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No harm, no foul? Expert views on the future direction of marine anti-biofouling technologies

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Abstract: The colonisation of submerged surfaces by marine fouling organisms is a global problem with impacts ranging from clogged pipelines and aquaculture nets through to hull fouling that increases fuel costs and green-house gas emissions and provide potential habitats for invasive species. Marine anti-biofouling techniques, such as copper plates on ships and functional coatings that release toxic biocides, were historically developed in order to reduce the frequency and expense of the physical removal of fouling organisms. For a time the solution was thought to be tributyltin self-polishing coatings, but these were later proven to be detrimental to the marine environment and subsequently banned. Today, the 'state-of-the-art' general-use coatings are based on the release of biocidal copper and booster biocides, but environmental concerns exist regarding their impacts on marine life and future legislation may put restrictions on their use. While non-biocide based alternatives include non-stick or foul-release coatings, these generally work best on fast moving vessels with little stationary time, even if recent developments seem to reduce this demand on speed. We utilised a targeted questionnaire to a range of experts that work with, or are affected by, marine anti-biofouling to assess their views about potential antifouling technologies of the future. The paper provide insights into the expectations and demands that need to be addressed in development and implementation of future marine anti-biofouling technologies and indicate how those views differ between professional roles.

Keywords: expert opinions, future anti-fouling technologies, marine biofouling.

1 Introduction

Upon submersion of a surface in the sea, organic material, bacteria and diatoms, biofilms, slimes, larvae of hard macrofoulers and eventually mature macrofoulers will make the surface their home [1]. On stationary marine constructs such biofouling may cause damage and loss of function [2-4]. On mobile constructs such as ships, biofouling also results in increased fuel consumption and reduced manoeuvrability [5, 6]. In addition, since ships travel over long distances across natural borders that tidal current patterns impose, biofouling organisms can spread from their natural habitat to new distant environments [7]. This may not sound so bad, but a creature living in balance with nature in its native environment may wreak havoc and severely damage the new ecosystem it is introduced to, which is not only of concern for environmental reasons but can also bring severe economic consequences.

Given the issues that may occur from biofouling it is no surprise that concerted effort has - and is - going towards its prevention. Early in human seafaring history preventive measures included application of wax, pitch, or metal sheeting of lead or copper [8]. Since then a wide range of sophisticated technologies have been tested and, with the introduction of self-polishing tributyltin coatings, it seemed that the problem of marine biofouling had finally been solved. However, these highly effective coatings were subsequently banned from use after it was discovered that they had severe negative impacts on the marine environment [9]. Currently, the most widely used and effective marine anti-biofouling coatings are based on slow release of biocidal copper and booster biocides. However, concerns are being raised regarding the negative environmental impact of copper accumulation, particularly in relatively enclosed waters such as marinas and harbours. Based on these concerns, a large body of work both in academia and industry is being undertaken to develop new more environmentally-friendly technologies. These efforts have resulted in a number of proposed technologies including deformation of elastomers under an applied electric field [10], enzymatic generation of hydrogen peroxide [11], cyclic uptake and release of copper naturally present in the sea [12-14] and vanadium pentoxide nanowires-mediated generation of singlet oxygen [15]. Major coating producers also have several coatings on the market that utilise physical mechanisms i.e. non-stick or foul-release surfaces rather than biocide release. Such coatings are now very effective but are still dependent on some movement of the vessel to function and application of these coatings is usually associated with an increased initial cost compared to biocide-based coatings [16].

Predicting the future of anti-fouling technologies is very difficult, especially when interested parties such as academic researchers, paint/coating companies, regulatory bodies, consultants and ship owners/managers may hold differing views on the most important aspects relating to the technology. It is the belief of the authors that understanding how the different parties view the future of marine anti-biofouling will enable a more informed decision making process and provide key direction/s for further research, communication and legislation. In this small-scale study, we utilised a questionnaire approach targeted to a range of experts that work with, or are affected by, marine anti-biofouling to assess their views on potential antifouling technologies of the future. The results were summarized and analysed through multivariate data analysis and major trends were identified and discussed.

2 Methodology

2.1 Survey design and participant recruitment

An anonymous online survey was constructed to ascertain how professionals working in different roles with, or being impacted by, marine biofouling viewed the future of antifouling technologies. The survey was constructed through the SurveyMonkey® platform following both UCL and UniSA research ethics guidelines (refer to Appendix 1 for the questions included in the survey). Approval for the study was given by UCL’s Research Ethics Committee and University of South Australia's Human Research Ethics committee.

The targeted recruitment base for participants were experts working with, or being impacted by, marine biofouling, in their different professional roles. A total of 36 inquiries were made about willingness to participate and 25 formal invitations were initially sent. These invitations were targeted at individuals divided between the following professional roles: academic research; consulting on marine biofouling; legislation regarding marine environment and/or marine anti-biofouling; management of ship(s) or shipping company and marine-product specialist in coating/paint company. The number of completed surveys from the different professional roles (Question 1) was monitored and additional invitations were sent out to individuals in the professional categories with low response rate, resulting in a total of 33 formal invitations. Out of the 33 invitations, 17 individuals completed the survey.

2.2 Data analysis

The responses to each question were analysed for simple trends using visual observation. In addition, the answers to Question 2 were subjected to multivariate analyses to test for differences among self-nominated groups based on similarities in the respondents’ importance rankings of the specified drivers. A presence/absence matrix of the top three most important drivers ranked by each respondent was constructed and from this a matrix of Jaccard similarities was then calculated among respondents using PRIMER v.6 [17]. PERMDISP tests were then applied to test for differences in the variance in rankings within roles and then ANOSIM analyses were utilised to test for overall differences in rankings among roles [17]. For these multivariate analysis tests among roles, respondents nominating ‘other’ (see Table 1) were excluded *a priori* because we could not confidently assign their alternative responses to one of our nominated categories and because, collectively, we expected that including this disparate group in our analyses may have confounded our tests among the other, more clearly defined roles.

3 Results

A total of 33 formal invitations to participate in the survey were sent out, resulting in 17 respondents that completed the survey. Thus, the invite-to-participation conversion rate was high at 52%. The core of the survey was to investigate how experts working with, or being impacted by, marine biofouling in their professional roles viewed the future technical developments in the field and to identify both general and role-specific trends. The first question to the respondents was to identify which field best described their professional activities (Professional Role). The roles and corresponding number of answers (Response Count) are shown in Table 1. The classification categories by which the selection of invited experts was based showed some interesting results in relation to the invite-to-participation conversion rate for the different roles. If we assume that the invitees were correctly classified by us, the conversion rate was very high for academics (80%) but low for management of ship(s) or shipping company (< 10%). For the other groups the rate was ≥ 50%, with more specific interpretation being hindered by some respondents classifying themselves as 'other'.

Table 1: The number of respondents identifying with a given Professional Role

Professional Role	Response Count
Academic research	4
Legislation regarding marine environment and/or marine anti-biofouling	3
Consulting on marine biofouling	3
Marine-product specialist in coating/paint company	3
Management of ship(s) or shipping company	1
Other (please specify) †	3

† The Professional Roles given by the respondents answering 'Other' were: Government laboratory research; Biocide producer; PhD. Scientist, institute research, innovation facilitator, project coordinator, scientific consultant for antifouling product producers.

After having identified which professional role they associated with the respondents were asked to rank major driving forces for the development of new marine anti-biofouling technologies (Question 2). Although on first view it appeared that the driver rankings in Question 2 may have been more variable among legislators than among respondents in other roles (Figure 1), PERMDISP analyses failed to detect differences in multivariate dispersion among roles ($F = 6.49$, $p\,(perm)_{4,9} = 0.09$). ANOSIM analysis did, however, detect a difference among the roles in rankings of top drivers ($p = 0.03$). Subsequent pair-wise differences were detected between Academic researchers and Consulting on marine biofouling ($p = 0.03$) and between Academic researchers and Marine-product specialist roles ($p = 0.03$); all other pair-wise comparisons between roles were non-significant ($p > 0.05$).

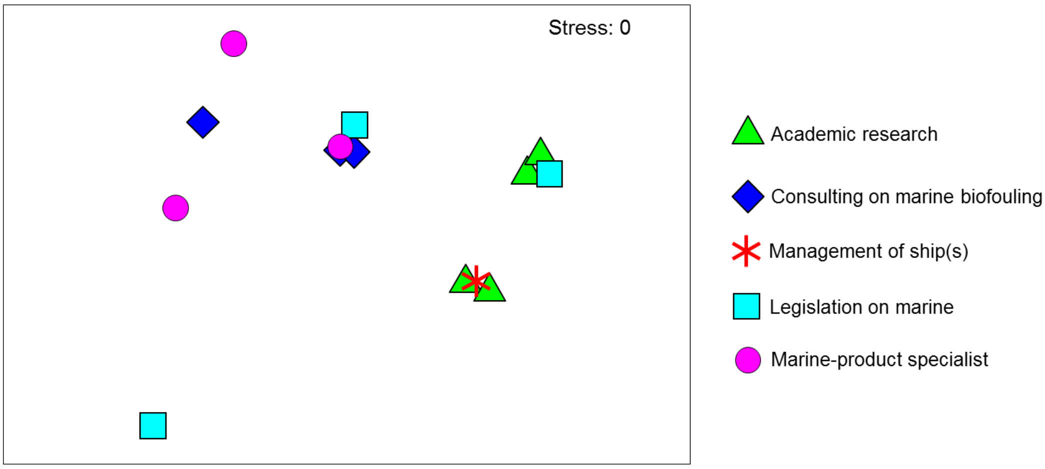

Figure 1: Multi-dimensional scaling plot of similarities in the ranking of major driving forces for the development of new marine anti-biofouling technologies (Question 2) among self-nominated roles.

A scatterplot of the importance rankings of the seven drivers (Figure 2) shows similar patterns to the multivariate analyses. Overall, the four environmental and performance drivers appeared to be ranked higher than the Occupational Health and Safety and cost and ease of installation drivers. Academic researchers ranked the two environmental drivers highest with all four respondents ranking one of the environmental drivers as most important with improved performance and improved lifetime/maintenance and Occupational Health and Safety and reduced cost of production/installation following. Ease of installation was the least ranked driver for this category.

In contrast, marine product specialists appeared to rank environmental drivers less often as most important and all three respondents ranked improved lifetime/maintenance and improved anti-biofouling performance in their top three drivers. Similarly, all three consultants ranked improving biofouling performance in their top three drivers but in contrast to the academic researchers ranked reduced marine environmental impacts lower. There was only one case where 'other' ranked higher than any of the other seven nominated drivers. In that case, the respondent ranked Occupational Health and Safety lowest (8) and a write-in suggestion about reducing hydrodynamic drag/fuel saving was ranked as the second most important driver, behind improved biofouling performance.

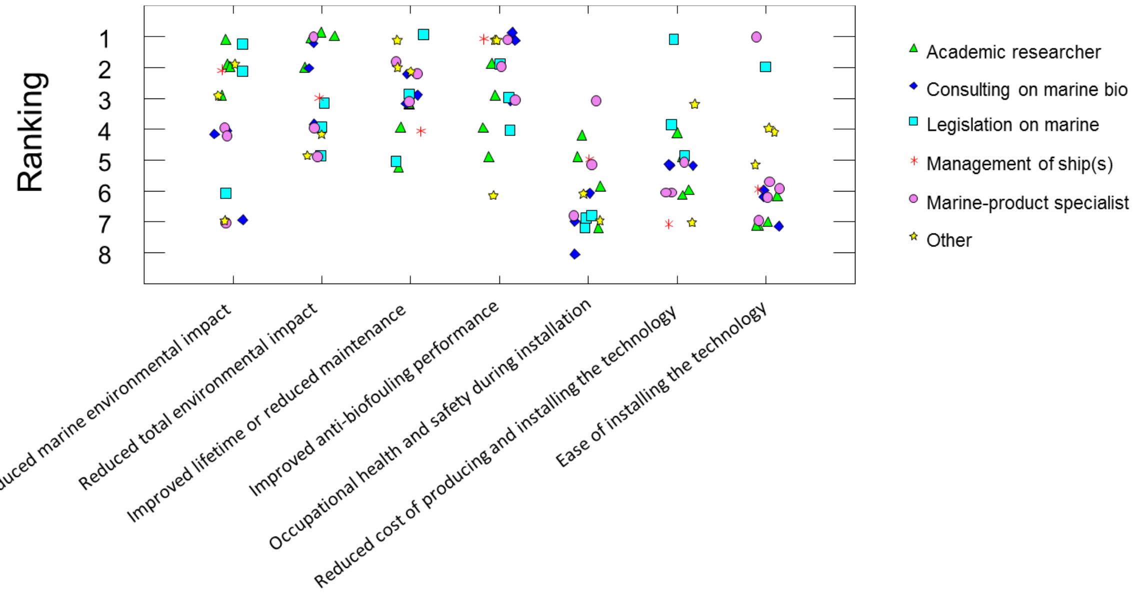

Figure 2: Scatterplot of respondents' importance rankings (1 = most important, 8 = least important) from Question 2. Note that 'other' is not shown in this diagram but in all but one case was ranked as least important.

In relation to the question regarding what was seen as the driving force/s for developing new marine anti-biofouling technologies, the subsequent focus of the remainder of the questions was which technologies the participants believed to have the best potential to replace today's copper releasing coatings for wide-spread general use, how they viewed the future legislation for the use of copper in anti-biofouling coatings and how they predicted that the cost of a new technology stated to be completely environmentally friendly would impact decision on implementation.

As shown in Figure 3 the majority of respondents (59%), with representation from each professional role, believed that a coating combining two or more of the listed approaches had the greatest potential to replace copper-containing coatings for general use, including on slow moving ships, ships spending long times at port and stationary marine constructs. This was followed by non-stick coatings being seen as a replacement alternative by 24% of the respondents. None of the other provided alternatives received any votes. Three respondents utilised the option to provide free text answers and responses detailed that mechanical hull cleaning, new polymers combined with biocides and coatings using newly registered biocides, with or without copper, were considered to be potential replacement technologies.

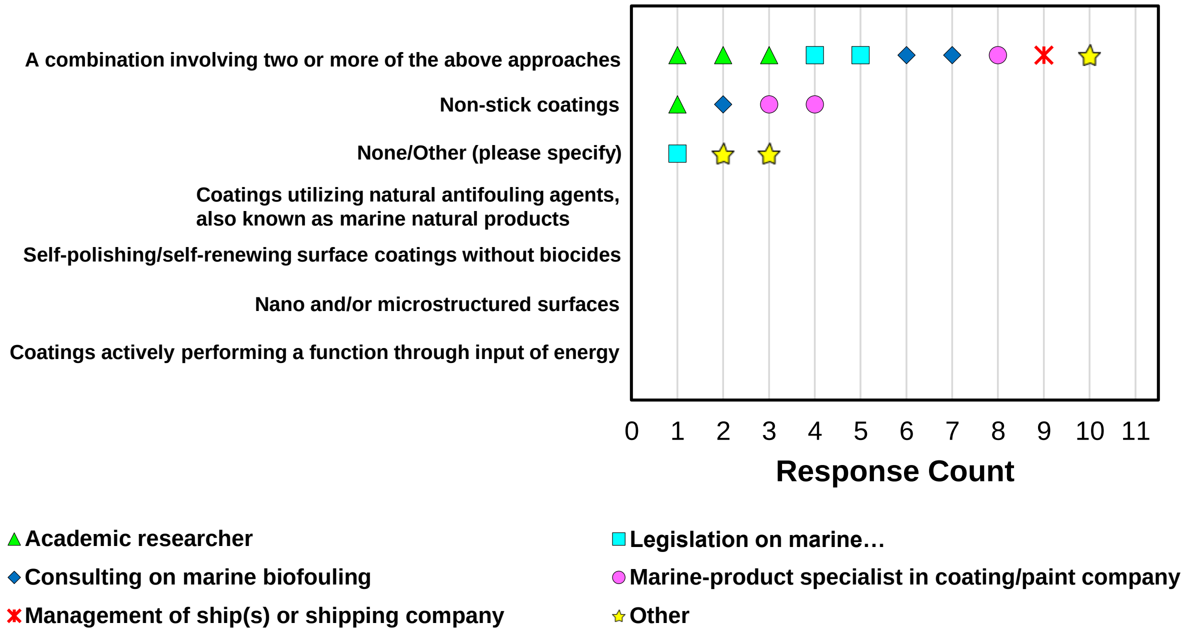

Figure 3: The response count from the different professional roles to Question 3: Which one of the following emerging marine anti-biofouling approaches do you believe has the most potential to replace coatings releasing copper and booster biocides, including use on slow moving ships, ships spending long times at port and stationary marine constructs? Response alternatives are given left of the y-axis in the figure. The three respondents that answered 'None/Other specified the following answers: Mechanical cleaning, like boat scrubbers; New polymer system combined with biocides; The 2 newly registered organic biocide Econea and Selectope, alone or with copper. Give the possibility to have product with less copper release and comply with possible new legislation.

With regard to the regulatory future of copper-containing coatings, the majority (53%) of the respondents believed that there would be tougher regulations with regard to copper release for all vessels. At first glance it seemed that predictions that regulations will vary for different vessels and a phase out and ban of copper-containing coatings were seen as likely by the same fraction of respondents (18% each). However, the answers by the two respondents that utilized the free text option were more similar to the provided choice of regulations varying for different vessels. In fact, their answers suggested that - in addition to variations with vessels- other factors would be taken into account such as application, location/route, business or pleasure use, etc. Thus 29% of the respondents had the view that regulations will vary depending on vessels and other factors. Noteworthy is that none of the respondents believed that the legislation for copper containing coatings will remain unchanged (refer Figure 4).

The participants were subsequently asked how they viewed the impact of price relative to the technology they (or their clients) currently use, on implementation of a new antifouling technology stated to be completely environmentally friendly, but yet proven to be so (Figure 5). Out of the 17 respondents, three out of four academics indicated that the question was not applicable to their professional role. Among the remaining 14 respondents, 43% believed that they (or their clients) would be willing to pay more for such a technology, with the same number (43%) believing they (or their clients) would pay up to the same amount. Interestingly, 14% responded that they or their clients would not implement the technology.

Four respondents made use of the option to provide open-ended comments (Question 6), expressing varied views including the following: the importance of fuel economy as a driver for improved antifouling products; that natural antifouling agent are also biocides; that trial applications of new technologies would be more acceptable than full application; that global regulations are welcome, but that it seems to be moving slowly towards this and that the European Union is expected to take the lead and that a technology to replace current coatings must be equally as 'good' as current coatings in addition to being environmentally friendly (refer Appendix II).

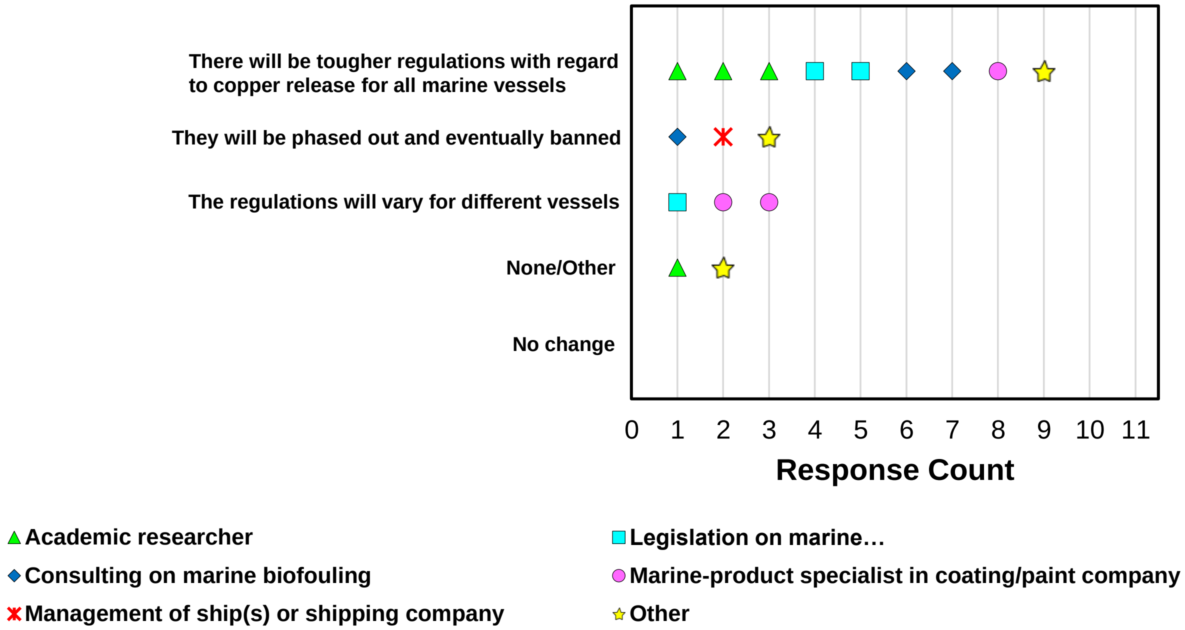

Figure 4: The response count from the different professional roles to Question 4: How do you view the regulatory future of copper-containing marine anti-biofouling coatings? Response alternatives are given left of the y-axis in the figure. The two respondents that answered 'None/Other specified the following answers: Will vary for type of vessel and location i.e. trading route/port; The regulation will vary for different application, not only vessel: fish farming; cargo and shipping; pleasure etc.

4 Discussion

This small scale study was undertaken to investigate the views on future marine anti-biofouling technologies by experts working with, or being impacted by, marine biofouling in different professional roles. The hypothesis was that there would be an indication of general trends and differences between professional roles that would be of value in decision making and justify a further more comprehensive study.

A high response rate was observed overall and the willingness of participants to contribute their expertise to this study was a pleasant (and greatly appreciated) surprise to us. Despite the good response rate, our sample size was still limited, with only a few respondents in each role category. Clearly, with low numbers, any conclusions made must be done with some caution, particularly when looking at comparisons among different self-nominated roles. In future studies, it will be critical to the project's success to engage and recruit participants from the 'management of ship(s) or shipping company' sector, as within the current study, the invitation-to-participation rate was estimated to be < 10% for this sector, in contrast to the other sectors which had a ≥ 50% participation rate. Although the results provide indications, it should be stressed that a larger and more comprehensive study will be required in order to draw firm conclusions on how representative views are for the differing roles. At this stage, any regional differences could also be examined and explored.

With regard to which anti-biofouling approach was considered to have the most potential in replacing coatings that release copper and booster biocides (including use on slow moving ships, ships spending long times at port and stationary marine constructs), it was clear that a majority (59%) were of the view that a combination of functionalities was needed (Figure 3). This number increased to 71% when taking into account that two of the respondents that listed 'other' approaches could be reclassified as using multiple functionalities. Among stand-alone technologies, non-stick (foul-release) coatings received some support (23%). One respondent believed that newly registered biocides, alone or with copper, would allow for less copper release so that legislative demands are met. No votes were given to natural antifouling agent (marine natural products), likely since they are also considered biocides, as pointed out by a respondent answering question 6. Similarly, nano-microstructured surfaces, coatings actively performing a function in response to input of energy and self-polishing/self-renewing coatings without

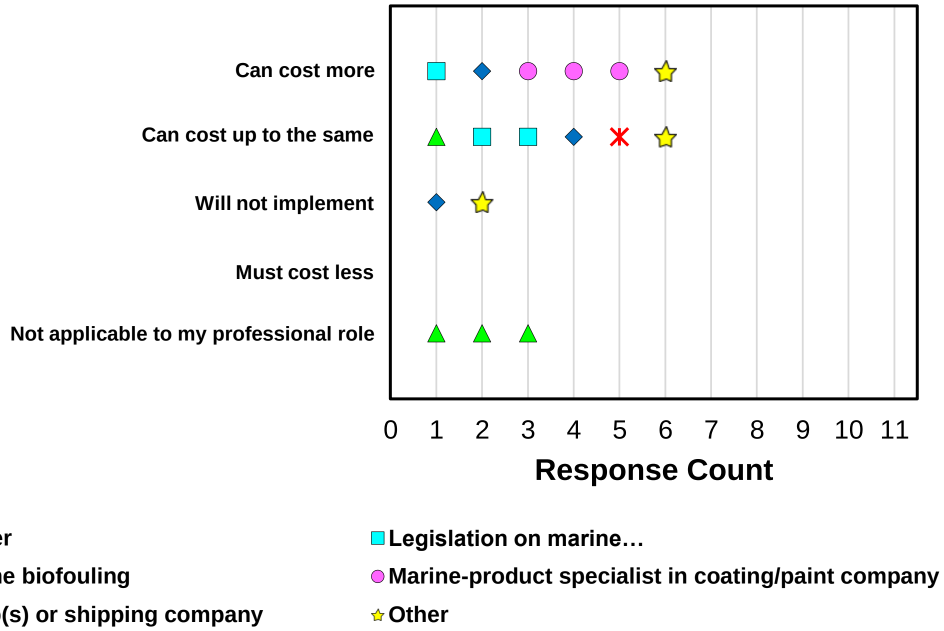

Figure 5: The response count from the different professional roles to Question 5: Relative to the technology that you or your customers currently sell/use, what cost do you estimate is acceptable for you or your customers to implement a new technology stated to be completely environmentally friendly but yet to be proven so? Response alternatives are given left of the y-axis in the figure.

biocides were not seen as likely replacements for copper-containing coatings. It therefore seems as if multiple functionalities in coatings is the perceived way of the future for general use (including on slow moving vessels and marine constructs).

When it comes to the regulatory future for copper containing coatings all respondents agreed that there would likely be changes in legislation. The majority view (53%) answered that there would be harder regulations for all vessel types. After considering the free-text answers by the respondents 29% of the respondents thought that the regulations will vary for different vessels, applications, industries, etc. and only 18% of the respondents believed that copper containing coatings would be banned (Figure 4). These results show that the wide-spread view was that copper-containing coatings will face tougher regulations, but not be banned completely. Interestingly, none of the respondents identifying as working with legislation believed that copper-containing coatings will be banned.

With regard to the impact of cost of a new technology proven to be environmentally friendly, an equal number of respondents answered that they (or their clients) would be willing to pay more than or the same as their currently used technology (for each case, 43% of the respondents feeling that they could answer the question in their professional role). The single respondent that identified with the role management of ship(s) or shipping company answered that such a new technology could cost up to the same as currently used technology. No respondents answered that the new technology would need to cost less, but 14% did state that they (or their clients) would not implement the technology (Figure 5). Interestingly, the marine-product specialists in coating/paint companies and the respondent identifying as biocide producer all answered that they or their clients would be willing to pay more. This observation is quite interesting given that these product providers are likely in good positions to make such predictions based on their current product range.

5 Conclusions

The views on future marine anti-biofouling technologies of experts working with, or being impacted by, marine biofouling in different professional roles was investigated using a targeted questionnaire. Some interesting trends were observed including:

- The category identifying as academics placed a greater emphasis on environmental concerns as a driving force in development of new anti-biofouling than other professional roles.

- Coatings combining two or more approaches for anti-biofouling were seen as most likely replacements of copper-containing coatings for widespread use (including on slow moving vessels and marine constructs). Non-stick coatings also received some support as replacement technologies.
- There was consensus that copper-containing coatings will face changed regulations in the future. A large majority of the respondents believed that future legislation will be harder for all vessels or depend on vessel type, application, location, etc. None of the respondents that identified as working with legislation believed that copper-containing coatings would be phased out and banned.
- There was a view that end-users are willing to pay the same or potentially more, compared to the technology they are currently using, for a technology stated to be completely environmentally friendly. Interestingly, all respondents who were identified as product providers indicated that they believed their clients would be willing to pay more for such a technology.

Although this study was performed using a relatively small number of participants (17) the findings can be used as indications of general views of professionals in the field and- interestingly -also indicated apparent differences in views between the identified professional roles. Knowledge on such differences could serve to guide academic research towards industry relevance from an applications perspective and to identify areas where further legislation or communication between parties is needed. We conclude that it is justified to expand the current study into a comprehensive large-scale investigation with an increased number of participants, questions and factors, such as geographical location and scale of business being taken into consideration.

Acknowledgements

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Presenting author biography

Dr Mikael Larsson is an engineer in chemistry and bioscience by training and received his PhD in materials science from Chalmers University of Technology in 2011. He has a strong background in polymer-based nanostructured materials. Currently he is applying his knowledge in materials design to develop new environmentally friendly marine anti-biofouling technologies, among others. The theme of the anti-biofouling research is materials that actively perform functions in response to a small input of energy.

Appendix I

Questions Included in the Survey

1. Which field best describes your professional activities?

- □ Management of ship(s) or shipping company
- □ Consulting on marine biofouling
- □ Legislation regarding marine environment and/or marine anti-biofouling
- □ Marine-product specialist in coating/paint company
- □ Academic research
- □ Other (please specify)

2. Below we have specified 7 major driving forces for the development of new marine anti-biofouling technologies. Please rank their importance relative to each other with 1 being the most important and 7 the least important. If you utilize the option to specify an additional driving force ("Other"), then please rank them 1 to 8 instead.

- □ Reduced marine environmental impact
- □ Reduced total environmental impact; from production to installation (e.g. green house gas emissions, solvent emissions, and leaching of biocides and other coating components)
- □ Improved lifetime or reduced maintenance
- □ Improved anti-biofouling performance
- □ Occupational health and safety during installation
- □ Reduced cost of producing and installing the technology
- □ Ease of installing the technology
- □ Other (Please specify in the Comments field - Question 6)

3. Which one of the following emerging marine anti-biofouling approaches do you believe has the most potential to replace coatings releasing copper and booster biocides, including use on slow moving ships, ships spending long times at port and stationary marine constructs?

- □ Non-stick coatings
- □ Coatings utilizing natural antifouling agents, also known as marine natural products
- □ Self-polishing/self-renewing surface coatings without biocides
- □ Nano and/or microstructured surfaces
- □ Coatings actively performing a function through input of energy
- □ A combination involving two or more of the above approaches
- □ None/Other (please specify)

4. How do you view the regulatory future of copper-containing marine anti-biofouling coatings?

- □ They will be phased out and eventually banned
- □ There will be tougher regulations with regard to copper release for all marine vessels
- □ The regulations will vary for different vessels
- □ No change
- □ Other (please specify)

5. Relative to the technology that you or your customers currently sell/use, what cost do you estimate is acceptable for you or your customers to implement a new technology stated to be completely environmentally friendly but yet to be proven so?

- □ Must cost less
- □ Can cost up to the same
- □ Can cost more
- □ Will not implement
- □ Not applicable to my professional role

6. Do you have any other comments, questions, or concerns?

Appendix II

Answers to question 6

Professional Role	Answer
Consulting on marine biofouling	Fuel efficiency is a major driver for improved antifouling products (by reducing hydrodynamic drag); Re: Q.3, "natural antifouling agent" = "biocide" Re: Q.5, partial, trial application would be more acceptable than a full application
Management of ship(s) or shipping company	I expect the EU to take the lead here if nothing happens on the global level and at present that seems to be working slow. Global regulation is welcomed from our end.
Other (please specify)	Comments question 5: It is not only important to prove a technology to be environmental friendly, it is important to prove that the technology is as effective as; as long-lasting as; as cheap as and as compatible to present standard methods of application-removal and all LCA-involved factors as the technologies used today. If not, all these aspects will influence acceptance and play a role in market penetration.