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Executive Summary

Biofouling has profound effects in different branches of maritime activities. It is the major cause for maintenance expenses in ship transport, buoys, and aquaculture. The settlement of marine invertebrates on the hulls of ships results in speed reduction, increased fuel consumption and therefore increased air pollution and CO2 production.

The main goal of the BYEFOULING project was to design, develop and upscale novel low toxic and cost-efficient environmentally friendly antifouling coatings. The approach in BYEFOULING was to tackle the different stages of the biofouling process, using innovative antifouling agents encapsulated in smart nanostructured materials, to optimize coating performance and cost all along their life cycle. A proof-of-concept for the most promising candidates was developed and demonstrators were produced and tested on field.

Studies on surface structuration, protein adsorption inhibitors, quorum sensing inhibitors (QSI), natural biocides and living active species were carried out. This information, together with efficacy and toxicity testing, was used to build different exploitation scenarios and aid in the definition of the most promising technologies for demonstration activities.

Nanostructured inorganic, organic and hybrid materials were synthesized, characterized and optimised as reservoirs for the encapsulation of active species. Screening paints and reference antifoulants were produced and sent for field tests.

Laboratory tests on anti-microfouling, anti-macrofouling, mesocosm and field efficacy tests of the antifouling paint prototypes and ecotoxicity tests were realised in the Atlantic Ocean, the Mediterranean and the Red Sea for the most optimized systems. The toxicity of active compounds and intermediate systems on marine organisms was investigated on different trophic levels. An appropriate comparison of BYEFOULING substances with commercially available ones was accomplished.

Parameters affecting the polishing of antifouling coatings were validated through computational models and experimental methods to obtain roughness functions required to predict drag reduction. Validation of roughness was achieved by towing tank tests and a new monitoring technique to track performance of a vessel in service was developed. LCA analysis was realised and models refined using industrial data.

Demonstrators based on BYEFOULING technologies for ships, aquaculture and satellite buoys were prepared and launched on specific exposure locations. Promising technologies including active species, nanocontainers and fillers were successfully scaled up. Demonstrators have finally been exposed and are currently surveyed in the field which will last beyond the end of the project.

Dissemination activities including organization of 3 workshops, 4 training courses, a public website and newsletters were realized and implemented. Partners have been actively disseminating the project achievements in conferences and peer-reviewed journals.

Based on the most promising antifouling results obtained from lab scale and field tests, several systems were selected for further exploitation. IP protection is ongoing and industrial partners are considering joint actions with the main producers for possible commercialisation.

Photo: USC

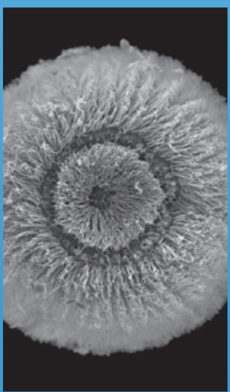


Photo: TAU


Photo: SMT

Summary description

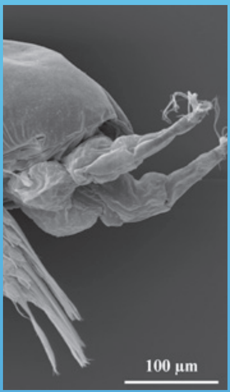
Biofouling has profound effects in different branches of maritime activities. It is the major cause for maintenance expenses of any (partially) submerged man-made surface, including ship transport, buoys, aquaculture, but also membrane bioreactors and desalination units, power plants' cooling water systems and oil pipelines. It poses also a significant problem for all the aquaculture industry, the broadest and the most documented impact being in marine fish aquaculture. The settlement of marine invertebrates on the hulls of ships results in increased erosion, reduction of speed, increased fuel consumption and therefore increased air pollution and CO2 production.

The main goal of the BYEFOULING project, supported in the framework of the Ocean of Tomorrow by the European Commission, is to design, develop and upscale novel low toxic and cost-efficient environmentally friendly antifouling coatings with enhanced performance compared to currently available products. The approach in BYEFOULING is to tackle different stages of the biofouling process using innovative antifouling agents, covering surface-structured materials, protein adsorption inhibitors, quorum sensing inhibitors, natural biocides and microorganisms with antifouling properties. Encapsulation of the innovative compounds in smart nanostructured materials will be implemented to optimize coating performance and cost all along their life cycle. A proof-of-concept for the most promising candidates will be developed and demonstrators will be produced and tested on field.

The specific objectives of BYEFOULING are:

- obtain coatings with extended service life
- reduce VOC content in coating formulations
- reduce fuel costs due to drag reduction in maritime transportation and fishing vessels
- increase operation life of floating devices
- reduce fish mortality as a result of conventional biofouling processes and respective control measures
- reduce maintenance costs

The project is organized in eight work packages (WPs) and is running from December 2013 to November 2017. BYEFOULING combines a multidisciplinary consortium involving 19 partners from SMEs, large companies, research organisations and universities in Europe, able to develop a full production line for new antifouling coatings. In **WP1**, the project is coordinated and directed according to a work plan. In **WP2**, novel compounds, development of interfacial microstructures and preparation and growth of antifouling microorganisms are under development. In **WP3**, different tools are used to incorporate the new antifouling approaches into coating formulations, including encapsulation to protect compounds from the coating matrices and to enable controlled release of active species, preparation of functional fillers with hydrophobic and biocide-active functional groups, and development of waterborne coating formulations. In **WP4**, assessment of antifouling performance and benchmarking of the obtained systems with commercial and state-of-art technologies are carried out. Ecotoxicity measurements are performed to investigate the effect of the developed materials in the ecosystems. In **WP5**, relevant parameters for application of coating formulations in subsequent stages are under testing. In addition, fundamental studies on adhesion of fouling organisms and effects of fouling on biocorrosion are under investigation. In **WP6**, reliable methods for evaluation of drag resistance of vessel hull coatings and for application of holistic and comprehensive assessment tools such as Life Cycle Assessment (LCA) are under development.



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In **WP7**, demonstration activities will be performed aiming at preparing three types of demonstrators, specifically for ships, aquaculture and buoys. To obtain enough paint and related components, up-scaling of the most promising technologies will be implemented. In WP8, the results will be disseminated and exploited. SMEs and industrial partners will use the developed technology to address new market areas.

Description of main S/T results foregrounds

The first part of the project comprised the development of new antifouling approaches and subsequent incorporation into coatings to achieve a proof of concept level-first period covering M1-M18. The second part of the project was assigned to testing and characterization with iterative optimization to improve coating performance-second period from M19-M30. Finally, the third and last part of the project were dedicated to the industrial implementation of most promising systems and demonstration activities-third period from M31-M48. In the following sections the main results obtained in each period are described in more detail.

1st period M1-M18

In **WP1**, an internal website (eRoom) was created for BYEFOULING partners with detailed information on the project. A routine for EB/MST meetings and reporting is implemented. The kick-off, 6M, 12M and 18M meetings were held for reporting results and discussing technical and management activities. The 6M, 12M and 18M reports (financial and technical) have been assessed and reviewed by the MST. Dissemination has been realised according to a revised decision procedure for publications. A project ethics committee is established to follow research activities on living animals.

In **WP2**, studies on surface structuration, protein adsorption inhibitors, quorum sensing inhibitors (QSI), natural biocides and living active species were carried out. For surface structuration, the feasibility of obtaining double wavelength-wrinkled surface with labyrinth morphology has been showed. In the field of biomimetic surface composition, several compounds have been extracted from different marine organisms, having potential antifouling properties. With respect to protein adsorption inhibitors, two types of systems are being studied: peptide-like and poly-zwitterionic materials. Different QSI compounds/ extracts were tested and a large number of novel marine bacteria with wide-spectrum enzymatic QSI activity have been already identified. In the field of Living Active Species, freeze-dried cells and endospores of different bacteria strains have been produced.

WP3 partners have focused on the synthesis and characterization of nanostructured inorganic, organic and hybrid materials that can be used as reservoirs for the encapsulation of active species, including dormant microorganisms with antifouling properties. The surface functionalization of the synthesized nanomaterials has been investigated to improve dispersion in polymeric matrices. Synthesis of carbon nanotubes (CNTs) with specific characteristics and different fillers with antifouling and hydrophobic functionalities were also performed. Finally, screening paints and reference antifoulants have been produced and sent to several partners to apply the first coatings for field and mesocosm tests.

In **WP4**, normalization of procedures to characterize antifouling systems was completed. Protocols have been written for laboratory tests on anti-microfouling efficacy, anti-macrofouling efficacy, mesocosm efficacy tests, field efficacy tests of the antifouling paint prototypes and ecotoxicity tests. Free compounds developed in WP2 and intermediate materials prepared by WP3 partners were all tested. Results on antifouling activity in lab tests were communicated to other WPs and the first field tests has been launched with the most promising BYEFOULING systems developed so far.


Photo: TAU


Photo: SMT


Photo: TAU

In the frame of **WP5**, data about surface characterization were collected. With respect to fundamental studies, partners have set up experimental characterization techniques and cultures of bacteria have started to produce biofilms. Most importantly, in conjugation with WP2, WP3 and WP4, different coating formulations were prepared and the first field tests have been launched.

In **WP6**, activities related to the development of the mathematical models for drag reduction prediction and activities related to LCA were performed. Models for studying self-polishing paints have been used, flow of fluids has been simulated and experimental designs studied to obtain relevant experimental data. Furthermore, the first results on LCA have been obtained.

In **WP7**, planning activities on demonstrator design and exposure locations both for ships, aquaculture and for satellite buoys have started.

In **WP8**, several dissemination activities have been realised, including organization of training courses, short visits and specific tools (public website and newsletters) for dissemination. The first BYEFOULING workshop was organised by USC, in collaboration with TAU (leader of WP8). A first draft of exploitation plan is also available.

2nd period M19-M30

In **WP1**, the internal website (eRoom) for BYEFOULING partners with detailed information on the project was updated to promote an efficient project internal communication. The homepage for public access was regularly revised with open information. EB/MST meetings were conducted monthly. The 24M meeting was held on 25.-26. November 2015 in Aveiro and the 30M meeting was held on 24.-25. May 2016 in Berlin. The 24M interim report (financial and technical) have been assessed and reviewed by the MST. The first periodic report was prepared and submitted to the Commission through the participant portal on 18. July 2015. An amendment of DoW and GPFs with minor changes was realised after internal revision of the project at SINTEF.

In **WP2**, studies on surface structuration, protein adsorption inhibitors, quorum sensing inhibitors (QSI), natural biocides and living active species were carried out. Part of the activities performed were a continuation of the developments reported in the previous reporting period (screening of new compounds, improvement of synthesis conditions, optimization of conditions to extract biomass). In addition, WP2 partners focused most of their final activities in this WP on the extraction, purification and identification of active components present in different extracts, for the most promising systems reported so far. This information, together with efficacy and toxicity testing obtained by WP4 will be used to build different exploitation scenarios and aid in the definition of the most promising technologies for demonstration activities (WP7).

In **WP3** partners continued their activities concerning synthesis and characterization of nanostructured inorganic, organic and hybrid materials that can be used as reservoirs for the encapsulation of active species, including dormant microorganisms with antifouling properties. Optimization of experimental conditions for synthesis, release studies of active species and fitting of kinetic models were done during the present reporting period. The task concerning encapsulation of active microorganisms was completed according to the plan and several results obtained concerning the encapsulation of bacteria spores are quite encouraging.


Photo: TAU

Several partners were also involved in the preparation of nanostructured materials for testing in WP4 and in the preparation of coatings for the second field tests, to be launched in the following reporting period. Additional focus was given to waterbone coating formulations and to the combination of different BYEFOULING technologies aiming at achieving synergistic antifouling actions.

WP4 continued the activities related to antifouling efficacy testing at lab scale (against micro- and macrofouling), mesocosm tests and ecotoxicity testing. In addition, WP4 compiled and processed the results obtained from the first field tests and coordinated the work related to the launching of the second field tests. Finally, compilation of results obtained so far allowed for an appropriate comparison of BYEFOULING substances with commercially available ones.


Photo: USC

In the frame of **WP5**, data about surface characterization was collected and made available to WP6, for modelling purposes. With respect to fundamental studies, partners have done several measurements to investigate the adhesion of cyprids on different coated surfaces and corrosion of mild steel was investigated in the presence and absence of sulphate-reducing bacteria. Furthermore, testing of coating formulations properties such as viscosity, adhesion and stability was carried out for model formulations containing different nanostructured materials produced in the frame of project.

In **WP6**, partners compiled several procedures to estimate the release of antifouling compounds from paints and compared with the parameters required for simulation of environmental concentrations in specific software packages. Experiments were also performed to obtain data for validation of models for drag reduction prediction. LCA analysis was performed and models refined using data provided by industrial partners. Moreover, selected BYEFOULING technologies were analysed using paint and maritime transportation models.

Photo: Jotun

In **WP7**, upscaling of active compounds and nanostructured materials was initiated, the design of a 3-D demonstrator completed and the testing of demonstrators defined for the next reporting period defined.

In **WP8**, several dissemination activities have been realised, including organization of training courses, short visits and specific tools (public website and newsletters) for dissemination. The second BYEFOULING workshop was organised by TAU, in collaboration with ABT and MNOVA.

3rd Period M31-M48

In **WP1**, the internal website (eRoom) for BYEFOULING partners with detailed information on the project was frequently updated to promote an efficient project internal communication. The homepage for public access was regularly revised with open information. EB/MST meetings were conducted monthly. The 36M meeting was held on 23.-24. November 2016 in Malta, the 42M meeting was held on 22.-23. May 2017 in Sandefjord and the final meeting was held on 8.-9. November 2017 in Santiago de Compostela. The 36M and 42M interim reports (financial and technical) have been assessed and reviewed by the MST. The second periodic report was prepared and submitted to the Commission through the participant portal on 31. July 2016. A draft of the final report was prepared for the final meeting in Santiago de Compostela.

Photo: USC

In **WP2**, although no main activities were planned, partners devoted time to complete tests towards the preparation of publications, as well as lab studies on new routes for appropriate upscaling of materials, purification and isolation of actives obtained from extracts.

In **WP3**, different nanostructured materials have been proposed for controlling the release of active compounds developed in the frame of WP2, to impart multiple functionalities to antifouling coatings. One important point that was considered from the beginning of the WP3 activities was the compatibility between the nanomaterials and coating formulations. The last months of the project, the effort in WP3 was focused on the development of new waterborne formulations with antifouling properties based on the macroCTAs. On the other hand, significant efforts were done for the preparation of the final coatings to be tested in the last field tests; a total of 90 PVC panels with 20x20 cm dimensions, were coated and dispatched to WP4 partners, for tests at different sites. In parallel, other partners in WP3 continued their work on the synthesis of their fillers and provided partners of WP7 with the necessary quantities of materials.

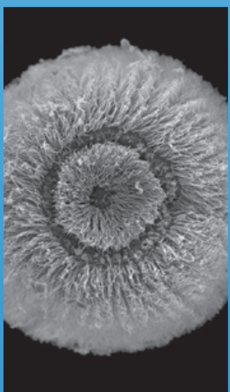
Photo: TAU

WP4 continued the activities related to antifouling efficacy testing at lab scale (against micro- and macrofouling), mesocosm tests and ecotoxicity testing. In addition, WP4 compiled and processed the results obtained from the second field tests and coordinated the work related to the launching of the third and final field tests. Additionally, field test experiments aiming at the optimization of coatings for nets were carried out in the Atlantic Ocean, the Mediterranean and the Red Sea with commercially available material. The first coating systems developed for aquaculture applications was tested under field conditions in the Mediterranean Sea and in the red Sea. The toxicity of active compounds and intermediate systems on marine organisms was investigated on different trophic levels. 24 hours acute tests on Artemia salina have been performed for all compounds while acute toxicity tests on mussels, unicellular algae, sea urchin embryos and fish eggs were performed on promising compounds. The chronic toxicity effects of 4 compounds selected for demonstration activities was investigated using the seabass model. Compilation of all results obtained allowed for an appropriate comparison of BYEFOULING substances with commercially available ones.


Photo: SMT

In the frame of **WP5**, partners have continued surface characterization of coatings prepared by different partners (WP3, WP5, WP7) with some of the roughness data being made available for WP6. With respect to fundamental studies, partners concluded measurements regarding to the adhesion of cyprids on different coated surfaces and corrosion of mild steel under biotic and abiotic conditions. In parallel, tests to coatings formulated by different partners were carried out.

In **WP6**, partners studied the parameters affecting the polishing of antifouling coatings, validated computational models and developed experimental methods to obtain roughness functions required to predict drag reduction. Validation of roughness was validated by towing tank tests and a new monitoring technique to track performance of a vessel in service was developed. LCA analysis was continued and models refined using data provided by industrial partners. Moreover, selected BYEFOULING technologies were analysed using paint and maritime transportation models, inventories were established and refined for various antifouling additives.

The main effort of the consortium in this final period was done towards preparation and launching of demonstrators based on BYEFOULING technologies.

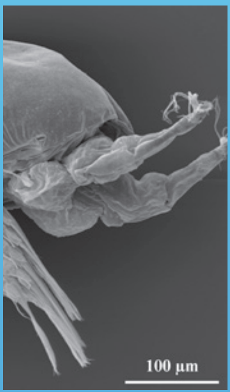

Photo: USC

3D-design for steel demonstrators with representative geometry was finalized and first field tests at exposure locations both for ships, aquaculture and for satellite buoys have been carried out as well as a vessel in service to track hull performance was monitored. Scaling up activities of technologies defined thus far as promising include active species, nanocontainers and fillers and have been successfully proceeding to reach industrial scale. Screening tests on solvent-borne paints formulated by incorporating the most promising technologies have been performed at a pre-industrial scale. BYEFOULING paint formulations were sent to different industrial partners and were applied on demonstrators. Those coated demonstrators have finally been exposed at different test locations and are currently surveyed in the field which will last beyond the end of the project.


Photo: USC

BYEFOULING is an innovative research project aimed at finding a new generation of environmental friendly antifouling coatings. As a result, knowledge and foreground dissemination, exploitation strategy and training activities play a major role in the project. The latter are related to the maritime industrial technical and commercial sectors (ship owners, fish farms, equipment producers, marina owners and operators, etc.), R & D entities and relevant organizations (paint industry, industrial engineering and design companies, universities, research institutes, etc.), public authorities (e.g., governmental, regional and municipal) and the public. A plan for enhancing exchange of reciprocal visits of partners, training of young scientists and students, courses and workshops has been outlined and it will enhance dissemination of the project rationale and achievement. Since the beginning of the project a project website has been fully functional. Partners have been active disseminating the project achievements in conferences and outreach activities. Publications have been submitted to peer-reviewed journals and recently this activity has been intensified. Dissemination has been conducted by training courses and workshops. Patent survey have been conducted as well as analysis of exploitable results.


Photo: Jotun

Description of the potential impact

The BYEFOULING project addresses high volume production of low toxic and environmentally friendly antifouling coatings for mobile and stationary maritime applications. The technology will fulfil the coating requirements as a result of the incorporation of novel antifouling agents and a new set of binders into coating formulations for maritime transportation and fishing vessels, floating devices and aquaculture. Readily available low toxic and cost-effective antifouling coatings will increase the efficiency of maritime industry and be the enabling technology to realize new products.

The potential impacts of the project can be divided into internal and external ones. Internally, academic partners (universities, research institutes) participating in BYEFOULING will form young researchers in an interfacial field where knowledge on biology, marine sciences, chemistry, physics, materials science and engineering, and coating technology come into play to generate environmentally friendly and at same time high performance products. This is a strong positive point when considering high-level education and competitiveness of jobs in the global market. In addition, the generated knowledge will be reflected upon publications in journals of high impact factor, which is always one of the main factors for assessment of public institutions applying for funding supports. From an industrial perspective, the involved SMEs and large industries have a unique opportunity to establish transnational networking developing high-level products that can be disruptive in the global market.

Photo: TAU

Photo: SMT

Photo: TAU

Externally, the impact of BYEFOULING can be detailed for different sectors. In the ship transport sector, BYEFOULING will offer more efficient and less toxic antifouling coatings, the operation and lifecycle costs will be significantly reduced, thereby increasing the efficiency and competitiveness of the ship transport industry. Furthermore, the project will contribute to reduce the negative impacts on the marine environment and CO2, NOx and SOx emissions. In the aquaculture sector, BYEFOULING products will improve the performance of marine operations, with better growth rates, improve water quality and provide a better control of disease vectors, reduce costs associated with copper waste disposal, enable lighter structures and improve resistance towards extreme weather and enhance the viability towards more stringent regulations on the use of biocides.

Finally, BYEFOULING is a project which opens new societal insights considering national and transnational objectives within EU for the forthcoming years. Specifically, it pertains to several aspects of so called blue growth. In this sense, BYEFOULING is targeting the generation of new materials coming directly from marine, renewable resources. On the other hand, the impact of antifouling coatings generated in BYEFOULING will have a profound impact on industrial activities directly related to the marine dimension. vectors, reduce costs associated with copper waste disposal, enable lighter structures and improved resistance towards extreme weather and enhance the viability towards more stringent regulations on the use of biocides.

BYEFOULING provides new societal insights by taking into account national and transnational objectives within the EU for the future. Specifically, it pertains to several aspects of what is termed "blue growth". BYEFOULING thus targets a new generation of materials derived directly from marine renewable resources; while the impact of antifouling coatings generated in the project will profoundly affect industrial activities directly related to the marine realm.

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