electrodes during discharges in gases at the atmospheric pressure. As the charges collect on the surface of the dielectric, they discharge in microseconds, leading to their reformation elsewhere on the surface. Similar to other electrical discharge methods, the contained plasma is sustained if the power supply provides the required degree of ionization, overcoming the recombination process leading to the extinction of the discharge plasma. Such recombinations are directly proportional to the collisions between the molecules and in turn to the pressure of the gas, as

explained by Paschen's Law. The discharge process causes the emission of energetic photons, the frequency and energy of which corresponds to the type of gas used to fill the discharge gap.

For Sample 5, the TL494 power source was used, powered at 96 volts and operating at a frequency of 25 kHz. The distance between the glass and the upper electrode was 2.5 mm, with a treatment time of 5 minutes. The maximum temperature achieved was 35 °C. It should be noted that this treatment process was not homogenous. It was observed that the plasma channels were not established on the entire surface of the treated sample.

For Sample 6, treatment was conducted using a transformer at a frequency of 25 kHz. The electric parameters of this transformer are 8 kV, 30 mA. The distance between the glass and the upper electrode was set to 2.5 mm, with a treatment duration of 5 minutes. The maximum temperature exceeded the threshold value of 45°C. This treatment process was consistent and homogenous.

Sample 7 was the untreated control sample (Witness).

2.2.1.3 Analysis of non-thermal plasma treatment

The analyses performed on the samples were the following:
- pictures before and after treatment using a metallurgical microscope type 5103 - M1000BD. Its maximum zoom is 1000x, but the pictures were taken with 500x zoom.
- measuring the roughness after treatment with a TMR120 type device. 5 distinct measurements were performed from which the Rz value was extracted. This value measures the difference between the highest peak and the lowest valley within the sampling length of five lines.
- measuring the chemical composition using X-Ray fluorescence spectrometer. It was used an Innov-X Vanta X-Ray device with a depth analysis of tens of micrometers.
- measuring the chemical composition using LIBS method (Laser Induced Breakdown Spectroscopy) for the surface of the samples.
The last 3 types of analyzes were performed with the help of portable devices. By definition, LIBS method gives the chemical composition of the surface of the inspected object, while the XRF method (X-ray fluorescence) method also reaches into the object, giving the chemical composition of both the surface and the depth of the object. Due to this difference, the results of the two methods may differ from one other. Because the LIBS analysis affects the surface of the samples, only a part of them (3 of 7) were subjected to this analysis even after Z903 +C LIBS device the non-thermal plasma treatment.

2.3   Field testing of environmentally friendly antifouling solutions in diverse marine environments

2.3.1   Antifouling solution production

Three type of textures were selected based on the outcomes of the Liverpool antifouling performance tests in 2024. This was one HD4, LD2 and R1. For plasma treatment, the adjusted mini torch was selected from the options. Stainless steel 316L 2B panels (50x50x0.9mm) were sent to CMU by LJMU for plasma treatment. CMU sent the plasma treated panels under vacuum (food quality) back to LJMU

for texturing. Plasma treated, texture treated and control panels under vacuum were put into sets for each site and sent by courier to partner sites.

2.3.1.1 Texture production

Please see 2.2.1.1 for production of textures HD4, LD2, S1 on 316L 2B stainless steel (50x50x0.9mm).

2.3.1.2 Plasma treatment

The purpose of the plasma treatment is to superficially modify the treated metal surface to increase the efficiency of the final treatment of LASER texturing that will be applied later. For this purpose, it is considered to obtain:
1) a smoothing phenomenon by reducing the roughness,
2) increasing the forces at the atomic level,
3) concentrating some chemical species on the superficial surface of the samples against the rust.
All these must be obtained without thermal damage of the treated surface!
Two types of electrical discharges with non-thermal plasma were chosen to treat the samples: Minitorch and DBD. The non-thermal plasma treatment was applied to several dozen naval steel samples provided by the LJMU partner. The sample dimensions were 5 cm x 5 cm x 1 mm.
The GlidArc technology is based on a series of electric discharges initiated between two electrodes of divergent shape that are elongated due to a gas flow axial blown. They start from the area of the minimum distance between the electrodes and go out in the area of the maximum distance, at which point a new discharge is initiated in the area of the minimum distance. The power source used for GlidArc is using a high voltage of minimum few kilovolts and a limited electric current, up to 1 A. Due to the high voltage of these sources, the electrons and photons (light particles) acquire a significant temperature and energy that they use to initiate specific reactions based on the active species created (radical OH, N2, O3, etc.). However, the ions (heavy particles) remain at a temperature close to the ambient temperature, which makes this type of plasma out of thermodynamic equilibrium. On the other hand, by limiting the electric current through discharges and due to the gas flow, the temperature of the plasma is low, which makes its non-thermal character.
The Minitorch is a technology derived from Gliding Arc technology. The geometry of the reactor is cylindrical. An electrode is placed along the axis of the cylinder, in the form of a rod pointed at the lower end. The second electrode has a tronconical shape, being placed at the lower end of the assembly, so that the minimum distance between the electrodes is near the exit from the reactor. An air flow is introduced through the upper side of the reactor, with the exit in the axial direction in its lower part, where a plasma jet is formed, as can be seen in Fig. 13 and Fig. 14. The minitorch is placed on a machine with numerical control of CNC3D type, that allows the choose of the followed trajectory, see Fig. 15, the adjustment of the travel speed and the distance to the treated sample. The samples had a fixed position, being placed on a magnetic table.
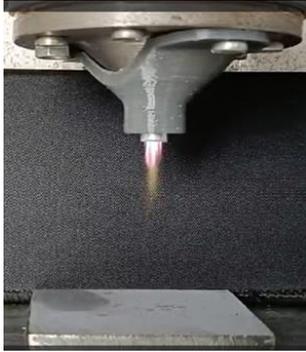
Fig. 13. Minitorch for non-thermal plasma treatment (5 kV, 100 mA power supply)
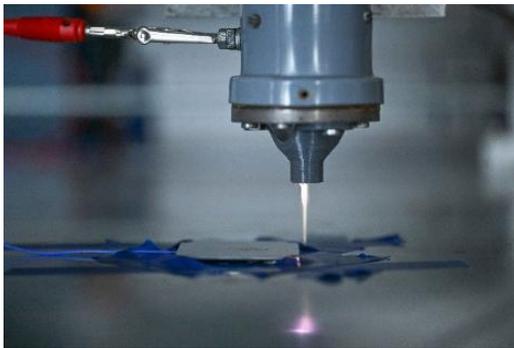
Fig. 14. Minitorch with single beam (10 kV, 50 mA power supply, final version)
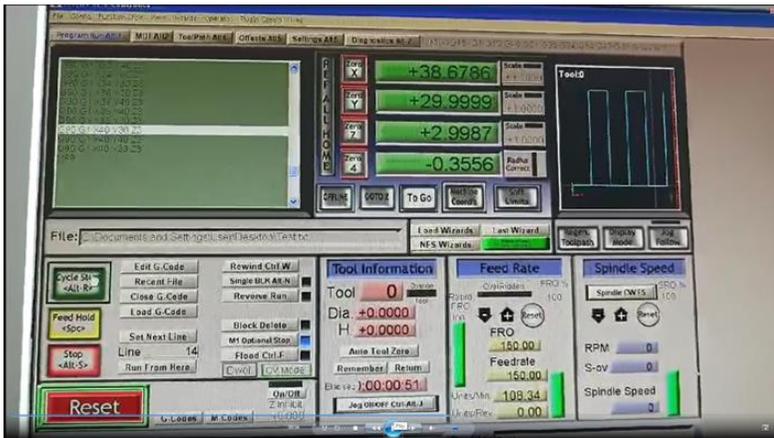
Fig. 15. Trajectory of the Minitorch on CNC3D machine on the top right corner

The DBD technology consists in producing an electrical discharge through a space that contains at least one solid insulator between two conductive surfaces. In our case, one conductive surface was that of the treated sample, and the other was an identical surface, of an untreated sample. Between them, two layers of dielectric were used, one of which is air, with a distance of 2.5 mm, and one of glass with a thickness of 2 mm, see Fig. 16. A multitude of random arcs (hundreds or even thousands) are produced into the gap exceeding 1.5 mm between the two electrodes during discharges in gases at the atmospheric
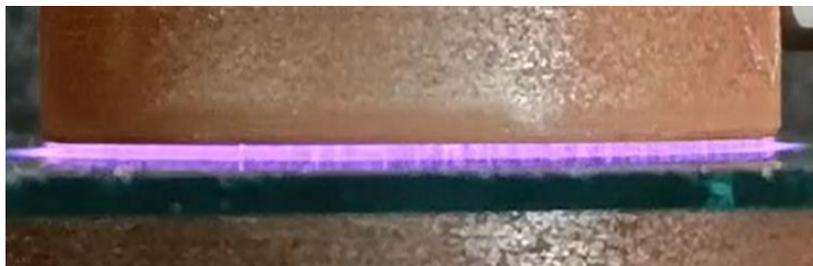
Fig. 16. Non-thermal plasma treatment using DBD technology with cylindrical geometry

pressure. As the charges collect on the surface of the dielectric, they discharge in microseconds, leading to their reformation elsewhere on the surface. Like other electrical discharge methods, the contained plasma is sustained if the power supply provides the required degree of ionization, overcoming the recombination process leading to the extinction of the discharge plasma. Such re-combinations are directly proportional to the collisions between the molecules and in turn to the pressure of the gas, as explained by Paschen's Law. The discharge process causes the emission of energetic photons, the frequency and energy of which corresponds to the type of gas used to fill the discharge gap.

For Sample 1, treatment was conducted using a transformer at a frequency of 25 kHz. The electric parameters of this transformer are 8 kV, 30 mA. The distance between the glass and the upper electrode was set to 2.5 mm, with a treatment duration of about 2 minutes. The maximum temperature exceeded the threshold value of 45°C. This treatment process was consistent and homogenous, see Fig. 17.

Sample 2 was treated using the minitorche. The treatment parameters were: treatment time 3 minutes, final temperature 34 oC, gas flow 7 m3/h, distance between the nozzle and the sample 3 cm. The power source used generates 10 kV, 50 mA at the industrial frequency of 50 Hz alternating current. The treatment time of 3 minutes corresponds in this case to two orthogonal passes of the minitorch over the treated sample, so the plasma is applied twice on the surface of the sample.

Sample 0 was the untreated control sample (Witness).

After the plasma treatment, the samples were placed in plastic bags that were vacuumed using a food vacuum device, FoodSaver FFS016X-01 type. The samples were kept in these conditions until the LASER texturing treatment were performed at LJMU or until specific analyses were done.
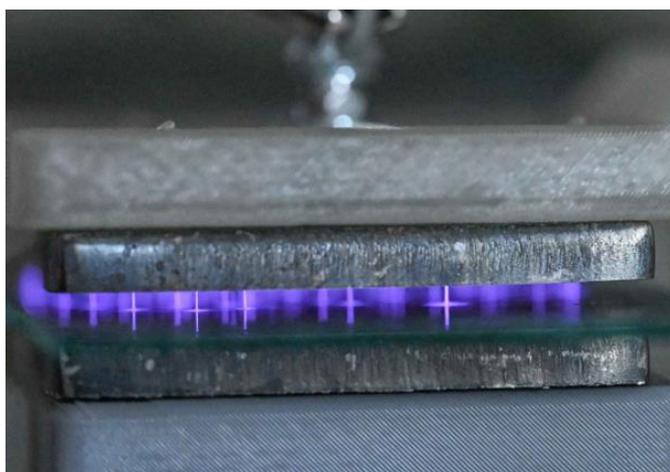
**Fig. 17. Non-thermal plasma treatment using DBD technology with planar geometry
Analysis**

The analyzes performed on the samples were the following:
- pictures before and after treatment using a metallurgical microscope type 5103 - M1000BD. Its maximum zoom is 1000x, but the pictures were taken with 500x zoom.
- measuring the roughness after treatment with a TMR120 type device. 5 distinct measurements were performed from which the Rz value was extracted. This value measures the difference between the highest peak and the lowest valley within the sampling length of five lines.
- measuring the chemical composition using X-Ray fluorescence spectrometer. It was used an Innov-X Vanta X-Ray device with a depth analysis of tens of micrometers.
- measuring the chemical composition using LIBS method () for the surface of the samples.
The last 3 types of analyzes were performed with the help of portable devices. By definition, LIBS method (Laser Induced Breakdown Spectroscopy) gives the chemical composition of the surface of the inspected object, while the XRF method (X-ray fluorescence) method   also reaches into the object, giving the chemical composition of both the surface and the depth of the object. Due to this difference, the results of the two methods may differ from one other. Because the LIBS analysis affects the surface of the samples, only a part of them (3 of 7) were subjected to this analysis even after Z903 +C LIBS device the non-thermal plasma treatment.

2.3.2   Field Testing

Field testing was conducted at all NOFOUL partner sites (Fig. 18), during March and April 2025, durations from 3 days to 4 weeks. Sites were selected by accessibility, lack of vandalism, water quality, water depth (minimum 1.5m), shade level, easy deployment, static deployment to avoid tidal impact. Partners were trained in biofouling and antifouling and received site-specific training and coaching by LJMU during the duration of the full period of preparing to sending photographs for assessment (see 5.1). Field testing and assessment followed as described in 2.2.1.2.
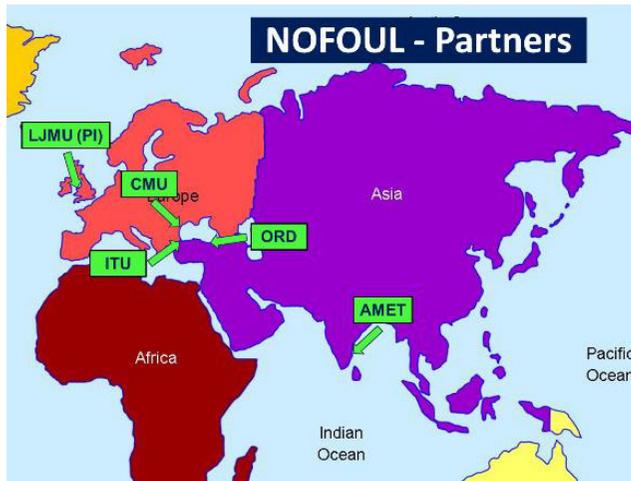
Fig. 18. The NOFOUL partner field sites Irish Sea (LJMU, UK), North Black Sea (CMU, Romania), Marmara Sea (ITU, Turkey), Eastern Black Sea (ORD, Turkey), Bay of Bengal (AMET, India).

2.3.2.1 Study Sites

Study sites were in sheltered areas such as marinas, ports or inlets (Table 2). Most sites were located in brackish waters. For most sites the exposure of the samples was during spring. Areas ranged from cold temperate to tropical in Europe to Asia (Table 3).

Table 2: Partner sites conducting the field tests including days of exposure, temperature and salinity.

| Partner Site	Exposure dates	days of exposure	Longitude/Lattitude	climate	average temperature [C°]	Salinity [psu]
LJMU	24th March to 22nd April 2025	29	53°24'96.5"N - 2°59'31.0"E	cold temperate	8	24
CMU	11th March to 3rd April 2025	23	44°10'30.7"N 28°39'42.4"E	temperate	9	14
ITU	13th March to 15th April 2025	33	40°48'49.39"N 29°17'39.29"E	warm temperate	9	22
ODU	8th March to 7th April 2025	30	41°04'61.99"N 37°48'66.87"E	warm temperate	12	18
AMET 1	27th March to 3rd April 2025	7	11°30'65" N79°48'06" E	tropical	26	22
AMET 2	5th May to 10th May 2025	5	12º 12'-12" N 70º 56' 80" E	tropical	24	40

2.3.2.2 Experimental design standardized

The experimental design for the antifouling field test was standardized between all sites. Partners build the standard frame (ABS piping) using a protocol. On the frame 6 carrier panels (e.g. PVC 20x20cm) were attached with cable ties. On each carrier panel five positions were set with Velcro (loop side). Coded samples sent by LJMU to the partners were set with Velcro (hook side) on the back and fixed on the positions on the carrier panels following the same coded map for all sites resulting in random organization of the samples. The experiments consisted of three different textures (HD4, LD2, R1) with and without non-thermal plasma treatment and a control (smooth) with and without non-thermal plasma treatment. All samples and controls were replicated by three. Factors were texture type and non-thermal plasma treatment. Frame and samples were positioned vertical facing outwards in 1metre depth.

2.3.2.3 Data collection standardized

Data collection was split into two sections: 1) for each partner, deployment (Table 3) and completion of experiment in the field, sample preservation, subsamples using a dissecting microscope and coded photography, sending these to LJMU; 2) photographs of subsamples of each sample analysed for percentage coverage of biofilm using the standard randomized 100 dots methods and ImageJ.

The partner data collection 1) included the evaluation of extra controls (smooth) for biofilm coverage after days or weeks depending on the geographical area. The control was assessed under the dissecting microscope and photographed. The ideal date for termination of the experiment at a site was a biofilm coverage at 50 to 60 percentage coverage. When the partner after discussion with LJMU terminated the experiment, the frame would have been removed from the water and each sample as per code was put in coded leakproof plastic containers (e.g. 65x65mm area) and preserved with Lugol's solution [49]. The amount needed is indicated by the seawater in the container stained brown to dark amber. The solution was meant to just cover the sample. The solution is used to stain carbohydrates in algae, bacteria and protists to yellow to light brown, fixated and making clearly visible against the substratum. The

samples had to be photographed using a camera connected with a dissecting microscope and a light source. Light microscopes were not suitable for the metal surfaces and textures. The dissecting microscope required to have a magnification that would fill the field of view as an area of about 600 to 700µm by 400 to 500 µm (Fig. 19; developed by S. Dürr, LJMU). Partners determined the needed magnification to achieve the set area size by using a calibration panel with a square laser engraved in the needed size and reading off the magnification. This microscope specific magnification was then used by the partner when taking the photographs of the subsamples on each sample. Each partner took 10 subsample photographs per sample randomly on the surface taking care to avoid edges of panels because of potential edge effects. This resulted in 240 photographs per site. Photographs were sent to LJMU via virtual transfer services.

The LJMU data collection was following the methods described for the summer 2024 testing at LJMU (see 2.2.1.2). Three random subsample photographs per sample were analysed using the 100 dots method (standardized random) using ImageJ. In total, 432 photos were analysed for percentage coverage of biofilm.

Table 3. Partner site name with photograph of their site when deploying the frame with samples.

Partner Site Name	Partner Site
LJMU	
CMU	
ITU	N/A
ODU	
AMET 1 Portonovo	
AMET 2 Marakkanam	
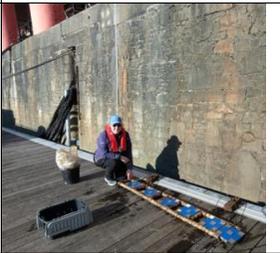
Fig. 19. Calibration panel with laser engraved square (660x450 µm) to determine the correct magnification needed for subsample photographs. The edges of the square would needed to define the edges of the photograph taken.

2.3.2.4 Statistical Analysis

For each three subsamples of each sample the mean was calculated. The mean was therefore the data point of each sample. Basic statistical analysis was conducted to determine differences between controls and factors texture type and non-thermal plasma treatment on biofilm coverage using a 2-factor ANOVA and following Tukey HSD post hoc test [48]. Data were first transferred with Arcsine transformation. Level of significance was 5%. Reduction of biofilm coverage relative to the control was calculated. For AMET Site 2 the texture type LD2 could not be included in the statistical analyses but were included in the graphical presentations. Data were presented in text and bar charts.

3. Results

3.1 Fine-tuning of antifouling solutions

3.1.1 Antifouling microtextures on metal surface

Profiles of the textures produced on 316L 2B stainless steel were imaged using the optical profilometer and these were used for measurements on the different textures (Table 4). Measurements shown a standard deviation of approximately 10%, showing the high reproducibility in the textures.

Table 4. Characteristics of the textures produced on 316L 2B stainless steel.

Texture	Valley depth (1) (μm)	Valley width (1) (μm)	Valley depth (2) (μm)	Valley width (2) (μm)	Peak height (μm)	Peak width (μm)
R 1	13 ± 1	33 ± 2			22 ± 2	12 ± 1
R 2	12 ± 1	35 ± 3			10 ± 1	8.0 ± 0.7
R 3	7.0 ± 0.6	54 ± 4			12 ± 1	12 ± 1
R 4	7.0 ± 0.6	49 ± 4			8.0 ± 0.7	11 ± 1
R 5	16 ± 1	59 ± 5			9.0 ± 0.9	10 ± 1
R 6	15 ± 1	60 ± 6			7.0 ± 0.6	8.0 ± 0.7
R 7	23 ± 2	61 ± 6			10 ± 1	7.0 ± 0.6
HD 1	17 ± 1	55 ± 5	6.0 ± 0.5	28 ± 2	12 ± 1	5.0 ± 0.5
HD 2	6.0 ± 0.4	23 ± 2			3.0 ± 0.2	7.8 ± 0.6
HD 3	7.0 ± 0.6	48 ± 4	3.0 ± 0.2	35 ± 3	8.0 ± 0.7	8.0 ± 0.8
HD 4	20 ± 2	43 ± 3			24 ± 2	20 ± 2
HD 5	30 ± 3	48 ± 4			25 ± 2	9.0 ± 0.8
LD 1	8.0 ± 0.8	67 ± 6			7.0 ± 0.6	8.0 ± 0.7
LD 2	17 ± 1	66 ± 5			10 ± 1	10 ± 1
LD 3	13 ± 1	71 ± 7			5.0 ± 0.5	7.0 ± 0.6

3.1.2 Plasma treatment on metal surface

It is observed that all non-thermal plasma treatments (Table 5) cause a decrease in the roughness values in relation to the untreated control. The lowest values are obtained in the case of treatment with the DBD technology and respectively with the Minitorch. This can be explained by the fact that these treatments determine a better homogeneity of the treated metal surface in relation to the application of GlidArc technology.

The treated surface of sample 5 looks better than that of sample 6, even if the temperature limit was exceeded. This overpassing can be avoided later by increasing the distance of the air gap between an electrode and the surface of the glass, which will limit the electric current values, therefore the temperature of the treated sample.

The XRF analysis emphasizes the increasing of Ni and Cr concentrations at the surface of the samples for 5 of 6 non-thermal plasma treatments. Similar results were previously obtained underlined the improved properties of naval steel samples after non-thermal plasma treatment.

Table 5: Results from the comparison of the different methodologies.

Sample / Plasma / Analyse	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Plasma Type	Minitorch (5kV, 100mA)	Minitorch (10kV, 50mA)	GlidArc, Q₁	GlidArc Q₂ < Q₁	DBD (25 kHz, TRAF1)	DBD (25 kHz, TRAF2)	Witness

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Rugosity	Rₐ [µm] 0.13	Rₐ [µm] 0.17	Rₐ [µm] 0.2	Rₐ [µm] 0.22	Rₐ [µm] 0.08	Rₐ [µm] 0.15	Rₐ [µm] 0.39

LIBS

Sample 1						Sample 2					Sample 3					Sample 4					Sample 5					Sample 6					Sample 7				
Mn%	Si%	C%	Ni%	Al%	Cr%	Mn%	Si%	C%	Ni%	Cr%	Mn%	Si%	C%	Ni%	Cr%	Mn%	Si%	C%	Ni%	Al% Cr%	Mn%	Si%	C%	Ni%	Cr%	Mn%	Si%	C%	Al% Ni%	Cr%	Mn%	Si%	C%	Al%	Ni%
1.53	0.163	0.186	0.074	0.038		0.941	0.162	0.160	0.056	0.030	1.30	0.171	0.186	0.001	0.033	1.490	0.198	0.087	0.075	0.035	1.25	0.159	0.205	0.076	0.032	1.88	0.174	0.219	0.152 0.075	0.037	1.67	0.180	0.218	0.102	0.077

XRF before

Sample 1						Sample 2						Sample 3					Sample 4					Sample 5					Sample 6					Sample 7			
Mn%	Si%	Cr%	Ni%	Cu%		Mn%	Si%	C%	Cr%	Ni%	Bi% Cu%	Mn%	Si%	Cr%	Ni%	Bi%	Mn%	Si%	Cr%	Bi%	Mo%	Mn%	Si%	Cr%	Ni%	Cu%	Mn%	Si%	Cr%	Ni%	Bi%	Mn%	Si%	Cr%	Ni%
1.395	0.166	0.027	0.013	0.01		1.392	0.209	0.024	0.014	0.009		1.401	0.2 28	0.026	0.009	0.002	1.411	0.223	0.011	0.005	0.011	1.418	0.1418	0.026	0.015	0.009	1.402	0.258	0.026	0.007	0.009	1.394	0.213	0.027	0.014

XRF after

Sample 1						Sample 2						Sample 3					Sample 4					Sample 5					Sample 6					Sample 7			
Mn%	Si%	Cr%	Ni%	Cu%		Mn%	Si%	C%	Cr%	Bi%	Cu%	Mn%	Si%	Cr%	Ni%	Cu%	Mn%	Si%	Cr%	Ni%	Bi% Cu%	Mn%	Si%	Cr%	Ni%	Cu%	Mn%	Si%	Cr%	Ni%	Cu%	Mn%	Si%	Cr%	Ni%
1.390	0.189	0.027	0.013	0.009		1.377	0.205	0.028	0.018	0.009		1.392	0.257	0.032	0.008	0.008	1.382	0.243	0.024	0.021	0.015 0.010	1.382	0.224	0.029	0.012	0.008	1.399	0.230	0.026	0.017	0.011	1.394	0.213	0.027	0.014

3.1.3 Antifouling field testing of textures

Biofilm percentage coverage was very low when lifted (60.23±15.68% on the control; n=3, subsamples=3).

There was no significant difference between type of texture and the control in biofilm percentage coverage (F:1.643 df 15 p=0.117; Fig. 20). Lowest biofilm percentage coverage in each family of textures was at HD5 (8±1.35%), LD1 (43.56±16.06%) and R1 (15.56±2.50%).
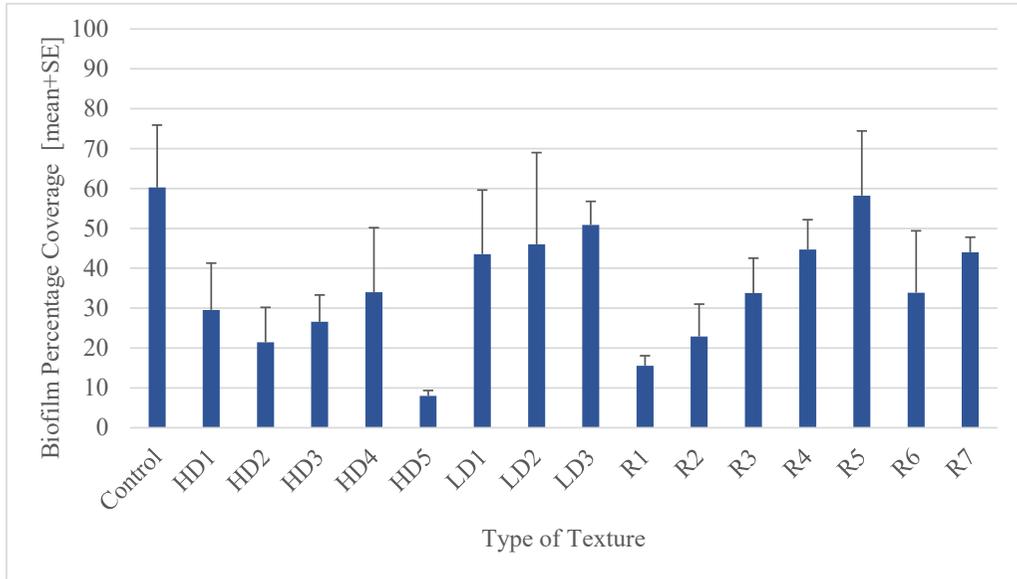
Fig. 20. Biofilm percentage coverage (mean+SE) for 15 different textures out of three texture families and the control.

3.2   Field testing of environmentally friendly antifouling solutions in diverse marine environments

3.2.1   Antifouling solution production

3.2.1.1 Textures

Selected best antifouling performance textures (HD4, LD2, R1) on 316L 2B stainless steel samples (50x50x0.9mm) were measured using the same methodology as described on 3.2.3 with demonstration of 10% standard deviation therefore reproducible.

3.2.1.2 Non-thermal plasma treatment

The results of the analyses are presented in the tables 6 and 7. From table 6 could be observed a decrease in roughness as result of plasma treatment. Chemical analysis cannot identify changes in concentration, as was obtained in the case of similar samples with a thickness of about 5 mm after the non-thermal plasma treatment.

(LJMU)

Table 6. Values of rugosity after the non-thermal plasma treatment

Rugosity (μm)	Sample 0 Witness	Sample 1 DBD	Sample 2 Minitorch
Zt1	0.16	0.19	0.16
Zt2	0.2	0.16	0.19
Zt3	0.21	0.13	0.17
Zt4	0.17	0.17	0.16
Zt5	0.16	0.18	0.16
Rz5 (average)	0.18	0.166	0.168

Table 7. Chemical composition at the surface of the treated samples

Chemical Element	Sample 0 Witness	Sample 1 DBD	Sample 2 Minitorch
Fe %	68.54	68.41	68.54
Ni %	10.31	10.3	10.19
Cr %	16.92	16.92	16.9
Si %	0.493	0.509	0.524
Co %	0.16	0.21	0.218
Mn %	0.956	1.021	1.021
Cu %	0.386	0.39	0.399
Mo %	2.057	2.052	2.036
V %	0.074	0.084	0.074
W %	0.058	0.062	0.058
Nb %	0.037	0.035	0.035
P %	0.012		

3.2.2   Field Testing in diverse marine environments

The field testing was conducted during March to early May 2025. Photographs of the subsamples were taken for each sample at each site (Table 8). Biofilm percentage coverage was assessed on three subsamples per sample at each site. Data analyses for each site are presented in text and graph.

Table 8. Photographs taken by NOFOUL partners with the help of a dissecting microscope for the different sites showing the different textures with and without non-thermal plasma treatment. Photographs were taken with phones or specialist microscope cameras.

Partner Site Name	Plasma treatment	Control	Texture HD4	Texture LD2	Texture R1
LJMU	Yes				
LJMU	No				
CMU	Yes				
CMU	No				
ITU	Yes				
ITU	No				
ODU	Yes				
ODU	No				
AMET 1 Portonovo	Yes				
AMET 1 Portonovo	No				
AMET 2 Marakkanam	Yes				
AMET 2 Marakkanam	No				

LJMU

Biofilm percentage coverage was good when lifted (90.11±2.80% on the control, 67.11±4.30% on the control treated with plasma; n=3, subsamples=3).

There was a significant difference between type of texture, plasma treatment and the control in biofilm percentage coverage (F:19.320 df 7 p<0.001; Fig. 21). The biofilm percentage coverage of the control was significantly higher than all textures with or without plasma treatment (p<0.001; HD: 24.56±5.24%; HD+P: 20.11±6.15%; LD: 41.56±9.09%; LD+P: 16.56±1.57%; R: 22.89±9.10%; R+P: 22.22±3.70%). Biofilm percentage coverage of control plus plasma treatment was significantly higher than HD (p=0.005), HD+P (p=0.002) , LD+P (p<0.001) , R (p=0.003) and R+P (p=0.003). Lowest biofilm percentage coverage was HD in the textures without plasma and LD in the textures with plasma. LD with plasma demonstrated the lowest biofilm percentage coverage at the site LJMU.

Fig. 21. Biofilm percentage coverage (mean+SE) for three different textures out of three texture families, with and without plasma treatement and the controls with and without plasma treatment at LJMU.

CMU

Biofilm percentage coverage was good when lifted (87.00±1.53% on the control, 80.56±1.64% on the control treated with plasma; n=3, subsamples=3).

There was a significant difference between type of texture, plasma treatment and the control in biofilm percentage coverage (F:8.049 df 7 p<0.001; Fig. 22). The biofilm percentage coverage of the control was significantly higher than all textures other than R+P (74.78±3.23%) with or without plasma treatment (p<0.001; HD: 67.00±1.20%; HD+P: 71.00±4.40%; LD: 59.89±6.15%; LD+P: 64.44±2.54%; R: 68.78±2.78%). Biofilm percentage coverage of control plus plasma treatment was significantly higher than LD (p=0.007) , LD+P (p=0.042). Lowest biofilm percentage coverage was LD in the textures without plasma and LD in the textures with plasma. LD without plasma demonstrated the lowest biofilm percentage coverage at the site CMU.
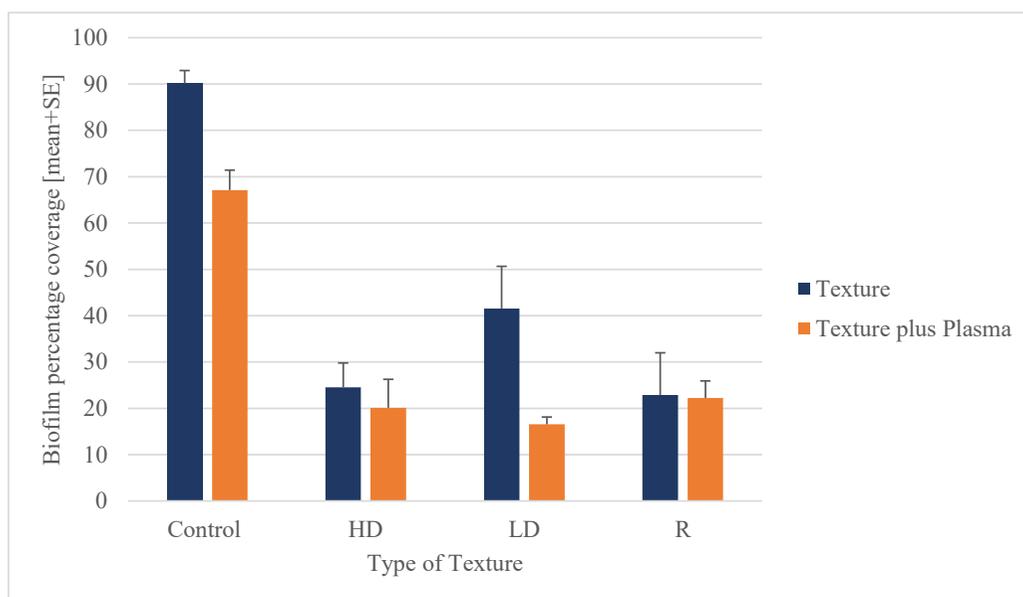
Fig. 22. Biofilm percentage coverage (mean+SE) for three different textures out of three texture families, with and without plasma treatement and the controls with and without plasma treatment at CMU.

ITU

Biofilm percentage coverage was very high when lifted (97.11±2.89% on the control, 99.78±0.22% on the control treated with plasma; n=3, subsamples=3).

There was no significant difference between type of texture, plasma treatment and the control in biofilm percentage coverage (F:1.067 df 7 p=0.427; Fig. 23). The biofilm percentage coverage of the textures with or without plasma treatment were similar (HD: 88.88±5.34%; HD+P: 88.00±1.76%; LD: 92±7.34%; LD+P: 91.22±4.39%; R: 86.78±9.37%; R+P: 87.67±6.31%). Lowest biofilm percentage coverage was R (not significant!) in the textures without plasma and R+P in the textures with plasma. R without plasma demonstrated the lowest biofilm percentage coverage at the site ITU.
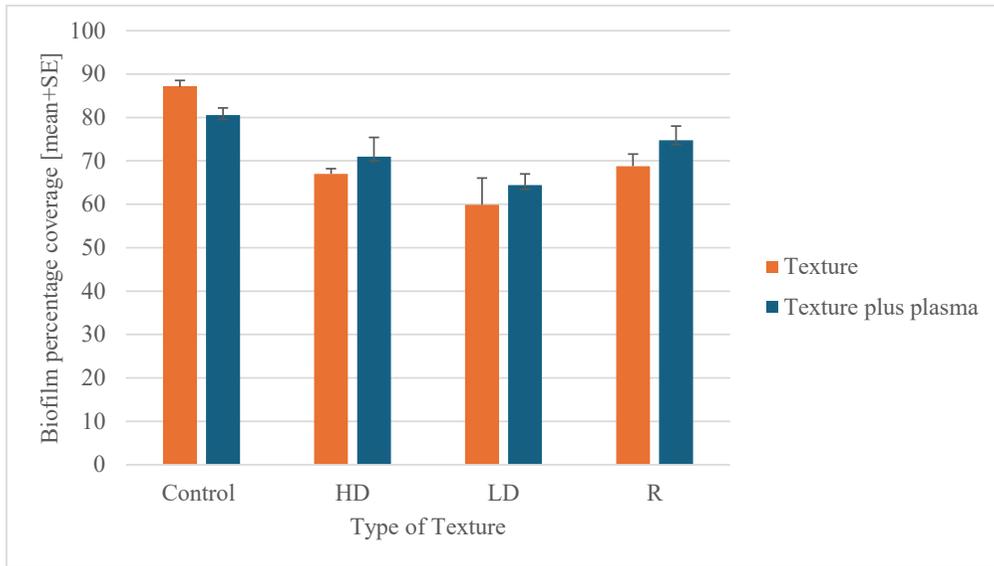
(LJMU)

Fig. 23. Biofilm percentage coverage (mean+SE) for three different textures out of three texture families, with and without plasma treatement and the controls with and without plasma treatment at ITU.

ODU

Biofilm percentage coverage was good when lifted (93.44±2.76% on the control, 91.89±3.63% on the control treated with plasma; n=3, subsamples=3).

There was a significant difference between type of texture, plasma treatment and the control in biofilm percentage coverage (F:4.028 df 7 p=0.010; Fig. 24). The biofilm percentage coverage of the control was significantly higher than LD (p=0.034; 59.11±12.60%). Biofilm percentage coverage of HD (94.00±4.70%) was significantly higher from LD (p=0.017). The biofilm percentage coverage of the other textures with or without plasma treatment and controls were similar (HD+P: 91.56±3.06%; LD+P: 78.22±9.01%; R: 75.44±4.83%; R+P: 76.22±4.30%). Lowest biofilm percentage coverage was LD in the textures without plasma and R (not significant) in the textures with plasma. LD demonstrated the lowest biofilm percentage coverage at the site ODU.
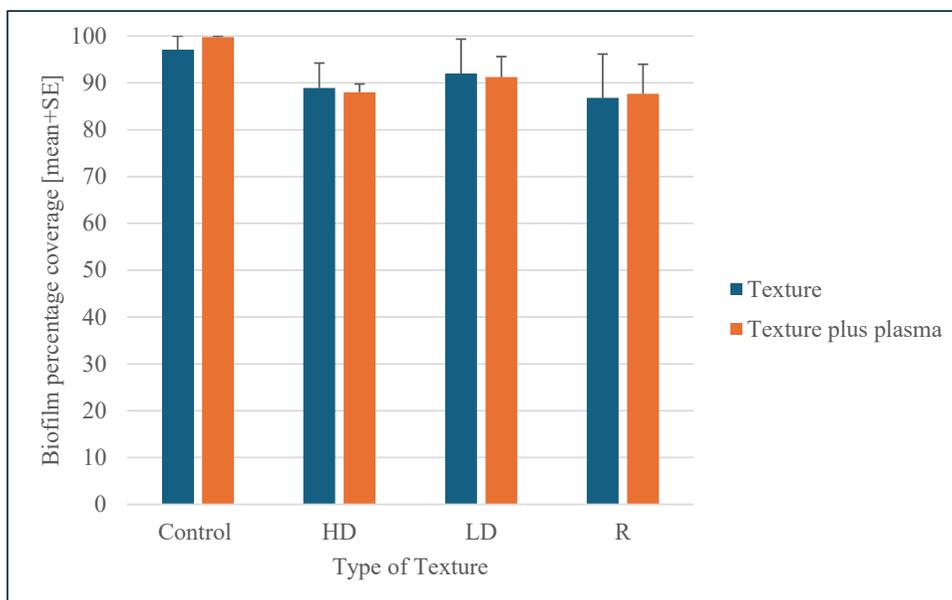
Fig. 24. Biofilm percentage coverage (mean±SE) for three different textures out of three texture families, with and without plasma treatement and the controls with and without plasma treatment at ODU.

AMET1

Biofilm percentage coverage was high when lifted (94.22±3.08% on the control, 96.56±0.48% on the control treated with plasma; n=3, subsamples=3).

There was no significant difference between type of texture, plasma treatment and the control in biofilm percentage coverage (F:0.897 df 7 p=0.532; Fig. 25). The biofilm percentage coverage of the textures with or without plasma treatment and the controls were similar (HD: 83.11%±8.37%; HD+P: 85.78±3.56%; LD: 93.33±3.67%; LD+P: 82.11±7.06%; R: 85.67±0.58%; R+P: 81.67±10.39%). Lowest biofilm percentage coverage was HD (not significant!) in the textures without plasma and R+P (not significant!) in the textures with plasma. R+P demonstrated the lowest biofilm percentage coverage at the site AMET1.
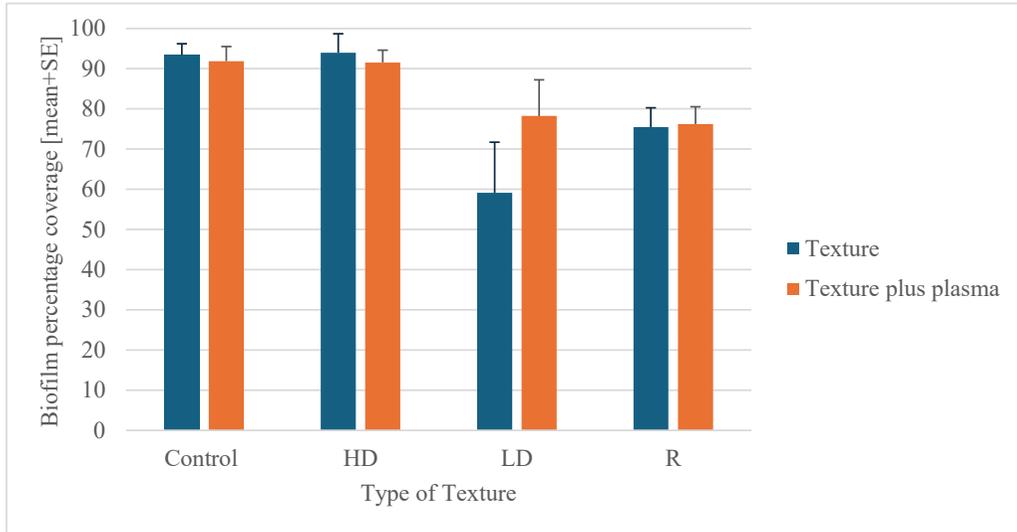
Fig. 25. Biofilm percentage coverage (mean+SE) for three different textures out of three texture families, with and without plasma treatement and the controls with and without plasma treatment at AMET1.

AMET2

Biofilm percentage coverage was good when lifted (83.44±10.27% on the control, 88.22±4.89% on the control treated with plasma; n=3, subsamples=3). LD plus plasma was not statistically analysed because only 2 replicates were available.

There was a significant difference between type of texture, plasma treatment and the control in biofilm percentage coverage (F:7.726 df 7 p<0.001; Fig. 26). The biofilm percentage coverage of the control was significantly higher than HD (p=0.034; 53.11±3.70%), HD+P (p=0.007; 44.11±5.50%) and R (p=0.027; 51.89±6.72%). The biofilm percentage coverage of the control plus plasma treatment was significantly higher than HD (p=0.014), HD+P (p=0.003), LD (p=0.023; 55.89±0.91%), R (p=0.011) and R+P (p=0.043; 59.33±4.81%). Lowest biofilm percentage coverage was HD in the textures without plasma and HD+P in the textures with plasma. HD+P demonstrated the lowest biofilm percentage coverage at the site AMET2.
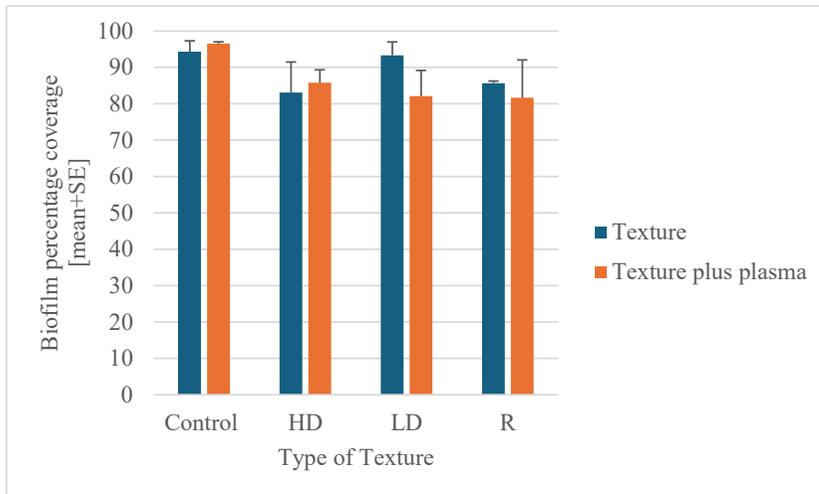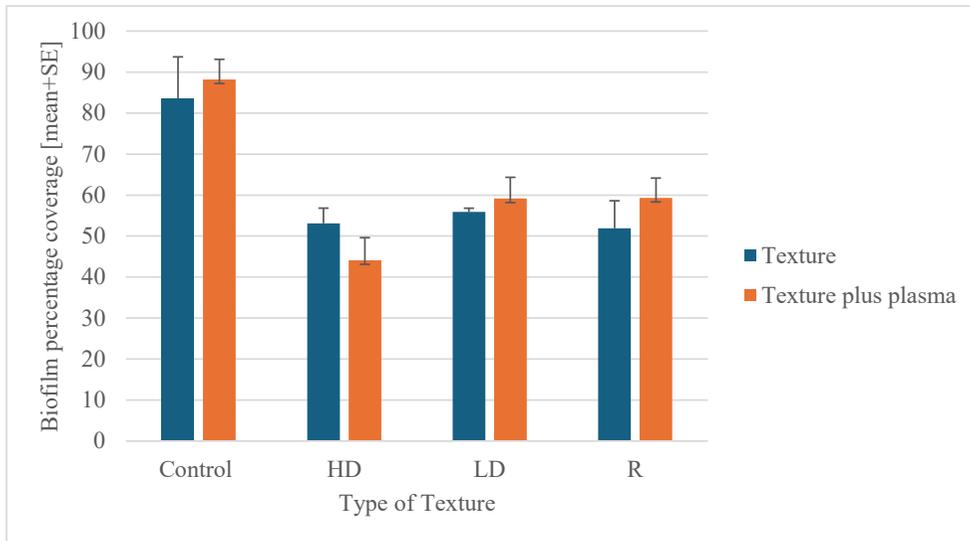
Fig. 26. Biofilm percentage coverage (mean+SE) for three different textures out of three texture families, with and without plasma treatement and the controls with and without plasma treatment at AMET2.

Best textures with and without plasma treatment for all sites:
HD and LD demonstrated significantly lowest biofilm percentage coverage at LJMU, AMET2, and CMU, ODU, respectively. HD and LD plus plasma treatment demonstrated significantly lowest biofilm percentage coverage at AMET2, and LJMU, CMU, respectively.

4. Discussion

The first step to achieve the final outcomes in best performing antifouling textures with and without plasma treatment in European and Asian marine environments was to test a number of three of LJMU texture families and select from this text the best performing textures from each family. The microtextures were produced using laser machining with an IR fibre laser model (SPI Laser (UK) G3 20 W nanosecond pulsed fibre laser) after fine-tuning of existing textures in the LJMU texture library. Textures quality was assessed using measurement obtained with a profilometer. Textures were then tested in the field. The antifouling performance of the textures against the control was not significant but there was a clear trend compared to previous experiments with these three texture families. The low biofilm coverage overall may have led to the lack of statistical evidence; the high numbers for the standard error may point towards a biofilm that is still in early development which is unusual for a summer experiment of that duration and may be due to the too cold and cloudy summer in the geographical region. Still from the trend and previous studies at LJMU, HD4, LD2 and R1 were selected for the field testing at all partner sites.

The pilot non-thermal plasma was focused on the type of plasma treatment to apply on the 316L 2B stainless steel panels before laser texturing. For non-thermal plasma treatment, some of the pictures taken after the treatment exclude the use of that technology for the final preparation of the samples in order to texture them with LASER. The number of analyses for each treatment with non-thermal plasma was determined to be much higher in order to generalise the observations and conclusions.

Based on the outcomes, the final treatment was determined to be with the minitorch technology, with a power source at 10 kV, 50 mA, and in addition with the DBD technology, using the source of 8 kV, 30 mA, 25 kHz. For both, the Minitorch and GlidArc treatments, an increase in the chemical concentration of nickel and chromium was observed, suggesting an improvement in corrosion resistance using either treatment. The lowest values of the rugosity after non-thermal plasma treatment are obtained with the DBD technology, and with the Minitorch.

Although both GlidArc and Minitorch technologies were used an axial air blow, the former was more difficult to apply for surface treatments of solids due to the variation of the plasma column in contact with the treated surface. The GlidArc technology was applied on the surface of naval steel samples may risk the equivalent of a surface heat treatment due to the planar geometry and the difficulty of moving the reactor on a pre-established trajectory. The Minitorch may produce a more stable plasma beam, which by moving on a pre-established trajectory with the help of the CNC machine on the one hand may avoid excessive heating of a part of the surface, on the other hand may ensure a relatively uniform contact with the treated surface. In CMU, these outcomes led to the use of the two treatment, the minitorch technology and the DBD technology to treat the stainless steel panels prior to laser texturing at LJMU. To avoid the decrease of the plasma treatment during transport and texturing, panels were kept in vacuumed bags or/and in desiccators.

All NOFOUL partners were received training in biofouling (workshop) and site-specific training in person by LJMU to run the field antifouling test (see Part 2) in order to achieve standardization of the experiment and thus, allowing comparisons between sites. NOFOUL partners including LJMU run the experiment, were able to determine the best antifouling textures with and without plasma treatment for each site and overall over all sites. The textures HD and LD demonstrated lowest biofilm percentage coverage at LJMU, AMET2, and CMU, ODU, respectively. The textures HD and LD, both plus plasma treatment, demonstrated lowest biofilm percentage coverage at AMET2, and LJMU, CMU, respectively. Here, only statistically significant outcomes from the experiments were included in the evaluation. Thus, AMET1 and ITU were not included at all in the selection, while ODU was taken part only in the non plasma treated textures. Even as the selection of the best textures may appear the same with and without plasma treatment (HD, LD) for these sites, nevertheless, the outcomes are not the same. AMET2 may

benefit from HD with and without plasma but LJMU may only benefit from HD under non-plasma conditions and may benefits more from the LD texture under plasma treatment, while CMU benefits from the texture LD with and without plasma treatment. Under the current assessment (three instead of 10 subsamples per sample were analysed due to time constraints to complete the final report) these outcomes may be strengthened and clearer with the higher number of subsamples. Even now, the outcomes of different types of textures with and without plasma in their antifouling performance was better at some sites and worse at other sites. Biofilm in quality and quantity may not the same globally, rather it may vary between the NOFOUL sites and even more globally at large and small scales. Thus the changes in biofilm may lead to different antifouling solution requirements as NOFOUL demonstrated with the unique and novel environmentally friendly antifouling solution textures with plasma treatment.

Part 2 – Maritime Education and Training (MET)

5. Methodology

5.1 Biofouling Training

5.1.1 Biofouling Workshop

The aim of the Biofouling Workshop (Phase 1) was to inform and develop biofouling knowledge, background, skills, antifouling field trial approaches, biofouling assessment requirements and standardisation for the planned participatory and collaborative research (international experiment in 2025). The workshop was interdisciplinary, intercultural and an informal agreement was presented which included to 1) get to know other partners; 2) Appreciate each other knowledge, background and contribution; 3) Discuss openly, with respect. Non-specialist NOFOUL partners from India, Turkey and Romania were taken part in the Biofouling Workshop at LJMU (United Kingdom) on the 23rd and 24th July 2024 to receive training from LJMU biofouling specialists on biofouling and antifouling.

5.1.2 Site-specific Training

Site-specific Training
The aim of the Site-specific Training was to develop biofouling skills specific for the site to be able to run the standardised antifouling field trial, and identify specific biofouling assessment requirements for the planned participatory and collaborative research (international experiment in 2025). Trainees were engineers and had not conducted any field experiments before other than one trainee who worked on pre-set up antifouling coating experiments for an engineering perspective. This lack of site knowledge required to introduce site specific training for the field experiment itself and the data collection.

5.1.3 IAMU Biofouling Network and Webinars

The aim of the Biofouling Network was to facilitate outside of the NOFOUL project for experts and novices, interest groups, academics and mariners to exchange knowledge on biofouling and antifouling, networking, training, and collaborations in projects. The Biofouling Network was limited to IAMU members. The network was set as a tool to find people within IAMU sharing the same interest, here biofouling and antifouling. Within the network the NOFOUL project can transfer their learning and knowledge while non-project interestees can benefit and exchange knowledge depending on their level of knowledge.

The organised network has the function for NOFOUL to disseminate outcomes, introduce IAMU members to the issues of biofouling and antifouling, offer training, networking, and collaborating. Particularly, training was identified as a key aspect in Resolution MEPC.378(80) (International Maritime Organisation, 2023) requiring mariners being trained in the subject biofouling and antifouling. The training for mariners and Higher Education lecturers can be an important role of the network. NOFOUL trained non-specialists demonstrated their capability to transfer knowledge to the IAMU Biofouling Network via webinars and to students of one of the partner universities (CMU) increasing the pool of training opportunities for mariners and Higher Education lecturers.

Webinars are at this point in time the key tools for connecting the interest group in the IAMU Biofouling Network. Members are globally distributed and depended on virtual meetings. The IAMU Biofouling Network webinars are designed by NOFOUL to focus on one biofouling or antifouling topic. The topic is presented by slide show and at least two presenters. The followed discussion is open to everyone; questions or contributions are to be presented by chat or speech with or without camera. During the

webinar a number of polls were introduced while after the webinar a survey was optional available to complete.

5.2 Higher Education maritime teaching on biofouling

The NOFOUL Project's higher education initiative on marine biofouling has demonstrated remarkable success in generating student interest and engagement. After a teaching class about marine biofouling where NOFOUL results were shared to students in Electrical Engineering at Constanta Maritime University (CMU), Romania in May 2025, a feedback analysis based on survey responses from 40 students (Fig. 27) and one teacher reveals strong overall interest in the topic, with a majority expressing desire to learn more about specific aspects of marine biofouling.

Fig. 27. Teaching about marine biofouling and NOFOUL's results at Constanta Maritime University.

6. Results

6.1 Biofouling Training

6.1.1 Biofouling Workshop

The five visitors from Constanta Maritime University (CMU; 2 persons), Istanbul Technical University (ITU; 1 person), Ordu University (ODU; 1 person) and the University Academy of Maritime Education and Training (AMET; 1 person) engaged actively in person with the training while additional partners from CMU (1 person) and ODU (1 person) engaged virtually (Fig. 28). The tools were short lectures (15 to 20 mins) followed by discussions in the group (15 to 20mins). Practical sessions (hands-on learning) were conducted in the laboratories (photonics laboratory, marine biosciences laboratory) and at the field site for antifouling testing (Fig. 29; Liverpool South Docks, United Kingdom). These tools facilitated knowledge transfer, exchange knowledge and methodologies on biofouling and antifouling. Visiting the laser texturing and biofouling labs, the field site Royal Albert Dock as well as experiencing practical sessions on biofouling identification using microscopes, adhesion strength of biofouling using a force gage and using image analysis for assessment were designed in order to provide activity breaks from the intense discussions and facilitated the 2-way knowledge exchange. At the end of each day feedback sessions were included to discuss in the group and set up actions on key points. Trainees pointed out that they learned many new aspects of the biofouling they never had heard about before and how it changed their understanding and perspective of biofouling. Trainees were much inspired by the practical work.

Fig. 28. A number of Biofouling Workshop participants in person and virtually in the Byrom St Campus, Liverpool, United Kingdom (23rd July 2024)

Fig. 29. Biofouling Workshop trainees learning about antifouling experiments in the field hands on at Royal Albert Dock, Liverpool, United Kingdom (24th July 2024)

6.1.2 Site-specific Training

Two separate training parts were considered that are site-specific and cannot be addressed by the trainer and coach when not on site. Thus, the trainer was required to complete a site visit to work with the trainee. The trainee is needed to complete work following experimental protocols and virtual coaching prior to the visit. The visits to each partner site was conducted by the trainer in early to mid January 2025. Samples were sent by courier mid-February 2025. Deployment, removal and preservation depended on customs and speed of biofilm growth at each site (3 days to weeks). Training part 1 was designed around the field trial with the tasks: 1) obtaining the materials, 2) building the experimental frame, 3) identifying the field site, 4) attaching the samples to be tested on the frame, 5) deploying the frame and the samples, 6) selecting environmental measurements during deployment of the samples, 7) determining the point of time for removal of samples, 8) removal, coding and preserving of samples. Trainees were required to complete Tasks 1), 2), and 3) based on a protocol and virtual coaching by the trainer. Tasks 1) to 3) were then corrected and validated during the site visit. Tasks 4) to 8) were prepared during the site visit with the trainer and trainee using knowledge transfer and coaching while after the visit the trainee was supported by virtual coaching and a guide for the samples. Training part 2 was designed around the treatment of the preserved samples with the tasks: 1) identification a dissecting microscope with suitable magnification, 2) taking photographs, 3) sending photographs to LJMU for assessment, 4) assessing photographs for percentage coverage of biofilm using a standard image analysis method used by undergraduate students up to researchers. Task (1 was required to be completed by the trainee prior to the visit by the trainer based on guidance. Tasks (2 and (3 were taught by knowledge transfer and guidance during the visit and after the visit via a protocol and virtual coaching by the trainer. Task 4 was included as an optional task for the trainee but was not expected because of the shortness of NOFOUL and the high time needs of the assessment. This task was supported by training during the visit, a protocol and coaching by the trainer past visit.

6.1.3 IAMU Biofouling Network and Webinars

The IAMU Biofouling Network was initiated by NOFOUL during the IAMU AGA 25 in their progress report presentation and with flyers (Fig. 30). The network grew from the initiation with each webinar. The IAMU Biofouling Network counts 47 members including NOFOUL partners and IAMU Secretariate. Members are from the UK, Romania, Turkey, India, Georgia, Philippines, Norway, Sweden, Japan, Montenegro, Panama, Ghana, USA and Croatia and from 16 IAMU member

Universities. Networks members are mostly academics and a few post-doctoral researchers, PhD students and even undergraduates.

The webinars participation was 71 at the first webinar (Topic: Biofouling general information; 9th December 2024), 44 at the 2nd webinar (Topic: Environmentally friendly antifouling; 25th April 2025) and 20 at the 3rd webinar (Topic: Field Tests and how to select an antifouling coating; 14th May 2025). This shows a trend of decrease in participation. This trend was expected; the first webinar demonstrated a new topic for IAMU to be offered by their association and more participants were attracted. In the following live webinars less participants may have been attracted because by then it was known that webinars are recorded and available at any time. Notably, new participants were attracted by each webinar and number of views of webinar recordings are not available.

The survey at closure of the webinars included 11 questions. Three questions were considered 1) "Would you like to be a part of IAMU Biofouling Network?" 2) "What is your current level of knowledge about biofouling and antifouling?" 3) "Would you like to see follow-up sessions on related topics?". Most participants (90%, 86%, 83%; Fig. 31) were taking part in the network or already were. The number of participants already in the network increased from webinar to webinar (14%, 27%, 33%). The level of knowledge on biofouling and antifouling of number of participants decreased from webinar to webinar (advanced level: 27%, 14%, 8%; Fig. 32) while the number of beginners increased from webinar to webinar (beginner level: 35%, 41%, 58%). Most participants would like to see further webinars on the topic (100%, 95%, 92%; Fig. 33).

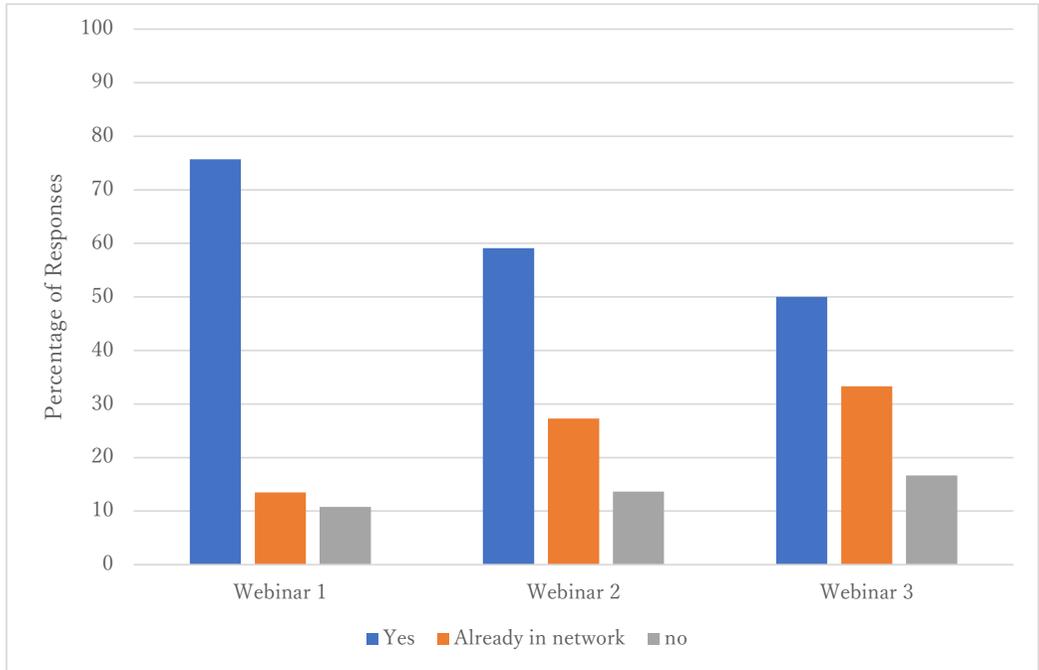**Fig. 30. The IAMU Biofouling Network flyer (@ S. Dürr, N. Jones)**

Fig. 31. Percentage responses for each webinar (Question: Would you like to be a part of IAMU Biofouling Network?)
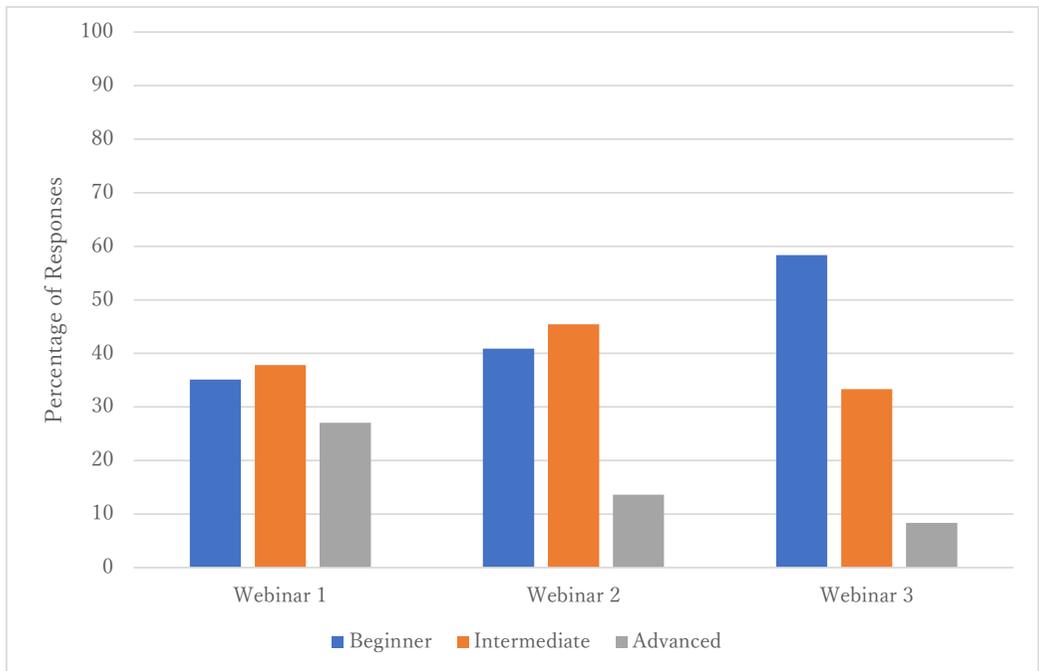

Fig. 32. Percentage responses for each webinar (Question: What is your current level of knowledge about biofouling and antifouling?)
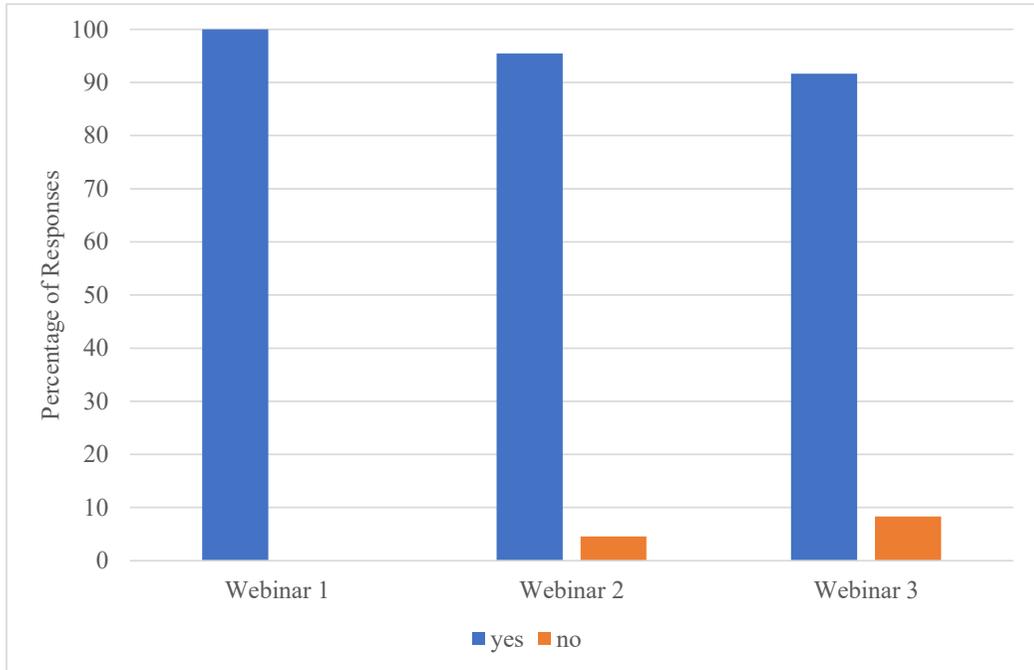
(LJMU)

Fig. 33. Percentage responses for each webinar (Question: Would you like to see follow-up sessions on related topics?)

6.2 Higher Education Maritime Teaching on Biofouling

Most students show openness to participating in similar projects in the future, though many desire additional information before committing. Engineering and design aspects, along with pollution concerns and environmental impact reduction, emerged as the most compelling components of the NOFOUL project. This educational initiative appears to have successfully fostered environmental awareness among engineering students.

The survey results reveal a notably positive reception to the marine biofouling educational content (Fig. 34). Among the 40 student respondents, 26 (65%) rated their interest level as either "High" or "Very high" after completing the class. Specifically, 22 students indicated "High" interest, 4 reported "Very high" interest, 13 expressed "Moderate" interest, and only a single student reported "Low" interest. This distribution demonstrates that the NOFOUL project's educational approach successfully engaged the vast majority of participating students, particularly remarkable considering these were primarily engineering students from the electrotechnics specialization.
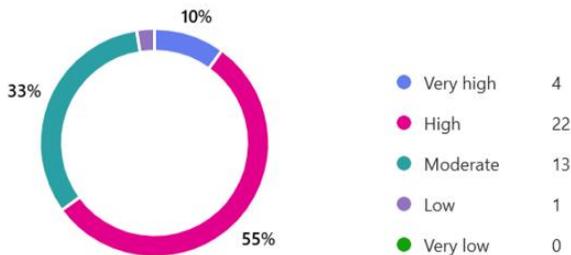

Fig. 34. Student' rate of interest in marine biofouling.

The strong interest levels suggest that marine biofouling, despite being a specialized topic, resonates with students when effectively presented. The overwhelming positive response indicates that the course content successfully bridged the gap between technical engineering concepts and environmental applications, creating relevance for students who might not have previously considered marine biofouling within their professional domain.

When asked about their interest in learning more about marine biofouling (Fig. 35), students showed a balanced but positive outlook. The survey revealed that 18 students (45%) definitely wanted to learn more, 18 students (45%) were uncertain but not opposed ("Not sure"), and only 4 students (10%) had no interest in further learning. This demonstrates that 90% of students remain open to expanding their knowledge on the subject, suggesting the course successfully established the relevance of marine biofouling.

Regarding participation in projects similar to NOFOUL (such as research, fieldwork, or engineering solutions), the results showed cautious but positive interest: 24 students (60%) selected "Maybe– I need more information", 13 students (32.5%) selected "Yes" and only 3 students (7.5%) selected "No". These responses indicate that while most students require additional information before committing to project work, there is substantial openness to practical engagement. The high percentage of "Maybe" responses suggests an opportunity for program enhancement by providing clearer pathways and information about project participation options.

The survey explored specific aspects of the NOFOUL project that interested students most, revealing distinct preferences among the participants. Engineering and design elements emerged as the most popular aspect with 10 mentions, aligning well with the students' academic background in electrotechnics. Pollution concerns (specifically microplastics and biocides) received 7 mentions, demonstrating that environmental implications resonated strongly with these engineering students. Other frequently mentioned areas of interest included: Environmental impact reduction (6 mentions), Antifouling technology (6 mentions), Scientific research aspects, Climate change connections, Field studies and sampling.

When asked about specific topics for further learning, student responses clustered around several themes: pollution and its environmental effects, anti-fouling technologies and systems, bacterial colonization processes or treatment systems for biofouling prevention. These topic preferences reveal an encouraging integration of technological and environmental thinking among these engineering students, suggesting the NOFOUL project successfully fostered interdisciplinary awareness.

The comments section of the survey provides valuable insights into the educational impact of the NOFOUL project. Several students highlighted the educational value of the course, with one noting: "Interesting and very educational". Another student commented on increased awareness: "I now am feeling a lot more informed about the serious impacts of biofouling", demonstrating the course's effectiveness in raising consciousness about environmental issues. Analysis of comment contents revealed that "importance" was one of the most frequently mentioned concepts, suggesting students recognized the significance of the biofouling topic. One detailed comment stated: "The course helped me understand the importance of sustainable practices and environmental responsibility. I appreciated

Fig. 35. Students' interest in learning more about marine biofouling.

the real-world examples and case studies, which made the topics more relevant". Some students also provided suggestions for improvement, with one recommending: "incorporating more interactive activities or fieldwork to better connect theory with practice" while another emphasized broader engagement: "We need to have more people involved that are interested in this domain and care about the marine species". These comments reflect students' desire for both deeper practical engagement and wider awareness of marine environmental issues.

The teacher reply in the survey provides a qualitative assessment of student engagement, motivation, and instructional outcomes in a higher education setting focused on marine biofouling. The respondent is specialized in ecology and environmental protection.

The teacher rates student engagement during the marine biofouling class as "Moderate." This suggests that while students were not universally highly engaged, a baseline level of attention and participation was maintained throughout the session. The teacher observed a noticeable increase in student motivation as the course progressed. This indicates that the instructional design or the subject matter had a cumulative effect, gradually fostering greater interest and involvement among students.

The teacher identified three main topics that sparked student interest:

- Functionality of the GlidArc system
- Microscopic observation of marine organisms
- Surface treatment of naval steel

These topics reflect a blend of applied engineering, hands-on scientific observation, and technological innovation, aligning with both the interdisciplinary nature of the NOFOUL project and the practical interests of students in technical fields.

Regarding potential for future involvement, the teacher believes that some students would be interested in working on similar projects, indicating that the NOFOUL project has potential as a springboard for deeper student engagement in marine biofouling research and technology.

As pedagogical observations, the teacher notes that students were active during lectures and that interactive discussions were particularly effective in engaging them. This aligns with pedagogical best practices, where active learning and dialogic teaching foster deeper understanding and retention. Students were not only engaged but also contributed ideas, such as proposing combinations of green technologies. This demonstrates the course's success in stimulating critical thinking and innovation, key outcomes in higher education settings.

7. Discussion – Maritime Education and Training

The outcome of the workshop was agreed to offer the workshop as a NOFOUL group to IAMU members to benefit in their Higher Education Teaching. The trial workshop was agreed as template for future Biofouling Workshops, particular for IAMU scientists, engineers and mariners.

The outcome of the Training part 1 led to mostly completion of the tasks with time delays. Task 1) and 2) was only correctly completed with the visit of the trainer. Task 3) was completed as so far as potential sites were identified and these were then validated by the trainer. Tasks 4) was demonstrated by the trainer during the visit while the coding was supported with a coding map for standardisation at all sites and virtual coaches. This task was then completed. Task (5 was completed (Fig. 36) while task (6 was not completed by all sites. Tasks (7 and (8 were completed late at sites with coding and preserving of samples were completed. Training part 2 demonstrated the difficulty for non-specialists to achieve specialist tasks. Particularly, Task (1 proved holding the progress of the data collection back. At no site was it possible to finalise the correct microscopes. Here, the variations in microscopes were underestimated and individual microscopes were not suitably checked by the non-specialist prior to the visit of the trainer. After microscopes were identified after the visit there were insecurity on magnification. This lead to the development of a calibration tool in the form of a small panel with a laser square in the size that the photograph should be showing using the microscope. This small simple panel was supporting the standardisation of the area the photographs of each site and tasks 2) and 3) were completed on the 25th May 2025. Task (4 was not completed by trainees but requested further training for assessment using image analysis. No experiments or samples were lost, photographs were mostly taken and in an adequate quality. Therefore the international participatory research experiment was completed. Teaching by demonstration (intentionally teaching) as in training and coaching together in the group followed by for each site separately (Fig. 37) was efficient showing that non-specialist can achieve the running of a field test and taking part in the assessment as far as sampling of panels using photography to be then assessed by specialists. The field experiments are planned to continue in 2025 by the trainee because of their benefits such as biofouling problem and invasive species identification, antifouling coating evaluation, collaborations (Table 9).

Fig. 36. Deployment of the frame and samples in the international participatory research experiment in India (@AMET).

Table 9. Issues and benefits of deploying of biofouling or antifouling experiments at a local site, collected by NOFOUL trainees.

| Issues	Benefits
Find a suitable site	Learn the biofouling problem
Costs (consumables, time)	Low cost approach to prove the viability of the best, lowest cost/ environmental impact coating for your site
Not specialist (complicated, lack of confidence)	Clear and visible results to show endusers
Interpretation of outcomes	Potential collaborations with same interest networks
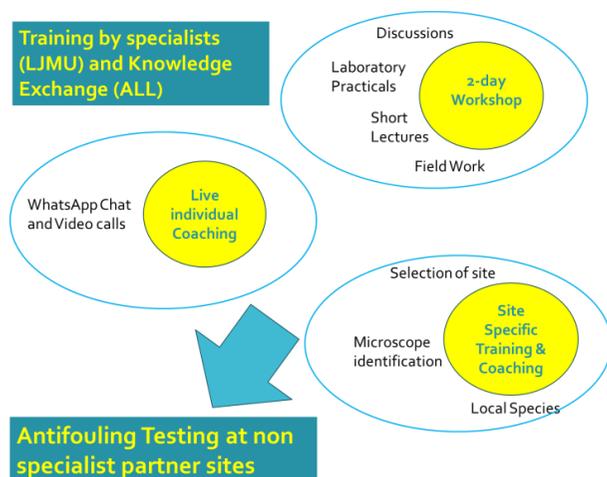
Fig. 37. Biofouling training leading to participatory research in NOFOUL

Overall, the IAMU Biofouling Network has a positive effect on IAMU members from webinar to webinar. During the webinars knowledge on biofouling is not just only transferred to participants but knowledge exchange is demonstrated in the question and answer sessions while developing into discussions. NOFOUL trained non-specialists disseminated the NOFOUL research and demonstrated their new knowledge and skill. During the last webinar participants requested training such as NOFOUL partners received and this demonstrated the importance for IAMU members to understand biofouling.

The NOFOUL Project's higher education initiative on marine biofouling demonstrates impressive success in engaging Electrical engineering students with environmental marine science concepts. The strong interest levels reported by students, coupled with their openness to further learning and project participation, indicate effective educational content and delivery. The survey reveals valuable insights about student preferences, highlighting engineering applications, pollution concerns, and environmental impacts as particularly resonant topics.

For future development, the program could benefit from providing clearer pathways to project participation, incorporating more hands-on activities, and expanding the connection between theory and practice through fieldwork opportunities. The positive reception among engineering students suggests potential for expanding such interdisciplinary environmental education across technical fields, fostering a generation of engineers with awareness of and interest in addressing marine biofouling challenges.

The teacher's feedback provides evidence that the NOFOUL project's educational approach is effective in gradually increasing student motivation, engaging students through a mix of theoretical and practical topics and encouraging active participation and creative problem-solving.

However, to maximize student involvement in marine biofouling research, structural support (mentoring, resources, recognition) is necessary. The insights suggest that further investment in these areas could transform moderate engagement into high, sustained participation, and foster the next generation of researchers and innovators in marine environmental protection.

The Future of Biofouling Understanding in Maritime

The NOFOUL project developed training and knowledge exchange approaches and trained non-specialists for biofouling. Their training was evidenced with a 2-day workshop and a participatory research field experiment, and resulted in their knowledge transfer in a Biofouling Network with webinars and Higher Education teaching.

In the future, trained non-specialists from NOFOUL can transfer their knowledge to IAMU members and to colleagues and students even further.

The concept and approach of training non-specialists at LJMU may be able to benefit other IAMU members in the future with further training workshops together with NOFOUL partners. The transfer of knowledge may initiate and facilitate further field experiments promoting experiments such as biofouling baselines for monitoring biofouling problem and non-native invasive species, and antifouling testing at the local site. These data may be collated in an IAMU data repository for applications such as modelling in commercial and environmental penalties, and Maritime Higher Education. This may result in further participatory research.

In recent years, there has been growing interest in participatory research as a means of making marine technology development more inclusive, adaptive, and responsive to stakeholder needs [44, 45]. Participatory research methodologies emphasize collaboration between researchers, practitioners, and end-users throughout all stages of the research process, from problem definition to solution implementation [40, 41]. In the marine antifouling context, this involves not only local stakeholders such as ship operators, coastal managers, and aquaculture farmers but also international technical partners, including engineers involved in the design, testing, and optimization of antifouling systems.

Interdisciplinary research collaboration is seen as a scientific partnership which can provide new ideas or solutions to highly complex problems. Antifouling may be one such complex issue with a solution being unlikely to come from just a single perspective (biological, coatings, ecological, engineering) but more likely from an international interdisciplinary and intersectoral collaborative effort [50].

Examples of such integrative efforts have emerged in recent antifouling research initiatives in Southeast Asia, the South Pacific, and West Africa, where international engineering teams collaborated with local stakeholders to co-develop and field-test coatings and mechanical cleaning systems tailored to tropical biofouling conditions and small-scale maritime operations [46, 47]. These partnerships may illustrate the potential for participatory research to enhance both technological performance and social legitimacy by ensuring that antifouling solutions are grounded in the lived experiences and operational constraints of end-users [51].

Conclusions

We met the deliverables. Our novel antifouling solution demonstrated that our bespoke microtextures, tested in the field under a number of different marine environments by local trained NOFOUL non-specialists using the same experimental protocol, showed antifouling performance by reducing the percentage coverage of local biofilm. This established a loop between our research and our biofouling training within NOFOUL facilitated the transfer of the new knowledge by the trained NOFOUL non-specialists to other non-specialists in IAMU such as in education and in the IAMU Biofouling Network. The intersection of participatory research and marine antifouling innovation, driven by training, knowledge transfer and exchange, network development with webinars, and Higher Education maritime

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teaching facilitated the viability of trained non-specialists within the biofouling and antifouling field. Through participatory practices, the co-creation of context-sensitive biofouling and antifouling engagement benefitting IAMU members was motivated by the intercultural and interdisciplinary team.

8. Gaps and Recommendations for Biofouling and Antifouling in IAMU research and MET

From the NOFOUL project the team were able to identify a number of gaps in MET, maritime industries and their association with biofouling and antifouling.

GAPS

- Biofouling and antifouling skills in MET is mostly ignored, taught at the side and/ or taught by untrained non-specialists. It is rare for students and mariners to be taught in this field by qualified personnel.
- Students and mariners need to be encouraged and make aware of the issues of biofouling and antifouling and enhancing student involvement.
- Scientific research in the field biofouling and antifouling for maritime students and mariners is mostly limited to desk exercises in the form of literature reviews limiting the understanding of subject.
- Ships need antifouling but antifouling solutions that are environmentally friendly are not applied, not well known, not further developed nor are encouraged technological innovations that are going over the status-quo.

RECOMMENDATIONS

- Increase the qualified personnel in biofouling and antifouling so students and mariners achieve their required skills in the field as in Resolution MEPC.377(80). Diversify teaching and training activities by mentoring, improving resource access, and their recognition and supported incentives.
- Accessibility of real-world experimental approaches for maritime students and mariners by maritime institutes.
- Encourage innovation in biofouling and antifouling solutions by expanding funding opportunities and facilitating start-ups within maritime institutes.
- Grow the IAMU Biofouling Network to support MET and real-world experimental opportunities in the form of participatory research.

9. Conclusions

The NOFOUL project team achieved all aims and objectives. All deliverables are met and dissemination of the project is ongoing with two scientific articles and conference presentation. With trained non-specialists NOFOUL demonstrated the antifouling performance of the environmentally friendly antifouling solution, the microtextures in optional combination with non-thermal plasma treatment. This antifouling solution is novel and demonstrated that different marine environments need bespoke microtextures as expected and are meant for niche areas on a vessel. The antifouling solution does not leach microplastics nor biocides in the marine environment. The persistence of the solution and its upscaling would need to be demonstrated in the future in a different funded project over multiple years. The project will continue within the IAMU Biofouling Network and with further collaborations between the partners (e.g., a funding application was submitted by AMET and LJMU in March). NOFOUL demonstrated the importance of biofouling and antifouling, gaps in knowledge and the opportunity in biofouling training for engineers and mariners to improve their biofouling and antifouling skills as required by IMO Resolution MEPC.377(80). NOFOUL developed a new way for MET, outside of the class room, the merge of real-world gaps in MET with experimental science developing a crop of trained non-specialists and specialists. With the IAMU Biofouling Network initiated by NOFOUL, the recommendations on biofouling and antifouling brought forward by NOFOUL can be addressed.

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