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IOC TECNICAL SERIES Nº 174

Biofouling Prevention and Management in the Marine Aquaculture Industry

Best Practices in Biofouling Management - Volume 1

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Report team

Author

Dr Sandra E. Shumway, Department of Marine Sciences, University of Connecticut, USA

Industry survey data providers

Paul Holtus, World Ocean Council

Maeva Cabanel, World Ocean Council

Editors

Pia Haecky, Intergovernmental Oceanographic Commission of UNESCO

John Alonso, International Maritime Organization

Lilia Khodjet El Khil, International Maritime Organization

Henrik Enevoldsen, Intergovernmental Oceanographic Commission of UNESCO

External reviewers

Xinhua Yuan, Aquaculture Technology and Production Team (NFIAT), Fisheries and Aquaculture Division (NFI), Food and Agriculture Organization of the United Nations (FAO)

Li Kang, Aquaculture Technology and Production Team (NFIAT), Food and Agriculture Organization of the United Nations (FAO)

Christine Rolin, Technology and Production Team (NFIAT), Food and Agriculture Organization of the United Nations (FAO)

Lovatelli, Alessandro, Technology and Production Team (NFIAT), Food and Agriculture Organization of the United Nations (FAO)

Serena Teo, Marine Biotechnology Lab, University of Singapore

Pei-Yuan Qian, Hong Kong University of Science and Technology

Proofreader

Julie Wickenden

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GloFouling Partnerships

Building Partnerships to Assist Developing Countries to Minimize the Impacts from Aquatic Biofouling (GloFouling Partnerships) is a collaboration between the Global Environment Facility (GEF), the United Nations Development Programme (UNDP) and the International Maritime Organization (IMO). The project aims to develop tools and solutions to help developing countries to reduce the transfer of aquatic invasive species through the implementation of the IMO Guidelines for the control and management of ships' biofouling. www.glofouling.imo.org

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The GEF-UNDP-IMO GloFouling Partnerships project aims at driving actions to implement the IMO Biofouling Guidelines and best practices for biofouling prevention and management in other maritime industries through policy development, capacity building, awareness raising and knowledge sharing.

For further information on the GloFouling Partnerships Project please contact:

GloFouling Partnerships Project Coordination Unit
Department of Partnerships and Projects
International Maritime Organization (IMO)
4, Albert Embankment, London, SE1 7SR, United Kingdom
Email: glofouling@imo.org
Web: https://www.glofouling.imo.org/

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1 Introduction

1.1. Scope and methodology

This report addresses biofouling management in relation to marine aquaculture industry operations, equipment and infrastructure. It covers shellfish, finfish and seaweed operations in estuaries and seawater. It does not address freshwater aquaculture activities.

As part of the GloFouling Partnerships Project being undertaken by the International Maritime Organization (IMO), in collaboration with the Global Environment Facility (GEF) and the United Nations Development Programme (UNDP), this report is one of a series covering best practices for biofouling management and addressing invasive aquatic species (IAS) for non-shipping sectors.

The focus of these reports is on biofouling management. Information about the general processes of biofouling, the ecological and environmental impacts, economics of management and the costs estimated to be associated with IAS are beyond their scope. Biofouling, control and mitigation on ocean industry structures, vessels and operations, as well as offshore oil and gas structures will be covered in separate reports.

Shipping and vessel-related biofouling management and IAS are the direct focus of the IMO Biofouling Guidelines (guidelines for the control and management of ship biofouling to minimize the transfer of IAS) and are also covered in other parts of the GloFouling Project. Although this report focuses on the non-shipping/non-vessel aspects of biofouling and IAS, some of the information may be applicable to vessels involved in marine aquaculture activities.

While offshore aquaculture does rely on vessels to deploy and maintain offshore netting platforms as well as to feed and harvest fish, biofouling species found in and around the farm are the same as those found in the homeports of these vessels. Support vessels for aquaculture operations are local boats, maintained in local waters, and travel short distances, thus they are not potential vectors for non-indigenous species (NIS). They may, however, serve as settlement surfaces for any biofouling organisms, in the same way as the aquaculture structures and gear themselves. Biofouling on boat hulls is a hindrance for owners and is regularly eradicated through antifouling coatings and cleaning.

This report has been prepared through the compilation, assessment and synthesis of the information from the marine aquaculture industry on current best practices in biofouling management. This includes outreach, consultation and discussions with industry representatives. It also includes information from the industry media, market reports and other grey literature, and the scientific literature related to the marine aquaculture industry and biofouling. It is not meant to be a comprehensive review, but rather it is intended to provide readers with an introduction to the topic and references for further investigation. This report also identifies many existing documents and guidelines related to best practices for biofouling management, especially those developed specifically by and for the marine aquaculture industry. See Appendix 1 for a list of reference materials .

1.2. Introduced species

An alien species is one that is not native to a location but has been introduced either accidentally or intentionally by humans. An invasive aquatic species (IAS) is an alien species that causes adverse economic or environmental impacts or harms human health. Invasive aquatic species are typically a small subset of the alien species in a given location. Introduced species are those that have been moved by humans to locations where they would not have spread naturally (e.g. not range expansions associated with climate change) and are out of place in time and space (Carlton, 1985; Ruiz et al., 2000). There has been much debate over the terms 'invasive' and 'introduced' species and the definition of invasive is not well defined for marine species. Several terms have been used to describe such species of concern. They have been variously described as 'exotic' species, 'alien' species, 'introduced' species and 'invasive' species (Colautti and MacIsaac, 2004; Colautti and Richardson, 2009; Naylor, Williams and Strong, 2001). Some authors have tried to make distinctions between species that are known to have economic impacts and those that behave differently in new areas as compared with their native habitats (Valéry et al., 2008). The term 'introduced species' is often used to denote a species that is spreading and causing economic or ecological harm; however, ecological harm can be hard to quantify and is rarely specifically assessed. Hence, ecological harm is often assumed, but not actually measured. Similarly, direct economic harms are often clearly present and demonstrable, while indirect economic harm is difficult to quantify. Generally, the economic and environmental impacts of most species have not been assessed and there are often long lag times between initial introductions and spread and the measured impacts for many species (e.g. Klinger, Padilla and Britton-Simmonds, 2006; Karatayev et al., 2009). Here, all species that are out of place in time and space relative to their natural distribution are considered and are referred to as 'introduced species' or 'invaders'. These species have been transported beyond their native range by human activities rather than through natural dispersal.

While transportation of fouled gear and shellfish can introduce biofouling species to new areas, this is not common as cultured animals are usually removed for sale and not returned to the environment and gear is cleaned prior to re-siting. These activities can, in limited circumstances, lead to the introductions of species to new areas and aid the spread of invasive species (Minchin, 2007; Rodriguez and Ibarra-Obando, 2008; Rocha et al., 2009; Ruiz et al., 2000). For example, in British Columbia, transportation of oysters covered with the invasive ascidian *Didemnum vexillum* introduced the ascidian to uninfected areas (Ferguson et al., 2017). In South Africa, translocated oysters are thought to have introduced four non-native species to the region: a sea urchin, an oyster, a crab and a brachiopod (Haupt et al., 2010). A parasitic worm, *Terebrasabella heterouncinata*, which causes shell deformities was introduced into California with South African abalone in the 1980s (Culver and Kuris, 2002). Other pest species believed to have been introduced via shellfish aquaculture activities include Japanese oyster drills and a turbellarian flatworm (Shatkin, Shumway and Hawes, 1997), Asian eelgrass (Thom, 1990) and seaweeds such as *Codium fragile* (Trowbridge, 1999). While all of these introductions may have deleterious impacts on the shellfish or the local environment, they are pests, not biofouling. The shell-boring worm, *Polydora uncinata*, is believed to have reached Chile on imported abalone brood stock (Radashevsky and Olivares, 2005).

It is generally a bad idea to introduce any species to a new location and it is particularly dangerous when invasive species reach new sites. Invasive species can be extremely damaging to aquaculture and the environment (Dijkstra, Sherman and Harris, 2007; Daigle and Herbinger, 2009; Lutz-Collins et al., 2009; Fletcher, Forrest and Bell, 2013; Fletcher et al., 2013). Once established, invasive species are nearly impossible to remove (Coutts, 2002; Coutts and Forrest 2007; Deibel et al., 2014). Prevention is the key to managing invasive species. The introduction of alien species via aquaculture activities has been reported, but confirmed examples are very limited (see papers by Katsanevakis et al., 2013; 2014; Stranga and Katsanevakis, 2021). Nunes et al. (2014) provided a comprehensive assessment of alien species invasions in Europe and noted that introductions via aquaculture were mostly reported in France and Italy, and associated with regions of extensive mariculture activities and areas previously recognized for invasions. When biofouling organisms are moved to new locations on shellfish and gear, they can also transport other noxious organisms along with them. For example, harmful algae can survive gut passage through the digestive tracks of ascidians (Rosa et al., 2013). Ascidian gut clearance rates vary, but intact and viable harmful algal cells may be released for 48 hours, or more, after they have been ingested by ascidians (Rosa et al., 2013). Ascidians attached to shellfish can consume harmful algae in one area, be moved to a new location as the shellfish are transported and then introduce harmful algae to the new location, which could lead to a bloom.

The Code of Conduct for Responsible Fisheries (FAO, 1995) and the ICES Code of Practice on Introduction and Transfer of Marine Organisms (ICES, 2005) and regulations in many countries concerning the use of alien and locally absent species in aquaculture validate the global awareness of the importance of regulating introductions wherever possible.

Figure 1. Biofouling on shellfish gear. Clockwise from upper left: Shellfish cages (photos courtesy of Tessa Getchis and Andre Mallet); oyster bag, tube worms on scallop cages, tunicates on scallop lantern nets, fouling on oyster bags (photo Sandra Shumway);

1.3. Biofouling in the marine aquaculture industry

Biofouling is the accumulation of organisms on surfaces such as the hulls and other submerged parts of vessels, the shells or carapaces of other species, equipment associated with fishing, mariculture, offshore energy and marine debris. In the marine aquaculture industry, biofouling occurs on nets (fish culture) and structures used for shellfish and seaweed cultures (e.g. trays, lines, ropes, docks), as well as on the cultured species themselves (seaweed and shellfish).

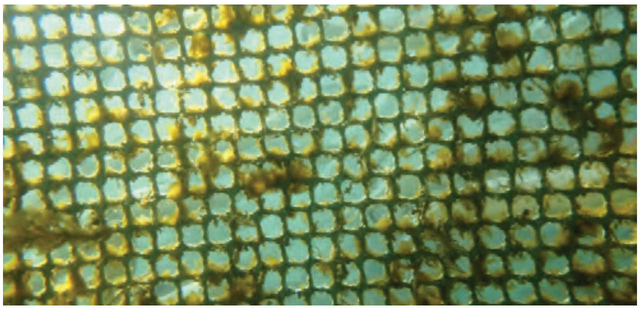


Figure 2. Hydroids fouling salmon netting (photo Alex Walsh).

Materials deployed in the marine environment, including aquaculture gear, routinely become colonized by plants and animals (see Railkin, 2004; Dürr and Thomason, 2010; Tucker and Hargreaves, 2008; Watson, Shumway and Whitlatch, 2009). These assemblages are commonly referred to as 'biofouling communities' – or simply 'fouling' – and vary with the location, crops, equipment, season, depth, temperature and other factors and are site- and species-specific. Globally, the assemblages are composed of the same suite of invertebrate taxa (ascidians, anthozoans, barnacles, bryozoans, hydroids, polychaetes, sponges) and once attached are very difficult to remove. Because the biofouling taxa are similar worldwide, most general-purpose antifouling methodologies are effective in a wide variety of marine systems (e.g. Bullard, Shumway and Davis, 2010). Biofouling is a ubiquitous issue in the aquaculture industry as it clogs mesh on bags and nets, restricts water flow and subsequently food and oxygen supply. Filter-feeding biofouling organisms also compete with filter-feeding crops for food. Heavy fouling results in major increases in weight and drag of the gear and makes maintenance and harvesting difficult if not dangerous (Figures 1 and 2). Gear and maintenance structures can also be damaged by the presence of biofouling organisms. Generally speaking, aquaculture facilities provide substrate and habitat for biofouling organisms, but do not serve as vectors for distribution.

Biofouling management in aquaculture includes: (1) preventing the initial settlement of fouling species by repelling or killing them; (2) inhibiting the development of settled organisms by reducing their adhesion ability or removing them while they are small and immature; or (3) removing or eradicating established biofouling growth. It is very important, however, to test the efficacy of new antifouling products in a variety of biogeographical areas to ensure that their efficacy is not region-specific.

Control of biofouling consists of preventative measures as well as removal. These measures are a regular component of aquaculture operations and comprise numerous approaches (see sections on methods below). Some methods have been shown to have negative or adverse impacts on the surrounding environment and nontarget organisms. Over time, these potentially harmful methods have been slowly eradicated in favour of more environmentally and efficient control methods. Currently there is no universally effective prevention method for biofouling and the development of better methods is ongoing (see Table 1 for general overview). Anti-predator nets are placed outside the fish containment nets and prevent birds, seals and other predators from entering the fish pens (Figure 3). These nets are commonly copper-coated. Successful development and demonstration of extended efficacy of antifouling coatings for the fish pens, as well as development of coatings for anti-predator nets, would have a profound positive impact on the aquaculture industry.

It must be kept in mind that aquaculture produces a live product for human consumption. Hence, materials used to thwart biofouling must be safe and the methods and materials employed are generally different from those used in the much larger commercial shipping industry. Biofouling in the aquaculture industry impacts not only the equipment and associated infrastructure, but also the organisms themselves (e.g. shellfish and algae). Clearing this material is critical to the grow-out process as the fouling and subsequent removal can be detrimental to shell quality and survival of the organisms and algae (see Dürr and Watson, 2010; Watson, Shumway and Whitlatch, 2009; Bullard et al., 2021 for general reviews). Though unsightly and logistically challenging, biofouling does not impact the safety of crop species for human consumption.

Figure 3. Copper-coated anti-predator netting on salmon pen (photo Alex Walsh).

Table 1. General techniques for preventing and removing biofouling

	Pros	Cons	Reference
Biofouling prevention strategies			
Selecting sites with few fouling organisms (e.g. low salinity areas, deeper sites, 'dropping lines', areas with limited established fouling communities)	Can reduce the pool of settling larvae and lower fouling loads	Not always possible, can result in lower growth rates of cultured shellfish	Southgate and Myers, 1985; Enright et al., 1993; Claereboudt et al., 1994; Lodeiros et al., 1998; Bourque and Myrand, 2006; Howes et al., 2007; Watson, Shumway and Whitlatch, 2009; Cowie, 2010; Aghzar et al., 2012
Selecting material and placement of gear and structures with lower fouling potential (e.g. light coloured surfaces, vertical orientation, different construction materials)	Can naturally reduce the willingness of settling larvae to attach to surfaces	Not always possible (especially adjustment of orientation); little information is available on the fouling properties of different construction materials; algal species may settle at higher levels on light-coloured surfaces	Pomerat and Reiner, 1942; Pomerat and Weiss, 1946; Huguenin and Huguenin , 1982; Dahlem, Moran and Grant, 1984; Connell, 1999; Glasby, 2000; Hodson, Burke and Bissett, 2000; Glasby and Connell, 2001; Thomason et al., 2002; Swain et al., 2006; Mason, Beard and Miller, 2011; Tanyaros and Kitt, 2012; Bloecher et al., 2013; Dobretsov, Abed and Voolstra, 2013; Ells et al., 2016
Addition of clay aggregate culture media to the culture gear	Effective at controlling tube worms	Can reduce growth of cultured shellfish; oyster survival often decreases	Dunham and Marshall, 2012; Marshall and Dunham, 2013
Avoiding seasons or times of the year when fouling organisms are reproducing	Can reduce fouling loads; if focused on specific problem species, can avoid/reduce fouling by particular species	Must know the settlement patterns of local fouling organisms; staggered reproductive periods for different species can reduce effectiveness	Yamaguchi, 1975; Green and Grizzle, 2007; Zhanhui, Jianguang and Jihong, 2010; Kripa, Mohamed and Velayudhan, 2012; Bloecher, Olsen and Guenther, 2013; Bullard, Davis and Shumway, 2013; Fletcher et al., 2013
Keeping gear out of the water certain times of year	Can reduce fouling of problematic species	Growers need to know fouling regime at their sites – data not always available; sites harbour diverse fouling communities – may be able to avoid some, but not all species	McDougall, 1943; Karlson and Osman, 2012; Bullard, Davis and Shumway, 2013; Sievers et al., 2014
Antifouling coatings	Reduce overall fouling loads for 3–6 months	Historical formulations harm shellfish, toxic to the environment; expensive, active ingredients accumulate in fish tissues (gills, liver, spleen, etc.); hydroid settlement not always impacted	Dafforn, Lewis and Johnston, 2011; Bloecher and Floerl, 2021; Edwards, Pawluk and Cross, 2015; Guardiola et al., 2012; Borg and Trombetta, 2010; Baldwin, Tatara and Scholz, 2011; Brooks and Mahnken, 2003
Bioactive age/ Netting (copper alloy)	Effective antifouling for up to 60 months, reduced frequency for cleaning, recyclable	Cannot be used for shellfish, extremely expensive, greater release of biocide (copper) over time than with coatings	Berillis, Mente and Kormas, 2017; Tsukrov et al., 2011; Yigit et al., 2018; Early et al., 2020; Chambers et al., 2012; Kalantzi et al., 2016
Biofouling release coatings	Easier to clean, protects netting and cage materials from UV degradation and abrasion, non-toxic	No antifouling, so cleaning is required; cost of coating netting and cage materials is prohibitive	Hu et al., 2020; Hodson, Burke and Bisset, 2000; Terlizzi et al., 2000; Scardino, Fletcher and Lewis, 2009; Tettelbach, Tetrault and Carroll, 2014
Biological controls	Once released, can consume fouling species with little additional intervention; can serve as additional cash crop	Obtaining enough biological control organisms can be difficult; not always effective	Hidu, Conary and Chapman, 1981; Enright et al., 1983; Minchin and Duggan, 1989; Flimlin and Mathis, 1993; LeBlanc, Landry and Miron, 2003; Lodeiros and García, 2004; Ross, Thorpe and Brand, 2004; Valentine et al., 2007; Carman, Allen and Tyrrell, 2009; Dumont et al., 2009; Epelbaum et al., 2009; Bloecher, Olsen and Guenther, 2013; Zhanhui et al., 2014; Sterling, Cross and Pearce, 2016
Streams of air bubbles	Reduces overall fouling loads, often dramatically	Hard to employ on a large scale; bubbles must flow continuously; stresses fish	Smith, 1946; Bullard, Shumway and Davis, 2010; Lowen et al., 2016

Removing biofouling			
Manual removal (e.g. scraping, power washing, etc.)	Very effective at removing fouling	Labour-intensive; required weekly; costly; can harm shellfish; can generate large amounts of waste material; some biofouling species can survive high-pressure treatment and fragments can survive and reattach; mechanical removal can result in reduced growth of cultured shellfish or shell damage; some species release larvae when stressed which can settle on newly cleaned nets	Chang and Wheaton, 1981; Parsons and Dadswell, 1992; Enright et al., 1993; Taylor et al., 1997; Bers and Wahl, 2004; Minchin and Sides, 2006; Coutts and Forrest, 2007; Bullard et al., 2007; Cheney, 2010; Paetzold and Davidson, 2010; Hopkins, Forrest and Coutts, 2010; Arens et al., 2011; Switzer et al., 2011; Carl, Guenther and Sunde, 2011; Coddington-Ring, 2012; Paetzold, Hill and Davidson, 2012; Morris and Carman, 2012; Reinhardt et al., 2012; Davidson et al., 2016
Air drying	Very effective at removing fouling from gear	Cannot normally be used with all shellfish – if tried can lead to shellfish mortality; cannot be implemented at traditional fish farming facilities; may not control all fouling organisms; does not remove calcareous shells or tubes	Lutzen, 1999; LeBlanc et al., 2007; Mallet et al. 2009; Darbyson et al., 2009; Hillock and Costello, 2013; Hopkins et al., 2016
Sprays and dips (freshwater, brine, hot water, acetic acid, lime, etc.)	Very effective at removing fouling in some situations	Cannot be implemented at fish farming facilities; often causes shellfish mortality; long exposure times (days) may be needed; can be costly; does not remove calcareous shells or tubes	Littlewood and Marsbe, 1990; Leighton, 1998; MacNair and Smith, 2000; Carver, Chisolm and Mallet, 2003; Coutts and Forrest, 2005; Forrest and Blakemore, 2006; Forrest et al., 2007; LeBlanc et al., 2007; Denny 2008; Paetzold, Davidson and Giberson, 2008; Locke et al., 2009; Watson, Shumway and Whitlatch, 2009; Piola, Dunmore and Forrest, 2010; Guenther, Fitridge and Misimi, 2011; Rolheiser et al., 2012; Mayrand, Sonier and Comeau, 2015; Carman et al., 2016; Comeau et al., 2017

Source: Modified from Watson, Shumway and Whitlatch (2009) and Bullard et al. (2021).

2 Ecological and economic impacts

2.1. Ecological impacts

The transfer of introduced species globally as a result of anthropogenic activities has been taking place for centuries. Biofouling has long been a conduit for the introduction and spread of alien marine species. Human activities have provided pathways for marine species to spread and cross natural biogeographic boundaries into new habitats predominantly via shipping, recreational boating, the installation and movement of industry infrastructure and equipment, the marine aquarium trade and the opening of canals (see Elton, 1958; Boudouresque 1999; Jackson, L., 2008; Rilov and Crooks, 2009; Shevalkar, Mishra and Meenambiga, 2020). Shipping and movement of vessels is the primary vector (Carlton, 2000; Hewitt and Campbell, 2010). As examples of the scope of the issue, it is estimated that biofouling organisms may account for up to 75% of non-native marine invertebrates in Hawaii (Eldredge and Carlton, 2002) and 78% of non-native marine species in Port Phillip Bay, Australia (Hewitt et al., 2004), some of which have become invasive.

Aquaculture structures generally serve as highly suitable habitats for biofouling species; however, there are few records of the introduction of IAS by these structures or culture practices. While marine aquaculture may introduce alien species to new environments, it is primarily the recipient of biofouling from organisms which have been introduced via other industries and pathways (Nunes et al., 2014), i.e. aquaculture usually serves to magnify IAS invasions rather than cause the invasions themselves. Aquaculture, especially shellfish aquaculture, can encourage the establishment of alien species by providing large amounts of gear or shell surfaces to which the IAS can attach. While theoretically these fouling organisms could be transported domestically or internationally during shipping of live shellfish, the shellfish are most routinely sent to market and not placed in the environment, i.e. this is not a major threat with regard to introductions or transfers. The practices employed to clean, prepare, pack and distribute live shellfish can either minimize or exacerbate the potential for the spread of biofouling organisms (see below).

For example, the movement of salmon cages is believed to have been responsible for the spread of the Japanese seaweed *Undaria pinnatifida* into the New Zealand Marlborough Sounds (White, O'Neill and Tzankova 2004) and the translocation of the sea squirt *Didemnum vexillum* from Port Shakespeare to salmon farms and mussel farms at East Bay (Pannell and Coutts, 2007).

Shellfish aquaculture can also serve as a vector for alien species (McKindsey et al., 2007). For example, the mussel *Mytella strigata* has recently been found at clam farms in Taiwan, China (Huang et al., 2021). In terms of overall scale, it is estimated that 13% of marine alien species in European waters were introduced via aquaculture (Nunes et al., 2014). The recent development of new structures and practices in China and Norway (Figure 4) has been suggested as a potential threat to transfer of IAS; however,

Figure 4. Offshore fish farm, Ocean Farm 1, delivered to Norway from China 2017 (photo Salmar).

mitigation actions are already in placewhich will thwart such transfer. These large structures are delivered from China to Norway and spend very short periods of time in transit. The furthest distances towed in the water are only approximately 200 nautical miles. Structures are suspended out of the water for transporting over greater distances and most of the farm (netting) is assembled on site. Aquaculture and associated practices are, today, generally not considered as primary vectors for the introductions of IAS.

Infestations of IAS can have various ecological impacts on marine aquaculture, including competing with native species for space and food, preying upon native species, altering habitats of other species, altering environmental conditions (e.g. decreased water clarity), altering the food web, displacing native species, reducing native biodiversity, spreading diseases and extinctions (Jackson, J., 2008).

2.2. Economic impacts

Biofouling in marine aquaculture is just one of the main barriers to efficient and sustainable production. The direct economic costs of managing biofouling in the aquaculture industry were estimated to be 5–10% of production costs as reported in Dürr and Watson (2010). Adams et al. (2011) reported costs to the shellfish industry, based upon an industry-based survey, at ~15%. Globally, this equates to direct costs of US$1.5 to 3 billion/year (Archana, Sundaramoorthy and Faizullah, 2019).

Biofouling in marine aquaculture is just one of the main barriers to efficient and sustainable production. The direct economic costs of managing biofouling in the aquaculture industry were estimated to be 5–10% of production costs.

Many indirect impacts remain largely unassessed, so the overall economic cost of biofouling in marine aquaculture is likely to be significantly underestimated (Fitridge et al., 2012).

Development of anti-fouling coatings for boat hulls is a > US$8 billion industry and commercial antifouling paints can prevent fouling on gear (Braithwaite, Carrascosa and McEvoy, 2007; Facts and Factors, 2020). Traditionally these coatings have not been widely used in the aquaculture industry (Watson, Shumway and Whitlatch, 2009) because they can leach toxic substances into the environment, have detrimental effects on cultured organisms (Davies and Paul, 1986; Paul and Davies, 1986; Voulvoulis, Scrimshaw and Lester, 1999; Callow and Callow, 2002; Omae, 2003; Thomas and Brooks, 2010) or render the cultured product unsafe for human consumption (Hites et al., 2004; Muñoz et al., 2010). Current research to develop environmentally safe coatings is ongoing.

Figure 5. Biofouling on seaweed farms. Clockwise from upper left: Fouling on Gracilaria tikvahaie (photo Sarah Redmond; from Getchis, 2014 with permission), mussels fouling Gracilaria, colonial tunicates fouling kelp (Saccharina latissimi), and Gracilaria (photo Anoushka Concepcion).

2.3. Biofouling problems and costs in the husbandry process

Biofouling on aquaculture facilities results in increased labour and maintenance costs (Bourque et al., 2003; Minchin, 2007). Biofouling costs to marine aquaculture are conservatively estimated to be 10–15% of production costs, the equivalent of US$1.5–3 billion annually (Adams et al., 2011; Fitridge et al., 2012). Bloecher and Floerl (2021) have recently provided a review of cost-effective management of biofouling in the salmon industry and biofouling management strategies to facilitate improved fish health and welfare, reduce environmental impacts and improve public perception of large-scale fish farming. Their proposed strategies are based upon efficient antifouling coatings, combining antifouling treatments with intermittent cleaning and regular grooming of nets.

Biofouling can have direct commercial effects due to production losses. Such losses may come from reduced water flows through nets and trays that result in reduced food supply and dissolved oxygen being available for the cultured stock (CRAB, 2006; Willemsen, 2005). Biofouling leads to a need for more frequent cleaning, net replacement and/or application of antifouling products. This can increase the stress on cultured fish and reduce growth rates and productivity. Diseases and parasites may also be introduced by biofouling which can lead to production losses (CRAB, 2006). For shellfish growers, production losses can also be caused by physical damage as fouling organisms bore into the shell or grow on the shell surface, which can affect the aesthetics of the product (Fitridge et al., 2012). Finally, biofouling organisms may compete with cultured species for food and oxygen and result in reduced growth rates and compromised productivity (Sievers et al., 2013; Fitridge et al., 2012; Taylor, Southgate and Rose, 1997). Conversely, while the impacts of biofouling on aquaculture are generally negative, biofouling can have positive effects on cultured shellfish, albeit limited in scope. Biofouling can increase food availability to shellfish by increasing primary production near aquaculture facilities (Ross et al., 2002). Biofouling organisms can also reduce predation on cultured shellfish by providing them with chemical or tactile camouflage, or granting them associational defences. For example, fouling by sponges reduces sea star predation on scallops (Armstrong, McKenzie and Goldsworthy, 1999; Farren and Donovan, 2007) and fouling by the ascidian *Didemnum vexillum* reduces green crab predation on blue mussels (Auker, Majkut and Harris, 2014).

Farmed kelp and other seaweed species are also prone to fouling by epiphytes and some invertebrates (Figure 5; see Visch, Nylund and Pavia, 2020 and references therein). This biofouling can impair growth, productivity due to weak and breaking fronds (Dixon, Schroeter and Kastendiek, 1981), reduced growth attributed to loss of light penetration from the fouling and decreased nutrient uptake (see Cancino, Muñozand Orellana, 1987; Hurd et al., 2014. While careful placement and consideration of depth and water currents can reduce biofouling in algal culture, this is a delicate balance and impacts blade growth, nutrient content and other components. Impacts of biofouling also vary between algal species, e.g. kelps vs other species (see Matsson, Christie and Fieler, 2019; Forbord et al., 2020).

3 Managing biofouling and invasive species in the marine aquaculture industry

Biofouling is ubiquitous in the marine environment and is one of the most serious problems facing aquaculture (de Nys and Guenther, 2009; Watson, Shumway and Whitlatch, 2009; Adams et al., 2011; Fitridge et al., 2012; Fletcher, 1995; Tucker and Hargreaves, 2008; Bloecher and Floerl, 2021). Biofouling dramatically increases labour costs, reduces the value of product and can harm cultured species (Claereboudt et al., 1994; Lodeiros and Himmelman, 1996; de Nys and Ison, 2008; Watson, Shumway and Whitlatch, 2009; Adams et al., 2011; Fitridge et al., 2012; Bannister et al., 2019). As a result, considerable effort is directed toward the prevention and control of biofouling at aquaculture facilities (Armstrong et al., 2000; Yebra, Kiil and Dam-Johansen, 2004; Chambers et al., 2006; Coutts and Forrest, 2007; Watson, Shumway and Whitlatch, 2009; Bloecher and Floerl, 2021). Mitigation techniques are available and can be effective, but most are costly, time-consuming or have negative impacts on the environment (Evans, Birchenough and Brancato, 2000; Voulvoulis, 2006). The search continues for an inexpensive, effective and environmentally friendly method to control biofouling (e.g. Hellio et al., 2001; Yebra, Kiil and Dam-Johansen, 2004; Majumdar et al., 2008; Maréchal and Hellio, 2009).

In addition to the associated increased costs, biofouling has negative impacts on the growth, condition and survival of cultured organisms. In shellfish aquaculture, biofouling organisms compete with shellfish for food and space (Osman and Abbe, 1994; Arakawa, 1990; Lesser et al., 1992) and can lead to the reduced growth of cultured organisms (Taylor, Southgate and Rose, 1997; Pit and Southgate, 2003; Lodeiros et al., 2007; Daigle and Herbinger, 2009; Sievers et al., 2013). Reduced growth can be caused by biofouling on the cage material (Claereboudt et al., 1994; Lodeiros and Himmelman, 1996) and by direct fouling on the shells of cultured shellfish (Lodeiros et al., 2007; Lodeiros and Himmelman, 2000). For example, the scallop Euvola ziczac was more heavily affected by fouling on culture nets than by shell fouling (Lodeiros and Himmelman, 1996), while fouling on the shell caused reductions in growth of *Crassostrea rhizophorae* (Lodeiros et al., 2007). Younger shellfish may be more at risk from fouling than older. Fouling by the colonial ascidian *Didemnum vexillum* in New Zealand reduced mussel density of small size class green-lipped mussels, but did not affect the growth or condition of larger mussels (Fletcher, Forrest and Bell, 2013).

While many techniques are available to remove biofouling organisms from aquaculture gear, none has been successful at eradication and biofouling remains one of the major costs associated with aquaculture operations (see Adams et al., 2011). The goal is to stop biofouling communities from becoming established, i.e. prevent the settlement in a cost-effective manner that also presents no harm to the cultured organism or environment (Figure 6).

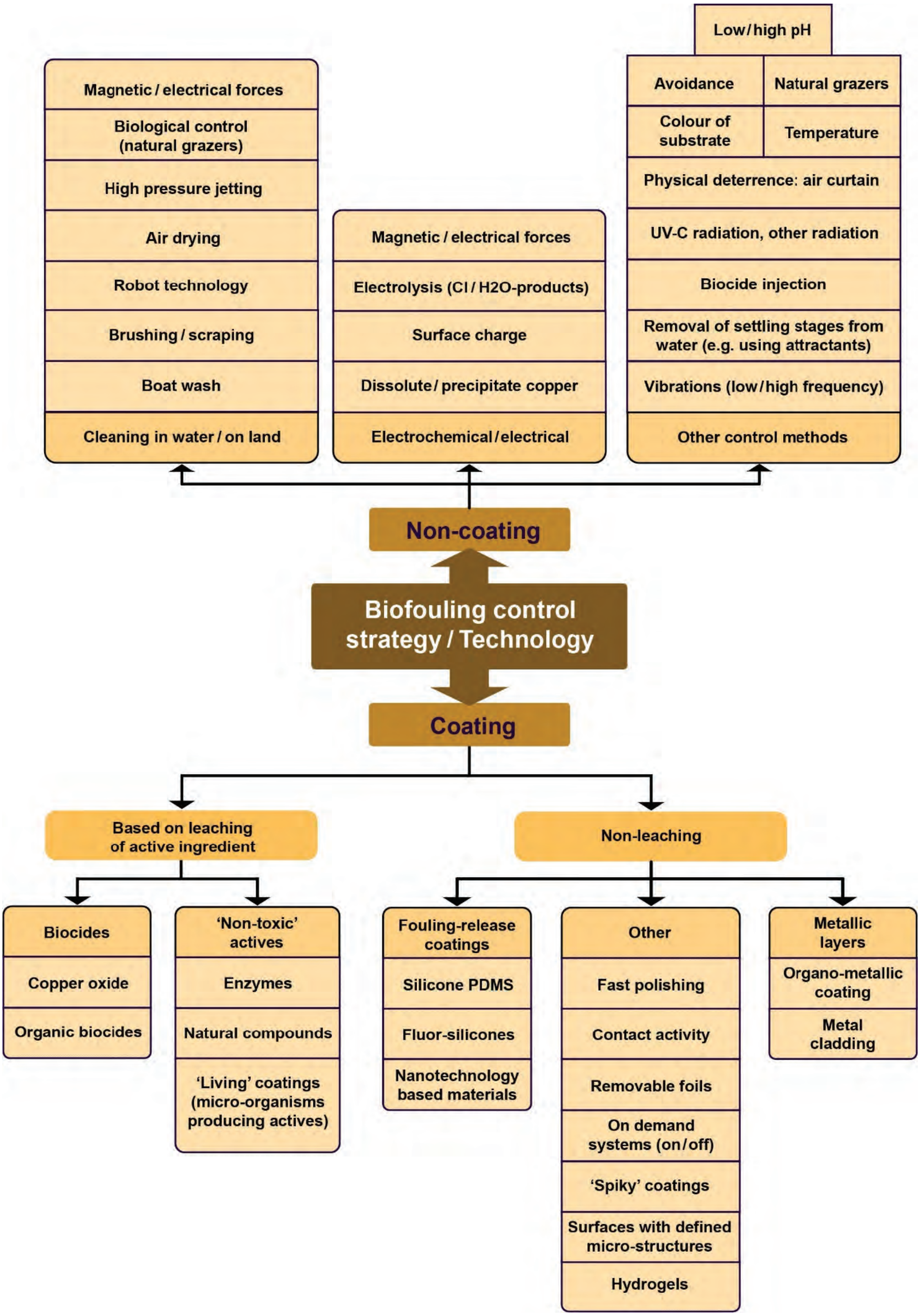


Figure 6. Generalized summary of potential and utilized strategies and technologies to combat biofouling. Many of these technologies are utilized in the aquaculture sector and new technologies are being investigated. Source: Sandra Shumway

3.1. Biofouling management strategies

Marine aquaculture companies manage biofouling using one or several of the following approaches: (1) repelling or killing the propagules of biofouling species; (2) preventing the development of settled organisms; (3) inhibiting the growth of biofouling organisms or reducing their adhesive ability; and (4) cleaning fouling from aquaculture facilities, infrastructure, equipment and cultured organisms (e.g. shellfish) (Jackson, L., 2008; Dürr and Thompson, 2010; Bullard, Shumway and Walsh, 2021).

In addressing biofouling, the marine aquaculture industry works to balance economic viability with environmental and animal health concerns. Key criteria considered for selection and development of the most suitable management strategies include whether the strategy will: (1) be effective against a broad range of biofouling organisms; (2) be environmentally friendly; (3) result in negative effects on the cultured species; (4) leave residues in the cultured species; (5) withstand handling and cleaning of the cultured organisms; and (6) be economically viable (Lewis, 1994; Bullard, Shumway and Walsh, 2021). Each company applies these criteria to tackling biofouling in relation to the species (or mix of species) they raise, the technology and infrastructure employed, the production processes they use, the packing and shipping methods used and market and consumer demands.

Marine aquaculture companies have a range of biofouling management strategies at their disposal and select an appropriate mix based on their specific needs and the species in question. These strategies can be broadly differentiated based on the use of coatings and non-coating options (Figure 6). All of these strategies and technologies are being used by industry to some extent and vary according to species, geographic region, biofouling species and local regulations. Among the non-coating approaches, the most commonly used are avoidance of biofouling, removing juvenile stages of biofouling organisms and the cleaning of gear.

3.2. Key management strategies

Biofouling in aquaculture has been an ongoing problem and will continue to be an issue globally. The impacts are often site- and species-specific, but the biofouling organisms are generally the same worldwide: ascidians, sponges, bryozoans, algae, barnacles, tube worms and molluscs. There have been numerous efforts to minimize the impacts of biofouling and studies continue to identify potential solutions to the problem. Biofouling is a costly problem for finfish, shellfish and seaweed farmers, the extent of which varies at the local and regional scale. Uncontrolled biofouling on aquaculture infrastructure and stock leads to increased maintenance costs and production losses, e.g. low growth and reduced product quality. Many biofouling control and management practices are used by the industry, sometimes as a combination of methods. More effective and economical approaches are needed to reduce production costs, secure the quality of product and address the possible role of aquaculture in the spread of IAS. It is estimated that improved biofouling management practices could result in potential cost savings of 5–10% of the market value of the cultured products.

For all systems:

- Routine monitoring and removal of biofouling is essential to minimizing the impacts of biofouling
- Gear should be designed and constructed to facilitate biofouling management, i.e. easy access to inspection and maintenance activities
- Biofouling species should be responsibly removed and disposed of to prevent further distribution or damage to the surrounding environment

All of the practices described herein are carried out locally, on-site and are highly individualized based upon fouling species and culture species.

The general practices of aquaculturists to eradicate biofouling are not considered vectors for transfer of IAS.

3.2.1. Shellfish culture

Industry practices are increasingly focused on preventing biofouling. While prevention can be challenging to implement, it can offer considerable advantages over cleaning and treatment after biofouling has occurred.

- Key preventative strategies include:
  - The spatial and temporal avoidance of biofouling through the monitoring of biofouling settlement and development.
  - The strategic selection of rope types or culture methods applying antifouling coatings and the use of fouling-resistant genotypes in culturing.
- Cleaning and treatment:

  Shellfish growers use a combination of cleaning and treatment methods to manage biofouling. Treatment types are based on the species being cultured, the culture method employed and the composition of

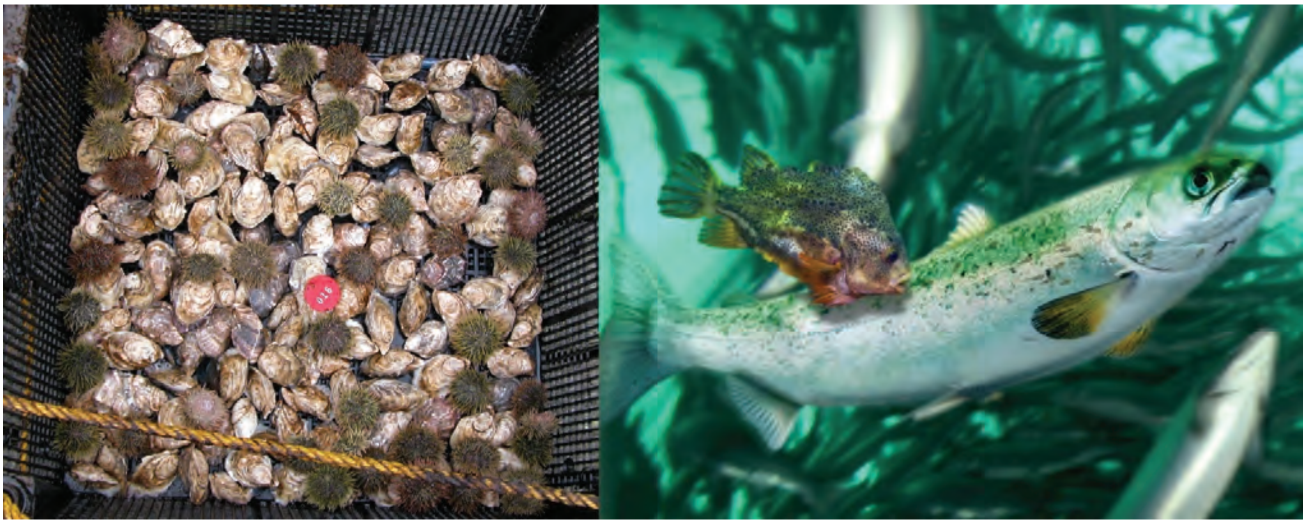


Figure 7. Left: Sea urchins used to control biofouling in shellfish culture (photo John Blackburn, Fisheries and Oceans Canada). Right: Lumpfish cleaning sea lice from salmon (photo Paulo Oliviera).

the fouling community. Key methods used to remove biofouling include:

— Air exposure: Exposing shellfish to periods of air drying can significantly reduce biofouling loads with little impact on stock fitness (Sievers et al., 2017).

— Manual removal: The manual removal of biofouling, typically by brushing stock and infrastructure, significantly reduces biofouling levels and increases the growth of the treated stock (Sievers et al., 2017).

- Monitor hatchery water intake carefully. Filtration, disinfection and regular cleaning of all materials (pipes, filters, tanks) can minimize colonization by biofouling organisms.

- Locate aquaculture grow-out facilities in areas with good current flow or high turbidity.

3.2.2. Finfish culture

Fish are cultured in cage-netting systems where they are contained in a net pen. Cage systems are fabricated with a rigid frame that supports flexible or rigid netting panels to form a pen. This type of cage system is deployed in protected bodies of water on the surface. Though not as prevalent, rigid and submersible cages are used for open-ocean fish farming.

Biofouling organisms include algae, ascidians, bryozoans, hydroids and bivalves. Biofouling blocks netting (net occlusion) of cage-net systems after only weeks of exposure. Water flow is restricted by biofouled netting resulting in anoxic conditions and the build-up of ammonia, conditions that compromise the health of farmed fish. Biofouling of netting serves as a refuge for fish parasites as well as pathogens. Parasites and pathogens compromise fish health and reduce growth rates (Edwards, Pawluk and Cross, 2015; Douglas-Helders et al., 2003; Tan et al., 2002; Bosch-Belmar et al., 2019).

Biofouling dramatically increases labour costs, reduces the value of product and can harm cultured species, significantly reducing the profitability of culture operations. Globally, costs of biofouling at aquaculture facilities exceed US$3 billion/year (Lane and Willemsen, 2004; de Nys and Guenther, 2009; Fitridge et al., 2012). Biofouling also increases weight and drag of cage-netting systems, reducing buoyancy, straining mooring systems and compromising structural integrity. Biofouling-induced stresses on cage-netting systems can result in system failure, loss of assets and fish escape (Braithwaite, Carrascosa and McEvoy, 2007).

Sea urchins and fish, especially wrasses and lumpfish (Treasurer, 1996; Eliasen et al., 2018; Imsland et al., 2015; Erkinharju et al., 2021) have been used to control sea lice on stock species such as salmon and sea bass. Biofouling is the natural food of 'cleaner fish', lumpsucker and wrasse species employed to clean sea lice *Caligus elongates* and *Lepeophtheirus salmonis* from salmon (Figure 7). The delousing abilities of these cleaner fish are compromised when an alternative food source is present (Bloecher and Floerl, 2021; Eliasen et al., 2018; Imsland et al., 2015). While there has been some reported success, there are limitations to effective control with regard to size, and the process is reliant upon a sustainable supply of the cleaner species.

Finfish culturing practices to address biofouling are primarily focused on net cleaning, the frequency of which depends on the cultured fish, regulatory requirements and biofouling accumulation rates.

Overall, for the farming of fin fish, the industry continues to rely on nets with biocidal coatings to limit biofouling as they require less frequent cleaning; however, the use of copper-coated nets can create the environmental risk of copper leaching and release when cleaning is undertaken (Skarbøvik et al., 2017). Companies also know that in situ cleaning practices must include waste retention systems and the proper disposal of retained material on land, in line with regulatory requirements. If waste retention systems are not available or fully effective, on-land cleaning is being used.

New practices are emerging around new technologies and materials, including:

- Cavitation-cleaning systems which have been identified as a promising technology for biofouling control on nets, as they limit coating degradation compared to other cleaning methods (Bloecher et al., 2019).
- Copper alloy mesh (CAM) that could help limit the use of antifouling paints, thereby preventing their hazardous effects on marine life.

3.2.3. Seaweed culture

As with shellfish and finfish culture, seaweed culture operations are increasingly strategically choosing farming areas with the lowest risk of biofouling (see Visch, Nylund and Pavia, 2020 and references therein). Key criteria for site selection practices include water movement, water temperature, cultivation period, timing of harvest and the choice of infrastructure materials, which all influence biofouling rates (Bannister et al., 2019). Locating aquaculture grow-out facilities in high energy areas with good current flow or high turbidity can reduce the opportunity for settlement.

Seaweed farming industry practices involve consideration of:

- The selection of farming locations in relation to the level of exposure to fouling organisms being highly specific to the species being cultured (Bannister et al., 2019; Visch, Nylud and Pavia, 2020)
- Outplanting before spring diatom blooms to avoid smothering
- Harvesting before cyclical sea temperature rise, as this helps avoid seasonal biofouling (Ateweberhan, Rougier and Rakotomahazo, 2015; Keesing et al., 2016)
- The selection of clean and healthy seedlings that are free of epiphytes to initiate cultivation in order to help prevent biofouling (Bannister et al., 2019)
- The use of culture media such Acadian marine plant extract powder (AMPEP), in order to enhance the antifouling defence mechanisms of several seaweed species, as a particularly promising method
- Induction of desiccation stress through aerial exposure (see Yan et al., 2011; Kim et al., 2017)
- Use of an acid wash (pH shock) method to remove diatoms and other algae (Kang and Kim, 2022)

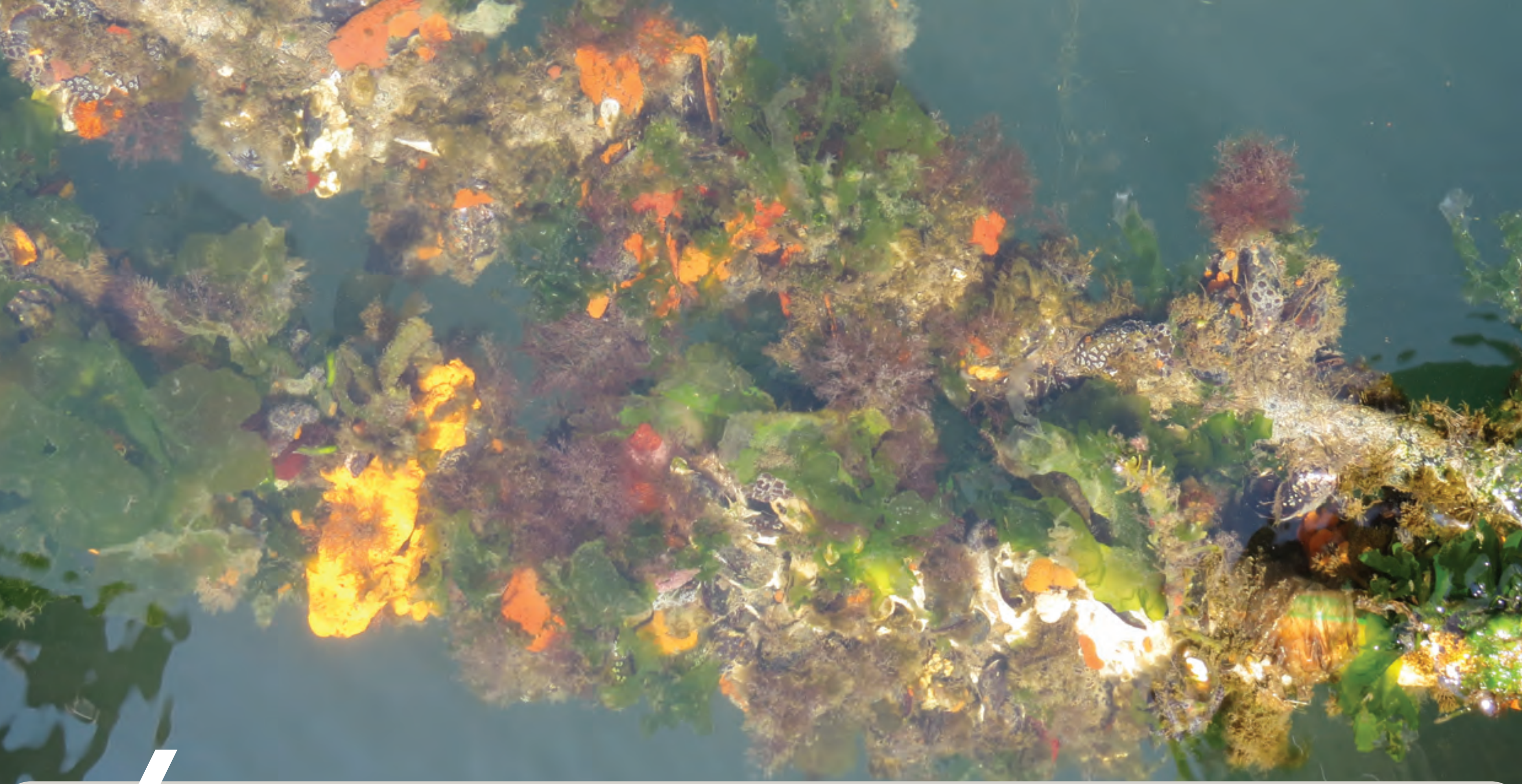
The periodic manual removal of fouling organisms on infrastructure and/or cultured algal species is commonly used, but this is labour-intensive and may have logistical limits to its applicability. As a result, more companies are looking at biological control as a highly species-specific antifouling method; there is a need for further research and testing in this area to understand the potential for biological control agents to be effective within specific culture settings. As algal culture continues to increase production levels globally, more attention will need to be given to control of biofouling.

3.2.4. Avoiding and preventing biofouling

Marine aquaculture companies are increasingly focused on avoidance and prevention as the most cost-effective and environmentally friendly option for biofouling management (see Bloecher and Floerl, 2021 for recent review). They are also adopting this as a pre-emptive approach to address biofouling and IAS. Methods used to avoid biofouling include choice of culture species, site selection, operational timing (e.g. deployment of spat collectors on mussel farms) and stock management (e.g. stocking densities). Avoidance of biofouling reduces both the direct impacts of biofouling organisms and the frequency and intensity of biofouling treatments. To achieve this, companies are increasingly developing protocols and processes for regular inspection, maintenance and cleaning of the production equipment and stock, including new stock, equipment and infrastructure as it is brought in. While preventative techniques can be very effective, they can be difficult to employ. The major focus is on preventing the initial settlement and development of biofouling organisms before the need for removal occurs. The composition of fouling organism is site-specific, not always known and temporally variable.

Prevention of biofouling is a high priority for aquaculturists. A simple form of prevention is to deploy aquaculture material at times or in locations (greater depths, different geographic areas, etc.) where less biofouling settlement occurs (Watson, Shumway and Whitlatch, 2009; Bullard, Davis and Shumway, 2013). Many invertebrate larvae are phototactic and settle near the surface of the water (Thorson, 1964; Strathmann, 1987). Thus, placing aquaculture gear at deeper depths can reduce overall biofouling loads (Claereboudt et al., 1994; Howes et al., 2007); however, moving shellfish to deeper waters to avoid fouling results in reduced productivity, so it is not always an ideal solution. Further, deeper gear deployment is not always advantageous because some fouling species exhibit greater settlement at depth (Aghzar et al., 2012) and less food can be available for culture organisms at deeper sites (Lodeiros et al., 1998). In addition to changing the location of aquaculture gear, physical disruption of settlement may also reduce fouling. Dunham and Marshall (2012) and Marshall and Dunham (2013) recently demonstrated successful reduction of biofouling in oyster (*Crassostrea gigas*) and Manila clam (*Venerupis philippinarum*) culture through addition of clay aggregate culture media to the culture gear. While these results apparently reduced biofouling, it has little to no chance of commercial success, as one of the most prevalent problems is the ever-increasing density in the cages.

Growers can also prevent biofouling by deploying gear after fouling organisms have settled, or by removing gear during times of high settlement. Many invertebrates settle during specific, discrete time periods (Yamaguchi, 1975; Green and Grizzle, 2007; Zhanhui, Jianguang and Jihong, 2010; Kripa, Mohamed and Velayudhan, 2012; Fletcher et al., 2013; Bullard, Davis and Shumway, 2013). Thus, keeping gear out of the water when problematic species settle can greatly reduce biofouling loads. Although this is potentially an effective preventive technique, it is often difficult to employ. To be successful, growers must know the detailed biofouling regime for their particular area. These data are not always available and due to geographical variance in the timing of settlement of species (Keough and Chernoff, 1987; Yund and Stires, 2002; Broitman et al., 2008), they can be difficult to extrapolate from other locations. Even when fouling regimes are well known, many different biofouling species are usually present at any given site (Karlson and Osman, 2012), each with its own settlement profile (Lagos et al., 2005; Bullard, Davis and Shumway, 2013). Thus, growers may be able to avoid the settlement of some species, but not all. Further, there is the added issue of 'what to do with the gear and shellfish for that fouling period'? It is not usually feasible to move hundreds of cages and millions of shellfish for the time period when fouling organisms are settling.



4 Strategic placement of gear

Some growers place their culture gear in deep water during larval settlement periods where larval biofoulers are absent. This can be effective, but can also stress the shellfish due to limited food resources at depth. Others have suggested placement of gear in surface waters based upon known local recruitment and settlement patterns of biofoulers (see Bullard, Shumway and Walsh, 2021). This effort may be effective in some regions, but only where there is a reasonable lag time between the settlement of the biofoulers and the need to deploy gear. Another mitigation measure involves simply trading old gear for new and disposing of the fouled material.

4.1. Make use of ecological knowledge

Marine farmers are modifying operational practices based on improved understanding of biofouling organisms. This includes selecting culturing areas and developing maintenance and cleaning schedules based on the life cycle of fouling species. For example, companies involved in seaweed farming are managing biofouling management through understanding and harnessing the natural defences of the cultivated seaweed species (Bannister et al., 2019). This 'integrated biofouling management' (CRAB, 2006) uses ecological knowledge of the biofouling organisms, the environment and the cultured species to achieve significant biofouling reduction.

4.1.1. Using ecological knowledge to reduce biofouling impacts to seaweed farming in Canada

Some long-lived macroalgae seaweed species possess biological attributes that reduce the impact of biofouling. These include blade detachment (shedding of the algal 'leaf) followed by rapid growth of new blades and periodic epidermal shedding (sloughing off of the surface layer). In Nova Scotia, Canada, the brown alga *Ascophyllum nodosum* sheds 25% of its frond epidermis per week for nine months of the year. Shedding removes epiphytes, such as the red alga *Vertebrate lanosaand*, the brown algae *Elachista fucicola* and *Pylaiella littoralis*. Farmers harvest at strategic times determined by combining the knowledge of the seaweed's natural defence mechanisms with the seasonal occurrence of biofouling.

4.1.2. Combination of strategies

Combining biofouling management strategies allows aquaculture companies to: (1) manage biofouling more effectively against a broad range of biofouling species; (2) ensure treatments will be effective while using lower chemical concentrations or temperatures; and (3) reduce treatment exposure times (Marine Pest Sectoral Committee, 2009; Bannister et al., 2019).

4.1.3. Combining strategies for more effective fouling control in shellfish farming

The marine aquaculture industry is applying preventative measures as new research results become available, e.g.

information on how the type and colour of culture or spat-collecting rope influences the severity and species of biofouling (Glasby, 2000; Mason, Beard and Miller, 2011; Tanyaros and Kitt, 2012; Dobretsov, Abed and Voolstra, 2013). Although materials that are less susceptible to fouling are increasingly deployed by companies, some biofouling inevitably develops. On-site treatment to remove the biofouling is still necessary, e.g. exposure to air, freshwater, heat, and organic acids and bases (Forrest et al., 2007; Mallet, Carver and Hardy, 2009; Rolheiser et al., 2012; Mayrand, Sonier and Comeau, 2015; Carman et al., 2016; Comeau et al., 2017).

Combinations of treatments are also being trialled. For example, for some mussel culture facilities, a cost-effective and environmentally friendly approach is >2 hours of freshwater immersion followed by at least 12 hours of desiccation (Gunthorpe et al., 2001). In another case, combining hot water immersion with acid treatments was more successful at controlling biofouling than the use of either treatment administered individually (Sievers et al., 2019).

4.2. Antifouling techniques and technologies

Any solutions for biofouling control in the aquaculture industry need to be cost effective, environmentally sound and relatively simple to implement.

Early efforts to thwart biofouling in aquaculture focused on applying chemical treatments previously developed for boat hulls and marine structures. Development of anti-fouling coatings for boat hulls is a US$8 billion industry (Facts and Factors, 2020) and commercial antifouling paints can prevent fouling on gear (Braithwaite, Carrascosa and McEvoy, 2007). Traditionally, these have not been widely used in the aquaculture industry (Watson, Shumway and Whitlatch, 2009) because they can leach toxic substances into the environment, can have detrimental effects on cultured organisms (Davies and Paul, 1986; Paul and Davies, 1986; Voulvoulis, Scrimshaw and Lester, 1999; Callow and Callow, 2002; Omae, 2003; Thomas and Brooks, 2010) or render the cultured product unsafe for human consumption. Most of these coatings were heavy-metal based paints and, while highly effective at reducing biofouling, are toxic to both fish and shellfish and the environment.

4.3. Coatings

Protective coatings are used to reduce biofouling and minimize cleaning requirements of netting. Additionally, protective coatings stiffen netting and protect fibres from abrasion and ultraviolet (UV) light degradation. Two classes of protective coatings are used: 1) antifouling coatings; and 2) biofouling release coatings.

4.3.1. Antifouling coatings

One of the most common and widely used antifouling practices in the marine aquaculture industry is the application of biocidal coatings on the surface of nets and structures. These paints leach small amounts of the active biocidal compounds, such as heavy metals and organic biocides, onto the surface, producing a thin, toxic layer which deters or kills fouling organisms. Historically, the aquaculture industry has borrowed antifouling technologies from other marine industries, e.g. marine transport, oil and gas. These antifouling coatings focus on chemical antifouling technologies, mostly based on copper oxide (Cu_2O). Originally developed for the shipping industry, biocidal coatings are now widely available and are used across all maritime industries, including aquaculture, as a result of their antifouling performance (CRAB, 2006). In addition to Cu_2O, organic biocides with improved environmental profiles (e.g. biodegradable) are available, but these are generally not being developed for marine aquaculture industry use.

Antifouling coatings are pesticides, biologically active treatments that contain active ingredients. Active ingredients and antifouling coatings are regulated by environmental agencies, approved for specific uses. Antifouling coatings used for fish farming are primarily based on active ingredients containing copper, such as cuprous oxide and copper hydroxide. Active ingredient concentrations in these antifouling coating formulas range from 15–30% by weight of active copper. Copper-based antifouling coatings provide 3–6 months service life on netting before the mesh must be cleaned in the water or removed for cleaning.

Presently, the anti-fouling coatings that are utilized in all four of the major salmon farming countries (Norway, Chile, Canada and Scotland) and the Faroe Islands are water-based, copper-containing paints (80% of market), or solvent-based, copper-containing paints. These products are lower-copper-containing versions (8-20% copper) of products sold to the recreational boat and big ship industries for use on hulls. The major coating suppliers to the salmon farming industry include: Steen-Hansen (water-based copper from Norway), Jotun (water-based copper from Norway), Sherwin-Williams (water-based copper) and Pinturas Hempel (solvent-based copper).

Copper-based antifouling coatings are used for farming finned fish where frequent manual cleaning of fouled surfaces is not feasible. Copper-based net coatings provide roughly 3–6 months service life depending on the copper loading. Paints and coatings that contain copper and other metals are slowly being phased out (see Dafforn, Lewis and Johnston, 2011 for review and discussion of hull fouling coatings and the use of metals) and the search continues for effective, affordable and environmentally safe antifouling coatings for the shipping industry and for aquaculture.

Booster biocides are added to antifouling paint formulations to extend the service life of the coating. The primary booster biocides used for fish farming are zinc pyrithione (CAS 13463-41-7), copper pyrithione (CAS 14915-37-8) and tralopyril (CAS 122454-29-9). Booster biocides have been shown to improve the performance of antifouling coatings for aquaculture; however, these biocides are toxic to fish and pose a risk to the environment (Bloecher and Floerl, 2021; Edwards, Pawluk and Cross, 2015; Guardiola et al., 2012; Borg and Trombetta, 2010).

The use of antifouling coatings on cage-netting systems poses a threat to the environment and jeopardizes the health of farmed fish. Antifouling coatings are known sources of pollution from aquaculture. Active ingredients found in antifouling coatings, primarily copper-based, leach from treated netting, affecting non-target species. Copper from antifouling coated netting is absorbed and accumulated by farmed fish compromising the safety of their consumption and marketability of the product (Baldwin, Tatara and Scholz, 2011).

Leaching copper from antifouling coated netting harms the environment. Levels of copper-based biocides build over time in sediments below cage-netting systems. In-water cleaning and land-based cleaning of biofouled netting releases high concentrations of copper into the water, environmental release rates that are not permitted by regulatory agencies. For this reason, net cleaning facilities must dispose of wash waters from antifouling coated nets as hazardous waste. Antifouling coated netting lost at sea due to storm damage continues to leach active ingredients, impacting non-target species and compromising the environment (Brooks and Mahnken, 2003).

4.3.2. Biocidal coatings

In the marine aquaculture industry, uncoated nets quickly become fouled with biological growth, with numerous impacts. In Australia, for example, some fish farmers who use uncoated nets are forced to change the nets every 7–10 days due to fouling. To avoid this, most companies have adopted the use of nets coated with biocides as a critical component for their business, with the most common types of antifouling coatings being copper-based.

In marine aquaculture applications, the efficiency of biocides in controlling biofouling rarely lasts for more than a few months or one season (Willemsen, 2005) and is not sufficiently effective against algae. Biocidal coatings are also not entirely satisfactory from an economic perspective because periodic cleaning and retreatment are required, and there are barriers to innovation and improving the efficiency of coatings.

There are also environmental, health and safety implications to the use of biocidal coatings. The detrimental effects on the survival and growth of shellfish and fish have prompted industry efforts to prevent or mitigate biofouling in aquaculture through alternative methods. Net washing plants have problems dealing with the copper being released during cleaning. The resulting waste and sludge must be specially disposed of, adding to costs (Willemsen, 2005). This consideration is all the more important with in situ cleaning, where the risk of copper release into the marine environment can occur (Bannister et al., 2019). Finally, biocidal coatings are subject to increasingly stringent regulation and increasing registration costs, limiting their viability as a long-term solution.

Copper, nets and the marine aquaculture industry

As copper is highly toxic to many marine invertebrates, particularly their larval stages, copper coatings have a long history of approved use in fish mariculture to address fouling. Copper-based antifoulant coatings such as copper alloy mesh are traditionally used and can withstand stronger currents than nylon, but nylon nets are less expensive (Berillis, Mente and Kormas 2017; Tsukrov et al., 2011; Yigit et al., 2018). For example, the aquaculture industry in Norway purchased 261 tonnes of copper in 2005. In temperate regions, nets must be coated each year and the application of copper antifouling paint provides protection for six months. With the right planning, companies ensure that the coatings are effective during summer when fouling is worst. While some studies indicate that salmon raised in copper-treated nets do not bioaccumulate copper, industry best practice is to introduce fish into nets one month after newly coated nets are in position, to minimize the potential for bioaccumulation.

In addition to being used in the coatings applied to nylon nets, copper is also used as the active ingredient in metal-based nets. Innovation in the construction of nets with copper-zinc, copper-nickel and copper-silicon alloys has spurred renewed interest by fish farmers in their use in Chile, Australia, Japan and elsewhere. Biofouling is minimal on copper nets, but the use of copper nets in industry is hindered by the weight, failure and breakage through corrosion and relative expense compared to nylon mesh nets. New techniques to construct light-weight mesh alloys may drive greater use of this technology by industry as benefits begin to outweigh costs.

Netting fabricated with copper-zinc alloys are the most common in aquaculture preventing biofouling due to the inherent toxicity of the metals. Advantages of copper alloy bioactive netting include five-year service life, netting is 100% recyclable, effective biofouling control and minimal cleaning requirements. Copper alloy netting requires cleaning biannually as opposed to bimonthly cleaning with copper antifouling coated nets. Drawbacks to using biologically active copper alloy netting are: 1) cost; 2) weight; 3) electrochemical corrosion; and 4) copper release into the environment. Copper alloy nets are extremely expensive due to the increasing cost of the metal. Copper alloy nets weigh more than nylon and polyethylene netting, requiring more buoyant cage systems. Copper reacts with dissimilar metals such as steel and aluminium in seawater. Steel and aluminium used for the cage structure and mooring systems electrochemically corrode rapidly in seawater when in close proximity to copper. More copper is released from copper alloy netting than from copper antifouling coated netting (Early et al., 2020).

Overall, the use of copper for antifouling coating or as part of metal nets may increasingly create image or perception challenges for the industry. Many countries are increasingly regulating the use of copper-based antifouling and the marine aquaculture industry will need to adapt to these regulatory developments.

Business barriers to improving biocidal net coatings for the marine aquaculture industry

Globally, most fish farmers are now using some sort of biocidal coating on nylon nets to extend the time between net changes. Ideally, a net would not have to be changed until the fish are ready to be moved to a larger net or harvested. Typically, nets coated with a cuprous oxide based antifouling coatings give good protection for at least 3–4 months, after which the net must be changed to ensure adequate water flow. When a net coating loses effectiveness, the fish farmer replaces the existing net with one that has been newly coated, returning the used net to the net supply company. The supply company cleans the net, makes necessary repairs and then recoats the net with a fresh antifouling coating.

With the need for improved net coatings, it would seem that this would attract innovation; however, there are numerous factors that make improved net coatings very difficult to introduce to the market. Coatings are usually developed by a coatings formulation company. If the coatings company develops an improved product that will last 6–7 months instead of 3–4 months, the net coater may not want to offer the improved product to the fish farmer. A net that that requires less frequent re-coating will reduce the net supply company's business, so there is little incentive to promote an improved coating product to aquaculture companies. If the coating supplier goes directly to the fish farmer, it is possible it will affect the supplier's existing business with the net company.

The situation is further complicated because the improved net formulation will usually contain new biocides which in more and more countries will require registration. Convincing a biocide supplier to spend the money to support registration is difficult because of the relatively small size of the aquaculture market. In addition, there is a significant cost to doing the research to supply the data required for registration, making it very difficult to get company interested in developing new, more effective biocides for the relatively limited aquaculture market.

Fouling-Release coatings

The most attractive non-toxic approach to controlling biofouling in aquaculture involves use of coatings that make attachment to treated substrates extremely difficult. The most promising is a class of 'foul-release' coatings which utilize materials that afford low surface energy substrates that make attachment by bioadhesive organisms difficult. The marine aquaculture industry is exploring the use of fouling-release coatings, also known as non-stick coatings, as the research and development of these continues to advance in the shipping industry. These biocide-free, low surface energy siloxane elastomers and fluoropolymers work on the principle that biofouling on a surface with low bioadhesion will be easy to remove. Attributes of effective 'foul-release' surfaces are low surface-free energy, low-elastic modulus and coating thickness (Hu et al., 2020). Though perfluorinated materials have extremely low surface energies, they are rigid and therefore release of biofouling organisms from these surfaces does not occur as readily as with silicone elastomers. When fouling-release coatings are used in the marine transport sector, the speed of the vessel produces the hydrodynamic shear required to remove weakly adhered fouling.

Such hydrodynamic forces are limited or non-existent in fixed aquaculture facility; however, the marine aquaculture industry is exploring the application of non-toxic silicone coatings to nets and panels in order to reduce the attachment strength of biofouling organisms and make them easier to clean, e.g. with high- pressure washing (Hodson, Burke and Bissett, 2000; Terlizzi et al., 2000). In addition, simple, but effective, methods using an air-bubble curtain in conjunction with fouling-release (Scardino, Fletcher and Lewis, 2009).

The most effective foul-release coatings are based on silicone elastomers, polydimethyl siloxanes (PDMS). High molecular mobility of PDMS lends to a low modulus of elasticity which, along with low surface energy, makes an effective release coating. Unfortunately, it is this high molecular mobility that leads to poor physical properties. Silicones are inherently weak and easily marred or abraded. PDMS have been investigated as a means of controlling biofouling on aquaculture netting (Hodson, Burke and Bissett, 2000). Treated netting readily fouled, but was easily removed by pressure washing. Release coatings in aquaculture have not been adopted due to their high cost and the requirement for bimonthly cleaning.

So, although these fouling-release coatings were originally developed for shipping and are not yet widely available for the aquaculture market, industry testing is showing that they also prove effective for aquaculture nets and infrastructure. A water-based silicone barrier release coating proved to be highly effective in reducing biofouling of lantern nets during the grow-out and overwintering of bay scallops, *Argopecten irradians irradians*, in New York, USA (Tettelbach, Tetrault and Carroll, 2014). The scallops exhibited higher reproductive and overall condition in nets treated with the silicone coating vs untreated nets. There were no consistent differences in shell growth in different net treatments; however, there are complicating factors in that, although the nets remained less affected by biofouling, scallops held in the coated nets experienced reduced survival after eight months, probably due to higher loads of epibionts on their shells. Nonetheless, the tests have shown that coating nets with the silicone barrier release coating would eliminate the need for a gear change in spring, thus reducing labour costs.

4.3.3. Other types of coatings and materials

The marine aquaculture industry is encouraging and supporting the development of innovations that could provide viable biofouling management options for the future.

Polymers with inherent antifouling properties

Polymers with inherent antifouling or non-stick properties have the potential to be used as raw materials for the manufacture of nets and trays for the aquaculture sector. The North Atlantic Fisheries College (Shetland, UK), as part of the EU-financed SPAN project, developed novel polymeric materials with antimicrobial and/or antifouling properties (SPAN, 2005) which could be applied to the biofouling management needs of the marine aquaculture industry.

Copper alloy mesh (CAM) nets

Marine aquaculture industry practices may shift to the use of copper alloy mesh (CAM) nets as a promising solution to combat biofouling in finfish aquaculture. These nets are able to prevent most biofouling (Chambers et al., 2012) and require less frequent cleaning, which results in an overall lower leaching rate of copper into the water column (Kalantzi et al., 2016). The use of CAM nets for gilthead seabream (*Sparus aurata*) culture in Turkey showed that CAM nets performed better overall (Yigit et al., 2018), suggesting that mesh from copper alloy materials is a viable antifouling option for the industry that could help limit the use of antifouling paints, thereby preventing their hazardous effects on marine life.

Gilthead seabream (*Sparus aurata*) is one of the most cultured and commonly consumed marine fish species in Europe, with seabream grow-out mainly in offshore cages. Deployment of copper alloy mesh (CAM) net cages for growing gilthead seabream in the Strait of Çanakkale, Turkey, resulted in reduced biofouling. Other benefits included better fish growth and feed utilization, relative wet weight gain of stock and duration of the efficacy of the mesh and level of dissolved oxygen inside the cages in comparison to traditional nylon net cages with industry standard application of antifouling paint, or cages with no fouling treatment.

During the grow-out trials, biofouling was visible on the nylon net without antifouling treatment after two months. On the nylon net with antifouling coating, biofouling became visible after about four months. Both kinds of nets subsequently suffered from a reduction in the effective mesh size due to fouling, which restricted water exchange and reduced oxygen inside the cages. The biofouling-free environment in the CAM pen had higher dissolved oxygen levels. These cages had improved fish welfare, with a reduced-stress environment due to cleaner and more sanitary culture conditions, which appear to have induced better utilization of diets for growth by the fish.

Concerns regarding initial investment costs discourage fish farmers from using new technologies such as CAM pens; however, even though there are initial cost differences, CAM may be more economical over the long term by decreasing operational costs such as net cleaning, repair or replacement. The economic value of CAM nets increased due to the better fish welfare and growth, which may increase fish quality and market value. In addition, more than 98% of the copper used in the CAM nets can be recycled at the end of the effective life of 3–4 years, while copper used in antifouling paints is lost permanently by leaching into the marine ecosystem.

4.4. Novel antifouling technologies

4.4.1. Biological control

Biological control for managing marine biofouling has met with limited success. Biological control makes use of organisms that feed on biofouling organisms. In selecting a consumer for use as a biological control agent, companies need to evaluate consumer influence on: (1) stock mortality; (2) stock productivity (e.g. whether growth rates decrease in the presence of the control animal); and (3) quality of product (e.g. whether there is a reduction in value or quality of the stock from impacts such as urchin spine damage to fish scales or damage to shellfish exterior) (CRAB, 2006).

In particular, the use of grazing organisms shows promising commercial benefits, depending upon the cultured species, the biocontrol species, the culture method and the density of grazers utilized. For example, foraging on biofouling by the fish *Siganus fuscescens* may improve survival of the pearl oyster *Pinctada fucata martensii* (Li et al., 2018). The isopod *Paridotea reticulata* has been used to consume the epiphytic red alga *Ceramium diaphanum* that grows on the commercially farmed red alga *Gracilaria gracilis* (Anderson, Smit and Bolton, 1998). Various invertebrate predators, including crabs, shrimp and sea urchins, have been used as biological controls in shellfish aquaculture (Lodeiros and García, 2004; Ross, Thorpe and Brand, 2004; Dumont et al., 2009; Sterling, Cross and Pearce, 2016). Some grazers used for biological control, however, may preferentially feed on the cultured organism instead of the biofouling species. This can be especially true when grazer densities are too high and food sources are scarce (Cruz-Rivera and Friedlander, 2011). In finfish farming, there are concerns about the most efficient way to keep grazers on the net. Some grazers are commercially valuable in and of themselves and can provide farmers with additional revenue (CRAB, 2006) (Figure 7).

Biological control is often used in Integrated multi-trophic aquaculture (IMTA). In IMTA, fish, shellfish and seaweed are grown together so that the waste and feed uneaten by one species, along with additional nutrients and by-products, can be used by the other species (Chopin, 2013). In these systems, different species can be grown together while using one or more species as biofouling agents (Barrington, Chopin and Robinson, 2009; Shpigel et al., 2018). For example, sea urchins and crabs can be grown with scallops to prevent biofouling on nets. This helps reduce maintenance costs and improves the growth rates of scallops (Ross, Thorpe and Brand, 2004). These IMTA systems also minimize excess nutrients entering the water column, which may more broadly limit the growth of fouling in the farm environment. Biofouling that occurs in IMTA, however, can pose a health risk to cultured fish as it can facilitate and amplify the presence of pathogens (Fitridge et al., 2012; Rosa et al., 2013). Thus, biofouling must be decisively dealt with in IMTA systems, since different species are intentionally cultured in close vicinity (Bannister et al., 2019).

4.4.2. Natural compounds and culture media

Natural compounds make use of the secondary metabolites produced by sessile marine organisms to keep surfaces free from biofouling (Hentschel et al., 2001; Pawlik, 2012). Secondary metabolites produced by many marine organisms inhibit biofouling and could be key molecules for the development antifouling coatings (Clare, 1996; Feng et al., 2009; Dahms and Dobretsov, 2017); however, developing practices that apply these types of compounds to fish or shellfish is a major challenge (Bannister et al., 2019). Nonetheless, a number of antifouling coatings based on natural products have been commercialized (Jacobson and Willingham, 2000; de Nys et al., 2004). Similarly, a culture medium can be used to cultivate natural antifouling compounds. For example, Acadian marine plant extract powder (AMPEP) has been tested and used as a culture medium to cultivate and mitigate biofouling on the red seaweed *Kappaphycus alvarezii* (Hurtado et al., 2009, 2012; Marriog and Reis, 2016; Hurtado and Critchley, 2018). Nevertheless, in shellfish culture, while the addition of culture media has significantly reduced biofouling loads, it has also caused significant impacts to the fitness of the cultured stock (Sievers et al., 2017).

4.4.3. Improving small-scale seaweed culturing through natural compounds and culture media

New practices involving the use of seaweed extracts to improve marine macroalgal production, including by addressing biofouling, are being explored. An important and extensively cultivated red seaweed in tropical to sub-tropical coasts, *Kappaphycus alvarezii*, is a major source of industrial carrageenan colloid. Cultivation of this seaweed has brought economic benefits to tens of thousands of seaweed farmers in South-East Asia and other minor producing countries.

The algae supporting this important production and commerce is, however, facing decreased productivity, loss of vigour and diminished crop quality. This is due to shortages in the availability of good quality propagules (seedlings) and also disease and biofouling (e.g. endo-epiphyte infestations). These conditions have affected the ability to grow and harvest saleable biomass, increasing the amount of repetitive labour and decreasing the income of seaweed farmers.

In seeking new practices to address this situation, Ascophyllum (aka. Acadian) marine plant extract powder (AMPEP), a commercial seaweed extract from the brown intertidal, macroalga A. nodosum was tested in the micropropagation and field cultivation of *K. alvarezii.* The use of AMPEP to mitigate both biotic and abiotic stressors has promising results in which the complex extract might improve stress tolerances in *K. alvarezii* in order to obtain higher productivity and enhanced quality characteristics (i.e. exposure to increasing surface seawater temperature, salinity fluctuations and attacks by pathogenic and opportunistic organisms).

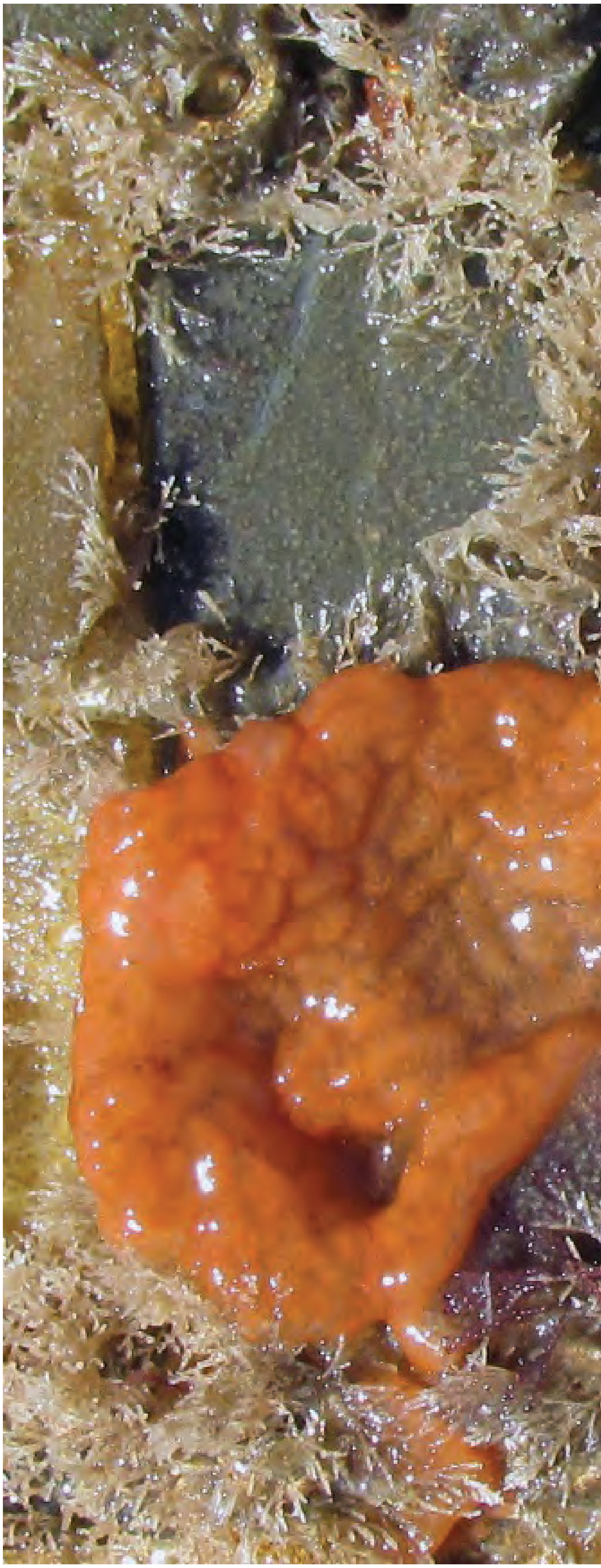
4.4.4. Selective breeding

The selection of clean and healthy seedlings that are free of epiphytes is used to curb biofouling in seaweed farming. Selective breeding to develop varieties that are less susceptible to biofouling is promising for some marine aquaculture, particularly the shellfish industry. For example, the genetic variants of the green-lipped mussel (*Perna calaniculus*), Pacific oysters (*Crassostrea gigas*) and abalone (*Haliotis iris*) developed in New Zealand have foul-resistant properties (Camara and Symonds, 2014).

4.4.5. Nanotechnology and microtextures

Another recent development in antifouling is protecting surfaces through the application of nanotechnology. The nano-properties of surfaces have a significant impact on bioadhesion and biofouling. These properties can be used to design new surfaces for industry applications that have fouling-deterrent and/or fouling-release properties. Many nanoparticles have been investigated and developed within the European AMBIO project, which have resulted in three patented technologies (AMBIO, 2010).

Natural defence mechanisms of marine organisms have also been investigated to define new biomimetic or bioinspired technologies to help control biofouling. Significant advances in nano- and micro-scale patterning have allowed the development of new materials (Scardino and de Nys, 2011), some of which have been tested and show satisfactory results for applications in industry. For example, the surface microstructure of biomimetic sharkskin is a promising antifouling technology (Pu, Li and Huang, 2016) that led to the development of an antifouling product called Sharklet AF™.



5 Biofouling management: Cleaning and treatment

Once biofouling communities become established, considerable effort must be expended to remove the material. All marine aquaculture industry operators employ cleaning as a key part of fouling management. These are carried out whenever possible by applying the appropriate cleaning techniques and equipment from among those synthesized below (CRAB, 2006). Best practices by aquaculture companies include regular inspection and maintenance of equipment, with the cleaning of equipment necessary prior to the movement of equipment from one area to another (Jackson, L., 2008).

Numerous methods have been applied over the past decades to prevent or minimize the effects of biofouling organisms on shellfish and aquaculture gear. Techniques vary geographically, according to species of shellfish and biofouling organisms, and the husbandry methods being employed. Methods are influenced by cost, effort and efficacy. Mitigation control encompasses a variety of methods, ranging from manual removal of biofouling to chemical and biological control. Most recently, newly-developed environmentally safe coatings have been developed to thwart the settlement of biofouling organisms (see Watson, Shumway and Whitlatch, 2009; Tucker and Hargreaves, 2008; Getchis, 2014).

Biofouling organisms and algae are most often either killed during cleaning processes or removed from the environment entirely when gear is cleaned. In some situations, the fouling material may be deposited on the benthos at the site and could result in ecological issues; this, however, does not constitute a significant vector for the introduction of IAS. Aquaculture structures and gear more typically serve as hosts for IAS introduced via other means, e.g. shipping.

Various methods have been used to remove biofouling, including hand removal and mechanical removal (pressure washing, tumbling, rotating bags and others). All are laborious, time consuming and expensive (see Cheney, 2010 and references therein). In addition, some techniques can result in reduced growth (Coddington-Ring, 2012) and shell damage (Chang and Wheaton, 1981). Perhaps the most common method is to remove fouling material manually by power washing, scraping and other means of physical removal (e.g. Hopkins, Forrest and Coutts, 2010; Switzer et al., 2011). Manual removal can be very effective, but requires considerable time (and hence labour cost) and can produce large quantities of waste material (Coutts and Forrest, 2007; Minchin and Sides, 2006). High pressure sprays are frequently used to remove fouling from gear or cultured organisms (Arens et al., 2011; Paetzold, Hill and Davidson, 2012). Some species, however, especially colonial ascidians, can survive high pressure treatments, and fragments produced from spraying can survive and reattach (Bullard et al., 2007; Paetzold and Davidson, 2010; Hopkins et al., 2011).

Figure 8. From left to right: a basic disk washer, a disk washer used from a supporting vessel, a disk washer used by a diver. (photos: Left Simone Durr, middle and right Collective Research on Aquaculture Biofouling (CRAB), 2006)

5.1. Shellfish

5.1.1. Brushing and scrubbing

Manual cleaning

Current industry practices for shellfish farming consider manually scrubbing or brushing shells the most simple and efficient process against biofouling. Manual cleaning is commonly used to address fouling on infrastructure and by shellfish farmers to remove biofouling from their stock. Industry operators undertake manual cleaning of infrastructure, such as trays, ropes, bags and cages, as an effective approach to fouling that generally does not damage the equipment. While this technique is effective, it is extremely labour-intensive and can damage or kill shellfish, leave the shellfish more vulnerable to predators, and make them less marketable. Thus, application of this method varies between species, e.g. oyster farming companies commonly clean their gear more frequently than scallop farmers. The practicality of manual cleaning depends on the site. Cleaning typically ranges from between four to eight times per year and can account for at least 10% of total person hours per annum. Manual cleaning can incur labour costs reaching up to 30% of total costs.

This method also results in large amounts of waste biofouling biomass. It is most often cost-prohibitive to transport this material to shore for disposal, so it is often dumped overboard. If this biomass is simply dumped on site, it can result in poor water quality (deoxygenation) and can smother benthic organisms. Further, many of the fouling organisms remain alive and can re-establish themselves on other surfaces (Bullard et al., 2007). It has also been demonstrated that dumping large amounts of filter-feeding biofoulers, e.g. tunicates, can result in dispersal and proliferation of toxic algal species in local waters (Rosa et al., 2013; Getchis, Rosa and Shumway, 2012).

Mechanical cleaning

Mechanical cleaning is commonly used to deal with fouling on infrastructure and shellfish stock, as well as for the nets and cages used in finfish culture. For some types of infrastructure, such as nets, companies undertake mechanical cleaning either *in situ* or by moving nets and equipment on shore. *In situ* disk cleaners for nets are used either from the surface, from a support vessel, from supporting structures around the cages, or by divers (Figure 8). If removal is done in the field, some biofouling organisms, especially colonial species that readily fragment, can survive and reattach to nearby surfaces (Bullard et al., 2007; Paetzold and Davidson, 2010; Hopkins et al., 2011). There are also concerns that fouling organisms may grow back quickly after disk cleaning because the cleaning may not fully remove the fouling organisms. To address these concerns, some companies mechanically clean nets and equipment on land.

Mechanical cleaning also engenders economic and operational considerations. The disk cleaners for nets can be a significant investment and have a life span of three to seven years. They are reasonably easy to use, but can damage nets. The cleaning often needs to be repeated every four to eight weeks and may need to be conducted as often as every five days on uncoated nets. Labour costs for mechanical cleaning are generally lower than manual cleaning and represent 0.3–1% of total costs, depending on the site.

Industry practices are moving to more effective technologies for cleaning biofouling. These include cavitation-based systems, which remove biofouling while causing very little degradation to antifouling coatings (Bloecher et al., 2019). These systems are based on the formation of bubbles in liquid due to rapid changes in localized pressure, and are usually associated with

Figure 9. Jet washing. Left: Collective Research on Aquaculture Biofouling (CRAB) 2006; right: True Chesapeake.

propeller wash that leads to metal fatigue and erosion (see Yang et al., 2021, for description). While effective in some situations, they are not suited for aquaculture as they require very rapidly moving water (>20 knots).

In shellfish farming operations, mechanical cleaning of the animals most often occurs before packaging for sale or transport. The practice can be highly damaging to the stock, however, and can lead to losses of as much as 20% by weight. In addition, the effectiveness of mechanical cleaning of biofouling on shellfish is not entirely satisfactory, as some fouling organisms (e.g. barnacles and tubeworms) are very difficult to remove. On many shellfish farms, mechanical cleaning needs to be repeated frequently or before sale, depending on the cultured species. Labour costs for mechanical cleaning of shellfish operations are significant and can represent 5–30% of total costs per annum (Adams et al., 2011).

Power washing

Power washing involves spraying gear and shellfish with water at high-pressure. This method is mostly used in oyster and mussel culture. While it is highly effective, it is labour-intensive, can damage less hearty shellfish and can be expensive.

High-pressure washing (jet washing) is used by many companies for cleaning infrastructure, as well as for clearing biofouling from shellfish stocks (Arens et al., 2011; Paetzold and Davidson, 2010). For infrastructure, jet washing is one of the most efficient and cost-effective cleaning methods. Care needs to be taken, however, if cleaning infrastructure with stock inside, as the washing can cause stress or damage to the animals. High-pressure washing usually needs to be repeated every four to eight weeks depending on local conditions.

On shellfish farms, many operators employ high-pressure washing as an effective technique to remove biofouling on stock. As with manual scrubbing, high-pressure washing is labour-intensive. With hardier species, the process can be used periodically during the growing season. In some situations, high-pressure washing has been successfully combined with mechanical cleaning. Labour costs associated with high-pressure washing can be up to approximately 10% of total farm costs per annum.

5.2. Fish culture cleaning

Cleaning net-cage systems in situ is the most practised method of biofouling control at fish farming facilities. Cleaning involves high-pressure water jets coupled with rotating cleaning disks. Cleaning is required bi-monthly in warmer summer months when biofouling is most prolific and every couple of months during the winter. Cleaning methods range from manual hand-held units controlled by divers to self-propelled remotely operated vehicles operated from support vessels. Cleaning is extremely labour-intensive and requires costly engineering support equipment (Comas et al., 2021; Bloecher, Olsen and Guenther, 2013).

On-site net cleaning stresses fish and compromises health. Fish, disrupted by cleaning operations, do not feed as regularly. Biofouling debris irritates fish gills and causes damage. Cleaning releases pathogens and parasites, leading to diseases that further compromise fish health, and resulting in increased fish mortality.

Net cleaning stresses the netting, reducing the life of the cage-net system. Antifouling coatings applied to netting are abraded away by cleaning releasing high concentrations of biocide into the environment, exposing farmed fish to potentially lethal concentrations. Removed biofouling from netting settles below cage-net structures and decays, creating anoxic conditions.

5.3. Treatments to address biofouling

5.3.1. Fish treatments

The marine aquaculture industry uses desiccation, or air-drying, of equipment and infrastructure as an effective mitigation method for a broad range of fouling taxa, especially in their early life-stages (Mallet, Carver and Hardy, 2009; Hopkins et al., 2016). In finfish culture operations, the deployment of desiccation may be undertaken as a 'double net' system, whereby half the net is pulled out to air-dry while the other half remains submerged. While this method reduces fish stress associated with changing nets, stress on the fish stock may also be caused by the decrease in water volume and increased crowding inside the pen. Companies have also experienced net damage from the hooks used to secure the drying area of the raised net. Although desiccation can be effective against biofouling, it needs to be repeated every four to eight weeks during the peak biofouling season. Labour costs are very low, e.g. 0.3% of total costs in one farm.

5.3.2. Shellfish treatments

Desiccation via aerial exposure

Exposure of gear to air is a common, relatively inexpensive and effective means of eradicating biofouling. It is labour-intensive as it requires 'flipping' bags on the aquaculture site. Growers periodically flip floating bags and cages to expose alternating sides to the air. This process kills the biofouling animals and plants and the bags can then be flipped again to clear the newly fouled undersides. While this can dramatically reduce fouling on cage material, it does not affect fouling on shellfish (Mallet, Carver and Hardy, 2009). If the shellfish themselves are exposed to air, mortality can occur among cultured organisms; blue mussels exhibited 40% decrease in sock weights seven months after a 40-hour exposure to air (LeBlanc et al., 2007). Many fouling organisms, including fouling shellfish and some tunicates, are very resistant to air drying and may not be killed by air exposure (e.g. Lutzen, 1999; LeBlanc et al., 2007). For example, the solitary tunicate Styela clava suffered only 11% mortality after 48 hours of air exposure (Darbyson et al., 2009). The process works, but is limited to hearty species of shellfish, mostly oysters.

In applying this practice, the length of exposure time for desiccation will affect each biofouling species differently (LeBlanc et al., 2007; Darbyson et al., 2009). Air-drying of nets can be combined with other biofouling management actions, such as the application of a coating or other cleaning practices such as scrubbing or high-pressure washing. Trial efforts in some farms where there are large amounts of hard biofouling species (e.g. barnacles and tube worms), suggest that scrubbing the equipment before desiccation results in greater reduction in biofouling than scrubbing after. Scrubbing before drying, however, means that live animals and algae could be released into the water column. These animals and algae are less likely to be alive after drying.

Dipping

In addition to physical removal, sprays and dips of noxious substances (acetic acid, lime, brine, freshwater, etc.) can be used to control biofouling (DeBrosse and Allen, 1993; Coutts and Forrest, 2005; Forrest et al., 2007; LeBlanc et al., 2007; Guenther, Fitridge and Misimi, 2011; Rolheiser et al., 2012). Some of these treatments can be very effective. For example, a single one-minute treatment of 5% acetic acid solution was sufficient to remove 55% of fouling organisms from test surfaces (Piola, Dunmore and Forrest, 2010). A one-minute immersion in 4% saturated hydrated lime killed fouling ascidians (MacNair and Smith, 2000). A ten-minute exposure to freshwater led to 87% mortality of the ascidian *Didemnum vexillum* (Denny, 2008). Despite their potential value, there are some serious downsides to all of these treatments. Perhaps most significantly, cultured organisms can be harmed by the treatments. For example, blue mussels experienced a 74% reduction in biomass after a 30-second immersion in 5% acetic acid (LeBlanc et al., 2007) and blue mussels typically experience 10–15% mortality after exposure to antifouling lime treatments (Locke et al., 2009). Another problem is that very long exposure times (1–2 days) or repeated exposures can be required for some treatments to be effective (Forrest and Blakemore, 2006). Additionally, not all fouling species are harmed by all treatments. Caustic substances can also harm non-target species (Paetzold, Davidson and Giberson, 2008; Locke et al., 2009), be costly to use in bulk and can cause environmental contamination. These methods can only be used with shellfish species capable of completely closing their shell valves to protect them from the external environment.

Dipping in freshwater

Shellfish growers frequently dip stock in fresh water as an inexpensive and effective antifouling treatment. Dipping for up to two days can be carried out for mussels and oysters. The main constraint is the need to change the water to maintain salinity below 10/00 (Forrest and Blakemore, 2006).

Freshwater dipping is mostly commonly used with mussels and oysters, but the technique is being considered for other bivalve species. Companies are exploring whether freshwater dipping may be beneficial in the case of seed stock being transported between sites, as the stock can be soaked while in transit. Freshwater soaking may be particularly valuable for thin-shelled species for which mechanical cleaning is not viable. While undertaking extended freshwater dipping, the decomposition of biofouling organisms when soaking in freshwater produces anoxic conditions which accelerate the effects of the treatment. In addition to removing biofouling, freshwater soaking has also been found to help control juvenile sea stars on mussel grow- out lines (Garnham, 1998), thereby limiting starfish predation and reducing stock mortality.

Hot water immersion

For shellfish farming operations, immersion in hot water is a simple biofouling treatment method that is being explored by the industry. For example, hot water immersion was effective at controlling three biofouling species (*Ectopleura crocea*, *Ciona intestinalis* and *Styela clava*) that affect two commercially grown shellfish (*Mytilus galloprovincialis* and *Ostrea angasi*). Depending on exposure times and temperatures needed, the technique can result in total mortality of the cultured stock (Sievers et al., 2019).

Dipping in and spraying chemical solutions

Shellfish culturing operators also dip stock in chemicals such as in acetic acid, hydrated lime, saturated brine and hypochlorite solution to kill biofouling organisms (LeBlanc et al., 2007; Piola, Dunmore and Forrest, 2010; Carman et al., 2016). Chemical dipping is generally most effective against soft-bodied species. For hard-bodied biofouling organisms (such as barnacles and tube worms), the treatment duration needs to be longer to be effective, but may result in higher stock mortality. Efforts to spray acetic acid directly on the fouling species *Ciona intestinalis* killed the biofouling ascidians in 15–30 seconds, without any corresponding stock mortality. This technique is limited to bivalve shells, which need to be closed before applying the treatment. On other species, there has been up to 50% stock mortality from tests on the applications of chemicals (LeBlanc et al., 2007).

Another common dip is concentrated brine, a super-saturated saltwater bath, for short periods of time (e.g. Carver, Thériault and Malet, 2010). This is commonly used on oyster gear and cultch and kills most fouling organisms. It is relatively inexpensive and, as with other dips, can only be used on shellfish species that can close their shell valves completely.

If long transport times are planned for the stock (e.g. 24 hours), chemical dipping is normally carried out after the journey, otherwise the stock must be rinsed before transportation (Forrest et al., 2007). Other trials on farmed mussels have shown that removing stock such as mussels from lines for spraying can increase biofouling mortality, but can increase the mortality of the stock as well (LeBlanc et al., 2007). In addition, there are both health and environmental considerations which must be addressed in relation to the use of chemical dipping or spraying procedures.

Encapsulation

Encapsulation involves wrapping fouled structures in plastic to create anoxic conditions that result in biofouling mortality. This method was originally developed for use on boat hulls, pontoons and piles (Atalah et al., 2016). It may be a viable option for removing biofouling from infrastructure such as mooring lines, buoys and trays. It is being considered for potential use in shellfish farming, e.g. wrapping mussel lines, but tests with farmers are needed to determine the viability of this approach. Some empirical evidence suggests that combining encapsulation with chemical dosing using acetic acid may greatly reduce treatment times (Forrest et al., 2007; Denny, 2008).

Gear manipulation

In some regions, growers have taken advantage of the fact that biofouling decreases with depth (Claereboudt et al., 1994) and lower their gear in the water column (ropes and cages) during times of heavy settlement of fouling organisms such as tunicates and other shellfish. This method is simple and effective but limited in applicability.

Biological controls

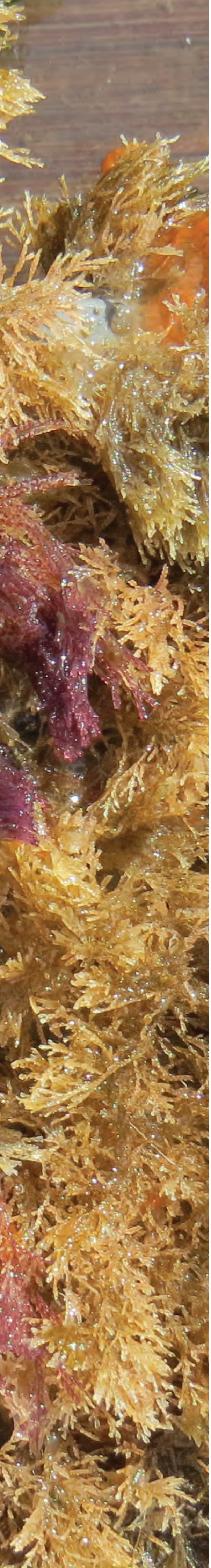
Numerous efforts have been made to identify biological controls, i.e. natural predators that can be placed in shellfish grow-out cages that will consume and control biofouling species. Sea urchins, crabs and shrimp can decrease biofouling on cages and shellfish by up to 74% (Hidu, Conary and Chapman, 1981; Enright et al., 1983, 1993; Ross, Thorpe and Brand, 2004; Dumont et al., 2009) and can lead to increases in growth and survival of cultured organisms (Minchin and Duggan, 1989; LeBlanc, Landry and Miron, 2003; Dumont et al., 2009). These efforts have been mostly laboratory- or small-scale studies and include periwinkles that consume algae on the surfaces of cages (Carman, Allen and Tyrrell, 2009), sea urchins that consume barnacles and tube worms (Lodeiros and García, 2004; Switzer et al., 2011; Sterling et al., 2016), and small fish such as mummichogs to consume juvenile sea squirts (Flimlin and Mathis, 1993). Although potentially helpful, especially if used in conjunction with other fouling mitigation strategies, the effectiveness of biological controls varies depending on location, availability of predators and composition of the fouling communities. Some fouling species, especially invasive species, are not susceptible to natural predators (Epelbaum et al., 2009). For example, only a few species consume the invasive colonial ascidian *Didemnum vexillum* and those species only attack stressed colonies (Valentine et al., 2007; Carman, Allen and Tyrrell, 2009). The majority of biological control efforts have been unsuccessful on a commercial basis.

Tumbling

Mechanical tumbling of oysters can remove some biofouling organisms, but can also damage the shellfish.

Aeration

Bullard, Shumway and Davis (2010) showed aeration in the form of a steady stream of bubbles was highly efficient at reducing settlement of biofouling organisms. The method was most effective against sea squirts (99%) but also significantly reduced barnacle settlement by 68% and hydroid settlement by 57%. While very effective, the scalability of the process is questionable.



Summary

Biofouling will remain a ubiquitous factor for aquaculture systems and development of improved methods for its eradication will continue to evolve. There are a multitude of methods and approaches to control biofouling in all forms of aquaculture and there is not, nor is there ever likely to be, one magic solution (Table 1.). Current methods and products used are species- and geographically specific and reflect an enhanced concern for environmental and product safety. Aquaculture systems and structures provide habitats for invasive species, but rarely serve as vectors per se for introductions.

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Appendix 1 – Reference Material

The following are considered key reference documents regarding biofouling management best practices in marine aquaculture:

Bannister, J., Sievers, M., Bush, F. and Bloecher, N. 2019. Biofouling in marine aquaculture: A review of recent research and developments. *Biofouling*, Vol. 35, No. 6, pp. 631–48.

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Acronyms

AMBIO	Advanced nanostructured surfaces for the control of biofouling
AMPEP	Acadian marine plant extract powder
CAM	Copper alloy metal
CRAB	Collective Research on Aquaculture Biofouling
EU	European Union
GEF	Global environmental facility
IAS	Invasive aquatic species
IMO	International Maritime Organization
IMTA	Integrated multitrophic aquaculture
SPAN	Speciality antimicrobial polymeric materials
UNDP	United Nations Development Programme

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IOC TECHNICAL SERIES Nº 174

Biofouling Prevention and Management in the Marine Aquaculture Industry

Best Practices in Biofouling Management — Volume I

This report is one of a series covering best practices for biofouling management and addressing invasive aquatic species (IAS) for non-shipping sectors, as part of the GloFouling Partnerships Project being undertaken by the International Maritime Organization (IMO), in collaboration with the Global Environment Facility (GEF) and the United Nations Development Programme (UNDP).

The focus of these reports is on biofouling management. Information about the general processes of biofouling, the ecological and environmental impacts, economics of management, and the costs estimated to be associated with IAS are beyond the scope of these reports.

This report addresses specifically biofouling management in relation to marine aquaculture industry operations, equipment and infrastructure. It covers shellfish, finfish and seaweed operations in estuaries and seawater.

There are a multitude of methods and approaches to control biofouling in all forms of aquaculture. Current methods and products used are species- and geographically specific and reflect an enhanced concern for environmental and product safety. Aquaculture systems and structures provide habitats for invasive species, but rarely serve as vectors per se for introductions.

For further information, visit the GloFouling website at https://www.glofouling.imo.org

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