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Biofouling and the shellfish industry

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Abstract: The impacts of biofouling on shellfish and aquaculture can be extreme and sometimes devastating. Biofouling is a major problem within the shellfish aquaculture industry, particularly with regard to the resultant increased labor costs and reduced value of product. The chapter discusses the impacts of biofouling, economic costs involved during culture, processing, the value of the end product, and the techniques employed to mitigate and remove biofouling organisms. While biofouling can have drastic impacts on the quality of product, most issues are associated with marketing and reduced aesthetic value. Biofouling does not impact the safety of the product for human consumption.

Key words: biofouling, shellfish, seafood quality, shellfish safety.

13.1 Introduction

Impacts of biofouling on molluscs (= shellfish) and aquaculture can be extreme and sometimes devastating. Biofouling affects all structures, both natural and artificial, immersed in the marine environment, although often in different ways (Glasby, 1999; Glasby and Connell, 1999; Railkin, 2004). Living organisms, such as gastropod and bivalve molluscs, can provide a massive amount of hard substratum that can be settled upon by larvae of marine organisms. In fact, in many benthic and intertidal areas, the surface area provided by shellfish may be equal to, or greater than, the inert substratum available (Railkin, 2004). Settling sedentary organisms generally recruit to both living and inert substrata (D'Antonio, 1985). Such biofouling of living substrata by both epibionts and endobionts is a major problem within the shellfish aquaculture sector, particularly with regard to the resultant increased labor costs and reduced value of product (Adams *et al.*, in preparation). While bivalves and other marine species have various natural defensive techniques to reduce recruitment of epi- and endobionts (see Wahl *et al.*, 1998), shells invariably end up fouled by marine organisms – this fouling may in turn facilitate the settlement of certain epibionts that capitalise on the protective abilities of the bivalves (Forester, 1979, Pitcher and Butler, 1987).

Within the shellfish aquaculture sector epi/endobionts affect cultured organisms in different ways (see below), and can seriously affect the costs involved during culture or processing; biofouling may also significantly affect the value of the end product (Adams *et al.*, in preparation). In this chapter we will discuss the impacts of biofouling on molluscan shellfish handling and safety, and the techniques employed to mitigate and remove biofouling organisms

13.2 Biofouling and shellfish

13.2.1 Affected bivalves

Impacts of biofouling on shellfish and shellfish culture vary with geographic location, shellfish species, habitat, and method of culture. Impacts of fouling differ between the intertidal (e.g., mussels, oysters), subtidal (e.g., scallops, oysters, mussels, abalone), and soft-sediments (e.g., scallops) (see Plate I). Permanently immersed animals and culture gear tend to be more heavily fouled than others. Bivalves which are infaunal (e.g., clams) have few or no epibionts in comparison with exposed shellfish which can provide a substratum for the larvae of fouling species.

Intensity of biofouling can vary between the two valves of an individual bivalve, and overall intensity of valve fouling can differ between wild and cultured bivalves. Often, cultured organisms must be removed from their natural conditions so that they can be cultured in a more economically feasible fashion. This has important implications for development of fouling communities on the shells. For instance, the scallop *Pecten maximus* is a benthic species that lives on soft-sediment with its lower valve imbedded within the sediment and with its upper valve covered by a thin sediment layer. The valves (particularly the lower) are, therefore, essentially unavailable as a settlement platform for biofouling larvae (Lodeiros and Himmelman, 2000) with wild stocks only being fouled on the upper valve (Ivin *et al.*, 2006; Schejter and Bremec, 2007). The lower valve, however, is not entirely unavailable to certain species, such as some endobionts (Evans, 1969). When scallops are cultured off the seafloor in trays or nets, both valves become available to biofouling organisms. Biofouling in culture situations can lead to increased stress or feeding competition for the scallops (Vélez *et al.*, 1995) which may result in reduced growth (Lodeiros and Himmelman, 2000). Such valve specificity by foulers is also seen in some species of oysters where the sponges *Cliona viridis* and *C. celata* infest only the lower valve of the flat oyster, *Ostrea edulis* (Rosell *et al.*, 1999). Such potential for differences in the impacts of fouling among individuals of species growing either naturally in beds or within aquaculture structures have financial implications with regard to harvest, maintenance and marketability.

13.2.2 Type and extent of fouling

As noted by Wahl *et al.* (1998), few species are solely involved in the fouling of other living organisms and all groups of fouling species, be they shelled (e.g., barnacles, serpulid worms, and other bivalves), soft-bodied foulers (e.g., ascidians), or borers (e.g., boring sponges) can impact wild and cultured bivalves and their fisheries. Fouling organisms can be species-specific with regard to host selection (Rosell *et al.*, 1999). Sponge endobionts were rare on mussel shells (*Mytilus edulis*), but prevalent on oyster shells (*O. edulis*) from similar water depths; thus such species-specificity is not necessarily controlled by the environment in which the bivalves are found.

The extent of fouling often varies with the age of the bivalve (Scardino *et al.*, 2003) and the ability of a given bivalve species to defend itself against foulers. Fouling species can be attracted to, or inhibited by, certain conditions on the substrata including light and shade conditions, color (James and Underwood, 1994), and surface texture. Fisher (pers. comm.) noted that on the exterior surface of the oyster shells, worm penetration sites were routinely associated with crevices and growth ring (radial ridges) areas in the shell profile, and suggested that these changes in the shell profile may facilitate recruitment of *Polydora* planktonic larvae during the settling out stage of worm life history) and chemistry (Lapointe and Bourget, 1999; Thomason *et al.*, 1994). These factors can be particularly important during the early developmental stages of a fouling community (Bourget *et al.*, 1994). Shell surface texture and chemistry appear to play an important role in defining the settlement levels of fouling organisms; however, this is very dependent upon the scale of surface roughness encountered (see Scardino *et al.*, 2003 and references therein). No single surface texture appears to prevent recruitment of a wide range of fouling organisms, and certain organisms even prefer to recruit to smooth surfaces (Scardino and de Nys, 2004).

Many bivalves possess physical or behavioral defences against fouling. The periostracum of bivalve shells is composed of a proteinaceous matrix, which Wahl *et al.* (1998) proposed as a potential defensive mechanism against fouling organisms and may also assist in the preventative formation of biofilms (Scardino and de Nys, 2004). The periostracum can be textured (e.g., *Mytilus galloprovincialis*) or smooth (e.g., *Pinctada imbricate*) (Scardino *et al.*, 2003). Although no single periostracum texture will inhibit all foulers, certain species-specific interactions have been identified for some bivalves (Bers and Wahl, 2004; Bers *et al.*, 2005). The periostracum also acts as a physical barrier against some boring organisms (Harper and Skelton, 1993) and it is this property which is being emulated in the development of new synthetic coatings designed to protect pearl oysters from biofouling (de Nys and Ison, 2004). It has also been noted that the presence and effectiveness of this system in protecting bivalves against fouling organisms diminishes with age in some species (Guenther *et al.*, 2006; Scardino *et al.*, 2003; Wahl *et al.*, 1998) through the deterioration of this barrier by environmental factors.

Other systems employed by bivalves include the cleaning of their shells and the facilitation of certain foulers that deter the recruitment of other fouling organisms. Foot-sweeping among bivalves, such as mussels, assists in the physical removal of new settlers (Thiesen, 1972), and reduces the build-up of a fouling community on the shell. This behavior is most effective in small mussels (<3 cm chell height) and larger mussels make use of additional defensive mechanisms (e.g., periostracum) to reduce biofouling. Scallops (*Chlamys opercularis*) fouled by the sponge *Suberites ficus* ssp. *rubrus* tended to have no other foulers on their shells (Armstrong *et al.*, 1999). Similarly, Pitcher and Butler (1987) found that the scallops (*Chlamys asperrima*) appeared to facilitate fouling by certain sponge species. Some fouling species (possibly including these sponges, and see below) produce secondary metabolites that can act as an antifoulant; however, such compounds can be either species-specific, requiring the host organism to produce a different one for every potential fouler, or so general that they can potentially affect the host (Wahl *et al.*, 1998). Wahl *et al.* (1998) also proposed that aggregations of bivalves, such as mussels, might reduce the level of fouling larvae present in the vicinity by filtering large volumes of water and creating a 'seston depletion effect' (Wildish and Kristmanson, 1985) thereby reducing fouling pressure. Mobile bivalves, i.e. scallops, exhibit less fouling on the more active animals. This is routinely seen in sea scallops (*Placopecten magellanicus*) and king scallops (*Pecten maximus*) where smaller, more active scallops are less fouled than the more sedentary larger (older) scallops.

The age of the shell is also often important in determining the effects and the extent of fouling on bivalves. Generally older bivalves are more heavily fouled than younger ones (Alvarez-Tinajero *et al.*, 2001; Guenther *et al.*, 2006). This is due, in part, to the reduction in the effectiveness of the periostracum and also to the fact that the animal has been exposed to fouling pressure for longer periods of time. It is important to note that age and size do not always correlate due to differing growth rates of bivalves in different environmental conditions; therefore, fouling tends to be more extensive on older rather than larger shells (Guenther *et al.*, 2006).

13.3 Problems and benefits of biofouling

Biofouling organisms influence molluscs by increasing competition for food and space resources, which in turn can reduce bivalve growth and survivorship, leading to reduced market value and increased costs to the industry. In this section we will outline several potentially serious effects that fouling organisms have on cultured shellfish.

13.3.1 Shellfish growth and predation issues

It is widely accepted that the main factors governing shellfish growth are the temperature of the surrounding water and availability of suitable food resources; however, fouling can also be an important factor influencing shellfish growth (Ruck and Cook, 1998; Rosell *et al.*, 1999; Lodeiros and Himmelman, 2000; Lodeiros *et al*., 2007; and see Enright, 1993), aesthetic shell quality and shape (through the presence of growth deformities) (Taylor *et al.*, 1997) and survival (Lodeiros and Himmelman, 1994; Minchin and Duggan, 1989; López *et al.*, 2000; Lodeiros *et al*., 2007). Lodeiros and Himmelman (2000) and Vélez *et al.* (1995) highlighted fouling as being particularly important in the reduction of growth for those bivalves (scallops in their studies) that are not naturally prone to heavy fouling pressure in their natural habitat. Fouling can also affect the equipment in which the shellfish are cultured (trays, lantern nets, etc.), thereby reducing the water flow, and thus the food supply, to the cultured species (Paul and Davies, 1986). While fouling is generally seen by growers as having detrimental effects on bivalves and increased costs to the industry, some positive effects of fouling have been documented. For example, some studies (e.g., Lesser *et al.*, 1992; Taylor *et al.*, 1997; López *et al.*, 2000) have shown that bivalve growth was not affected by fouling, while others have shown that certain levels of fouling on the equipment infrastructure can improve growth (Ross *et al*., 2002); therefore investing in control measures may not always be necessary (LeBlanc *et al.*, 2003). In this section, we will concentrate on direct effects of epibionts and endobionts on shellfish.

In addition to improved growth effects due to the presence of fouling on infrastructure (Ross *et al*., 2002), some positive effects have also been shown where the fouling occurs directly on the bivalve shells. For example, sponge–scallop mutualistic interactions occur (e.g., Bloom, 1975; Chernoff, 1987). In these interactions, the bivalve provides substrate for sponge growth and allows the sponge to take advantage of its feeding current, the toxic sponge protects the scallop from predation and additional fouling pressure (Armstrong *et al.*, 1999 [*Chlamys opercularis* and *Suberites ficus* ssp. *rubrus*]; Forester, 1979 [*Chlamys varia* and *Halichondria panicea*]). Forester (1979) also showed that this mutualism was present only on the scallops in the studied area and not on oysters; it was hypothesized that the mutualism would assist the escape response of a mobile species, but not benefit a non-mobile one. The mutualistic relationship also resulted in more rapid scallop growth (Chernoff, 1987) and the scallops tended to have greater soft tissue content for a given age (Pitcher and Butler, 1987). Mutualistic interactions have been shown for other bivalve–epibiotic associations, such as the scallop *Patinopecten yessoensis*, and its epibiontic macrophytes (Ozolinsh and Kupriyanova, 2000). Vance (1978) showed that clams (*C. pellucida*) benefit from their mutualistic relationship with their diverse assemblage of epibionts, which reduces clam predation by asteroids. Other studies (Enderlein *et al*., 2003) have shown reduced predation by crabs (*Carcinus maenas*) when the bivalve (*Mytilus edulis*) has been fouled by hydroids.

Despite the presence of some mutualistic relationships, sponges can also have negative impacts on bivalves. Sponges may overgrow the scallop hinge and affect its movement, thus reducing efficiency of escape from predators (Forester, 1979). Sponge endobionts are also known to have negative effects on growth and meat condition of bivalves (Wargo and Ford, 1993) by increasing their metabolic costs (e.g., repairing shell damage) and impairing the opening/closing of the shell, which can lead increased predation (Rosell *et al.*, 1999). Endobionts can also reduce the reproductive output of bivalves (Kaehler and McQuaid, 1999).

Littlewood and Marsbe (1990) showed that epibiont fouling is potentially a refuge for some bivalve predators. In their study, the polyclad turbellarian flatworm *Stylochus frontalis* found refuge within the biofouling assemblage found on the oyster *Crassostrea rhizophorae*; the foulers kept the worms moist when exposed to the air, thereby preventing their desiccation and allowing them to continue predating on the oysters once submerged. These types of interaction may be particularly important to the industry as aerial exposure of fouled gear and shellfish is one measure utilised in the control of fouling. Additionally, certain fouling species can also increase predation pressure on bivalves by improving the handling characteristics of the prey item by the predator (Enderlein *et al.*, 2003). Crabs (*Carcinus maenas*) in this study were able to handle mussels (*M. edulis)* encrusted with barnacles (*Balanus* sp.) more easily than clean mussels, within a given size class.

13.3.2 Shell quality and fouling

Regular removal of epibionts during grow-out or post-harvest processing techniques generally prevents fouling from impacting the quality of the shell; however, endobionts (e.g., sponges, clams, polychaetes, bacteria) can have a serious impact on shellfish when prevalent. Endobionts bore into the shell and affect the strength and quality (primarily aesthetics) of the shell. While this may have little impact on the bivalve meat, it can have major implications for the sale of shellfish which are sold based on shell quality, such as the yellow abalone (*Haliotis corrugate*) (Alvarez-Tinajero *et al.*, 2001). Shell quality is particularly important for bivalves sold on the half shell and some species (e.g., oysters) may be more affected by borers than others (e.g., mussels) (Rosell *et al.*, 1999). The resultant increase in metabolic costs and the production of conchyolin to repair shell damage caused by borers can result in the presence of mud blisters. Such aesthetic imperfections result in a reduction in the market value of the shellfish. In addition, the strength of the shell is often compromised by the borers (Kaehler and McQuaid, 1999) and may result in processing and shipping difficulties (Wesche *et al.*, 1997). Borers may commonly exhibit species-specific impacts.

Though the infestation of *Polydora* does not represent a serious threat to the overall health of the oyster (though energy spent to wall-off worms can be considerable during periods of heavy infestation), contamination of oyster meat by shell fragments and the off-odor (anaerobic) mud and detritus from broken knobs and/or blisters is not acceptable for either the shucked-meat market or (especially) the half-shell market. Extensively infested oysters, which result in brittle shells that crumble upon attempting to shuck, are not suitable for the half-shell market. One of the few instances where shell quality has been shown to improve through the presence of another species was during a study of crabs as biological control agents in oyster culture (Enright *et al.*, 1993). Three species of crab were utilized in this study (*Cancer irroratus, Carcinus maenas*, and *Pagarus acadianus*) with the hermit crab (*P. acadianus*) proving to be the most effective at fouling control on the cultured bivalves (*Ostrea edulis*). Additionally, the action of the crabs' mandibles led to a desirable shell shape, thereby increasing the esthetic quality of the product.

A recent survey (Adams *et al.*, in preparation) noted specific impacts on individual species of shellfish. Clam (*Mercenaria mercenaria*) growers in Florida noted that 'any small amount (of fouling) and the clam will be thrown away; the buyer doesn't want the look of other growth on them.' They also noted that fouled clams do not grow evenly, producing an inferior product in a market that desires uniform size. Growers also indicated that fouled animals are 'weak' and 'less healthy', and have lower meat yield and decreased shelf-life. Species sold for the half-shell market, especially oysters, are particularly prone to the damage caused by shell fouling. As in clams, biofouling on oysters can severely alter shell shape and can also result in thinner, weaker shells – a problem when shucking. Sulfur sponge (*Cliona celata* and related species) also weakens the hinge and makes shucking difficult. Fouled oysters are regularly scrubbed prior to sale and fouling organisms are chipped off, resulting in shell damage, reduced shelf-life and subsequent reduced market value. Further, some fouling organisms such as tube worms (*Spirorbis* sp.), slipper limpets (*Crepidula* spp.) and jingle shells (*Anomia* sp.) emit a foul odor which buyers mistake for bad oysters. Mud worms (*Polydora* sp.) on the interior of the shells affect appearance of the shucked product and are not evident until after the product is sold.

As summarized in the following quotes from growers: 'if clams aren't pretty, they are harder to market;' 'customers don't like an ugly product;' 'if clams look bad, i.e. barnacles, wholesalers won't buy product,' appearance is everything. Scars left on shells after removal of barnacles were noted by both clam and mussel growers as reducing market value. In terms of shellfish safety and marketing, biofouling is an aesthetic issue. While it can have substantial negative impacts on marketing, it does not affect the safety of the product for human consumption.

13.3.3 Biofouling costs

In a recent survey (Adams *et al*., in preparation), shellfish growers were asked to list the impacts of biofouling on their aquaculture operations. Some generalities were noted for all shellfish species including reduced growth, mortality, increased labor associated with the removal of the fouling organisms, and decreased market prices. It was also noted that, because the growth rate of the shellfish is reduced, they are not ready for market during the season(s) when prices are at their highest.

Although fouling can reduce the price of shellfish in the marketplace (Armstrong *et al.*, 1999; Adams *et al.*, in preparation), costs to the industry related to biofouling have not been accurately calculated. It would be nearly impossible for a mussel farmer, for example, to determine which losses of stock are related to fouling pressure as there are so many factors involved (e.g., the alteration of predator–prey interactions, shell weakening leading to processing losses). Bivalve growers are more interested in the end results – what yield can be achieved for a given effort and market value of the product. It is from these projected costs that growers determine appropriate capital investment (e.g., equipment for cleaning and processing, and labour costs), and time/effort costs in their production. Thus, there are few estimations of the loss in product value related to fouling pressure, and these are all approximations.

For example, the overall estimate related to the biofouling costs within the oyster (*O. edulis*) trade is 20% of the final market price (Enright *et al.*, 1993); it is 30% for the scallop *Placopecten magellanicus* (Claereboudt *et al.*, 1994). These estimates are region-specific as well as dependent upon differences in methods used for growing the bivalves (i.e., rope culture, culture in trays suspended in the water column, trays placed on the seafloor) and cleaning the fouling from their shells. As mentioned in Section 13.3.1 there are instances where the fouling can facilitate scallop growth which results in significant savings to the grower. Armstrong *et al.* (1999) estimated these savings to be as much as £100,000 (sterling) per annum for a farm producing 3 million scallops.

A recent survey of European producers has highlighted some of the costs to the industry related to biofouling and its removal (Collective Research on Aquaculture Biofouling – EU Project COLL-CT-2003-500536-CRAB). For oysters, cleaning costs, in relation to total operational costs, ranged from 5% to 30% per annum with operations employing a variety of cleaning techniques and technologies. Oyster producers at the northern sites in the study (i.e., Norway) employed mechanical cleaners while more southerly sites (i.e., Portugal) employed manual labor to remove fouling from the shells. Despite such obvious differences in removal techniques, the biofouling removal costs to the operations were roughly the same at approximately 30% of the total operational costs. A typical large mussel operator in Europe suffers up to 20% losses of all stock processed from mechanical cleaning machines, with total cleaning costs in the region of 20% of total operating costs. Despite the losses and the costs involved, such cleaning is essential because it adds significant value to the product when mussels are packaged in vacuum packing with or without sauces and also in the half-shell trade where aesthetics are known to be of particular importance (see Section 13.3.2).

13.3.4 Handling and packaging issues

The authors are not aware of any studies which have examined the effects of biofouling on the handling and packaging of bivalves, with most information coming directly from the processors. Processing for the value-added market involves, for example, the packaging of bivalves with sauce or cooked. If the bivalves are to be packaged in their shells, the shells must be free of fouling because they are otherwise likely to rip the vacuum packaging material into which they are placed, they need to be aesthetically pleasing, and fouling organisms could impart unwanted scents and flavors to the product.

Further, the product shell needs to have low amounts of biofouling in order to achieve the best market value if sold as whole weight, not meat weight. In addition to a reduced price caused by the poor aesthetics of the product due to biofouling, the increase in the weight due to fouling on the shells is lost profit to the farmer.

13.3.5 Disease

Biofouling can be a known vector for disease. For example, within the finfish industry, amoebic gill disease (AGD) is a major health problem for the stock species (Clark and Nowak, 1999; Munday *et al.*, 2001). The cause of AGD is due to *Paramoeba pemaquidensis*. Although the paramoeba is present naturally in the water column, it is also known to be present on certain fouling species recruiting to salmon cage nets; such fouling can act both as a vector and a reservoir for this marine amoeba (Tan *et al.*, 2002). Tan *et al.* (2002) showed the presence of the species on agar cultured from the mussel *M. edulis*, and other fouling species (including a hydroid, a bryozoan and an ascidian). Morton *et al.* (1999) showed that the dinoflagellate *Prorocentrum lima* (associated with diarrhetic shellfish poisoning (DSP); see Chapter 2) is often found in association with the brown alga *Ectocarpus* sp. Any reduction in the metabolic condition of bivalves due to foulers (see Wargo and Ford, 1993; Section 13.3.1 of this chapter) may lead to the increased susceptibility of these bivalves to attack from disease.

Related to the above concerns is the fact that under certain conditions foulers can increase the concentration of plankton near fouled structures (e.g., Ross *et al.*, 2002). If such increases involved plankton associated with shellfish poisoning, this may have significant effects on the health of the cultured stock or the marketability of product due to public health concerns.

13.4 Current removal/treatment methods

13.4.1 Husbandry practices and shellfish cleaning

There are a variety of husbandry practices and prevention techniques (see Table 13.1) which can be employed to reduce the level of fouling (Southgate and Beer, 2000; Adams *et al.*, 2007, unpublished data). These techniques are particularly

Table 13.1 Generalized examples of techniques used to prevent biofouling in shellfish aquaculture

Approach	Effects on biofouling	Advantages/disadvantages
Avoidance by positioning		
Increasing the depth of deployed gear during biofouling recruitment season	Larvae of some species (e.g., barnacles, ascidians) tend to be photo-sensitive and settle near the surface	Reduced labor costs; not effective for all biofouling species
Removing gear during the biofouling recruitment season	Reduced colonization of gear by larval settlement	Not effective for those biofouling species with long recruitment periods; can result in reduced shellfish growth
Chemicals		
Copper, chlorine, quicklime, acetic acid	Reduces settlement of many biofouling species	Chemicals may have negative effects on the shellfish and environment
Biological control		
Herbivores	Can control fouling by seaweed	Negligible effects on shellfish; only effective for plant control
Predators	Can control some species of fouling organisms	Concerns regarding negative effects on the shellfish

important at sites where economic margins are low and farming cannot take place unless the fouling pressure is low (Lodeiros and Himmelan, 2000). Many compromises are often required by aquaculturists to maximize biofouling reduction and there are no hard and fast rules for reducing fouling – trial and error is often the only way to identify the best culture methods for a particular area. There is also no point in reducing or eliminating fouling when the consequences of such actions also reduce the growth of cultured species. Some studies have shown reduced fouling in intertidal oyster beds due to desiccation stress caused by regular air exposure (Crawford *et al.*, 1988); however, exposure to air limits the duration during which bivalves can feed and may reduce bivalve growth. Compromises that balance reduction in fouling with sufficient food availability may help in these situations (e.g., Leighton 1978). In other situations, floating aquaculture bags are flipped periodically to expose the fouled surface to air, thus killing the communities and not impeding growth of the shellfish.

Because fouling pressure can decrease with depth (Claereboudt *et al.*, 1994), another simple solution that may reduce levels of fouling is to temporarily lower the depth of gear during times of heavy biofouling recruitment (Enright, 1993).

However, the ability to maintain cultures at such a depth requires appropriate infrastructure to haul the equipment up and down at deep water sites. This is often not available to small-scale farmers. A practical demonstration that shows this practice can be helpful is the technique of ‘dropping lines’ used by the Canadian long-line mussel (*M. edulis*) industry. By dropping mussel long-lines to the seafloor, the secondary set of mussels can be avoided or selectively controlled by crabs and sea stars (Bourque and Myrand, 2006). However, if left for too long (>1 week) on the seafloor, the predators can impact the primary mussel stock as well as the secondary set, so vigilance is required when using such techniques.

Currently, anti-fouling coatings are not widely used within the shellfish aquaculture industry, although they have been shown to reduce fouling on structures utilised by finfish farmers (e.g., salmon pens). Some coatings, e.g. those containing tri-butyltin (TBT), have resulted in negative effects in cultured shellfish, such as reduced growth and shell thickening (Batley and Scammell, 1991) and other species. Additionally, the metal compounds in such coatings often accumulate in the flesh of the bivalves, and cause concern for the food industry and public health officials (see McIntosh *et al*., 2005; Boyle *et al*., 2006; Milne, 2006). Metal concentrations may also cause indirect problems for the shellfish industry; for example, the presence of zinc has resulted in false positive results during tests for the presence of paralytic shellfish poisoning (PSP) and has led to stoppages in some shellfish sales (Aune *et al*., 1998). The accumulation and depuration of toxic metal compounds varies with the species being cultured (Boyle *et al*., 2006), as do the impacts of increased metal concentrations on the growth and survival of the bivalves (Davies and Paul, 1986; Paul and Davies, 1986). Moreover, efforts are underway globally to eliminate the use of anti-fouling materials containing heavy metals, especially copper, tin and zinc.

In addition to using metal-based coatings to protect aquaculture gear, waxy coatings can be directly applied to shellfish to smother and kill endobiotic organisms (see Leighton, 1998 and references therein). This coating technology has been constantly improved and is now a marketable and effective product (de Nys and Ison, 2004); however, such coating techniques will only be effective for bivalves such as oysters that are able to seal their valves completely when they are dipped into the coating solutions.

While the preceding techniques are sometimes used to reduce shellfish fouling, mechanical and chemical cleaning techniques remain the most common means of removing fouling organisms from shellfish and aquaculture infrastructure (see Table 13.2). These techniques vary from air-drying, to dipping in caustic solutions, to simply scrubbing with a stiff brush. All are effective and it is up to the individual grower to determine the most appropriate method for the species they are culturing.

Different cleaning techniques are best suited for different shellfish species. Some species (e.g., *M. edulis*) grow relatively quickly and may need to be cleaned only once prior to sale. The most common cleaning method for this

Table 13.2 Examples of fouling removal techniques

Procedure	Shellfish	Effects	Adventages	Disadvantages
Manual brushing and scrubbing	Various species	Removes all biofoulers	Very effective	Labor intensive, tedious and can impart damage to shellfish
High-pressure water spraying	Oysters	Removes all biofoulers	Very effective	Labor intensive; potential damage to shellfish; only effective for some species
Burning	Oysters	Kills all biofoulers	Very effective	Technically demanding and dangerous; potential damage to shellfish
Brine dipping	Oysters and oyster clutch	Kills seastars, boring sponges, some macroalgae, hydroids, ascidians and slippershell	Cheap, safe and reasonably effective	Labor costs
Freshwater dipping	Juvenile mussles; oysters	Kils some ascidian species	Cheap and safe	Can cause juvenile mussles to drop off mussel ropes; labor costs
Exposure to air accompanied by desiccation or freezing	Oysters and mussels	Mixed results; especially on intertidal species and some ascidians	Cheap and safe	Mixed results; labor costs
High-temperature water immersion	Oysters	Kills biofoulers	Reasonably effective	Expensive; can cause shellfish mortality

species is to place the mussels into a tumbler or a brush grader – the mechanical action of the shells hitting one another removes much of the fouling (J. Maguire, pers. comm.). Such machines cost approximately US$27,000. Therefore, only larger farms or processing plants are likely to possess them. Longer-lived and slower-growing species generally require more frequent cleaning. Oysters (e.g., *Ostrea edulis*), for instance, take approximately 3–4 years to reach marketable size. Their periostracums naturally deteriorate with age and as the animals get older they require more frequent cleaning. Additionally, the action of cleaning oysters (i.e., scraping and scrubbing the fouling off of the shells or power-washing) can damage the periostracum (Bers and Wahl, 2004) and leave the shells more susceptible to fouling. Therefore, as the animals get older, expenses involved with cleaning increase (Guenther *et al.*, 2006). In some areas, animals need to be cleaned once per month to control fouling (Taylor *et al.*, 1997). While labor intensive, such cleaning also increases oyster growth rates and reduces shell deformities (Taylor *et al.*, 1997) Thus, the benefits outweigh the additional cleaning expenditure.

Although the effects of mechanical cleaning are generally positive, the act of handling animals during the cleaning process can lead to negative effects on bivalve growth and survival. This is particularly true for the species that are unable to close their valves completely, such as scallops. The removal of these species from subtidal environments for cleaning can lead to a 9% mortality loss (Parsons and Dadswell, 1992). Such handling-induced mortality levels have not been noted for oysters (Taylor *et al.*, 1997), which can fully close their valves.

Cleaning bivalve shells by hand is extremely time consuming and is often only feasible in areas where labor costs are low or farms are small (Enright, 1993). When mechanical cleaning is not possible, other cleaning techniques may be used, such as dipping bivalves into various solutions (e.g., hot water, brines, freshwater, etc.) or exposing them to air. Air drying may take several hours, while dipping may only take a few seconds; however, both of these techniques are useful only for bivalves capable of closing their valves completely (e.g., oysters and mussels); bivalves that are not able to fully close their valves may be harmed by these cleaning processes. Additionally, the temperature tolerance of the cultured stock must be taken into account when dipping bivalves in hot water or exposing them to warm air. Enright (1993) noted that the temperature tolerances of the oysters *Crassostrea gigas* and *Crassostrea virginica* were well above that of mussels, i.e., mussels will die from heat exposure before oysters are adversely affected (this fact may be helpful in situations where growers want to remove mussels fouling oyster shells). Dipping techniques have also been shown to be better than air drying at controlling certain bivalve predators which take refuge in the fouling material (Littlewood and Marsbe, 1990) and in the control of endobionts in abalone shells (Leighton, 1998). Weak acetic acid solution has also been proposed as a technique for the control of ascidians in bivalve culture. Exposure to this solution for 10–30 seconds was shown to kill the ascidian *Ciona intestinalis* without any mortality to the mussel or oyster stock species (Carver *et al.*, 2003). One considerable drawback to dips and air drying is that 'hard' foulers (e.g., barnacles, calcareous worm tubes) are generally unaffected.

Control of *Polydora* by dipping (saturated brine) or air-drying has shown little success on the adult, established invader. This is probably largely due to the mode of infestation by these marine boring worms. These control methods are thought to impact newly settled *Polydora* larvae and juvenile worms that are in the initial stages of boring. Once they create a living space within the valve of the oyster (blisters/knobs created by host response) which maintains its own respective environment even though there is always an association with the external environment (they are filter feeders) this space serves to buffer the affect of dipping and/or air drying. Thus, these control methods are effective only during times of early worm infestation periods, when they are settling out onto shell substrate.

Biological control

Small-scale experiments have shown the potential benefits of using grazers and predators to control biofouling, but currently there are few industrial-scale applications of these approaches. Enright *et al.* (1983) showed the grazing gastropod *Littorina littorea* controlled the fouling on the oyster infrastructure, resulting in a 30% increase in growth rate of the oysters. This increase in growth rate could shorten the growing period and reduce the culturing costs to the farmer (Cigarría *et al.*, 1998); however, herbivorous species can only control algae and other foulers are likely to remain unaffected (Enright *et al.*, 1993).

Non-algal foulers require predatory control. Some success in this area has been achieved through the use of crabs. The benefits of crabs in reducing fouling were initially observed accidentally by Hidu in 1978. After further experimentation Hidu *et al.* (1981) noted their success in controlling mussel fouling in oyster culture. Enright *et al.* (1993) showed that crabs reduced fouling of *Ostrea edulis* by 76–79%, which led to increases in oyster growth by 10–60% and improvements in shell quality. Fouling control has also been achieved with the predatory dogwhelk (*Nucella lapillus*); these snails were utilised in scallop and oyster culture where they reduced the presence of fouling mussels and increased the survivorship of cultured scallops and oysters (Minchin and Duggan, 1989). Urchins were successfully used to control fouling on the infrastructure and shells within suspended oyster and scallop culture (Lodeiros and Garcia, 2004, Ross *et al.*, 2004); they reduced fouling by 74% on infrastructure and 71% on oyster shells. Urchins may also reduce abundance of barnacles and tube worms (Minchin and Duggan, 1989). Fish have also been employed to control the build-up of ascidians in bivalve culture trays (Flimlin and Mathis 1993). Hidu *et al.* (1981) cautioned against the use of predatory species as they may consume stock species. While use of biocontrol is appealing, especially as an environmentally sensitive means of fouling control, the availability of sufficient numbers of predatory animals may limit its application.

13.5 Future trends

Scientific research and industry practices in the culture of bivalves are often separated. Research often produces solutions that are impractical to the farmer, owing to the costs required to implement fouling control measures at large scales effectively. Continued efforts to develop measures of fouling control need to be carried out with the end goal that they can be applied on an industrial scale. It is likely, therefore, that the application of future fouling control procedures will be reasonably simple. Improved bivalve husbandry techniques are likely to focus on reducing or eliminating the recruitment and subsequent growth of fouling species. This will result in cost savings by reducing the necessity to remove fouling from bivalve shells and associated aquaculture structures (e.g., trays, ropes).

As labor costs continue to increase, so does the need to reduce man-hours for any given operation in a bivalve culturing setting. As the major labor cost within the industry is generally the cleaning and processing stages, improvements in husbandry procedures will assist in cost reductions as will potentially applicable recent developments in shellfish coatings. Such coatings will negate the impact of borers, by acting as a barrier in the same way as the naturally produced periostracum. This will have implications for the health of the shellfish and the quality of the product – leading to improved market value. Additionally the coating will prevent the recruitment to the shell of other fouling epibionts, thereby reducing cleaning costs. However, the use of such coatings, at present, is feasible only for certain species of bivalves, e.g. oysters.

As the aquaculture sector moves away from certain coating technologies on its infrastructure (the use of copper-based products, for example) due to their environmental impact, so the need for the improvement of husbandry, cleaning, and non-toxic coating methods increase in importance. Numerous efforts are underway globally to develop anti-fouling net coatings and inclusions that will reduce biofouling.

13.6 Sources of further information and advice

The primary sources of research reports within the aquaculture sector are scientific journals, e.g. *Aquaculture*, *Aquaculture International*, *World Aquaculture* and the *Journal of Shellfish Research*. Individual government bodies (e.g. CSIRO and the Fisheries Research and Development Corporation of the Australian Government; Department of Fisheries and Oceans, Canada; IFREMER, France and CSIRO, Australia; NOAA and the National Marine Fisheries Association in the US) are also involved in research within the aquaculture sector. These government bodies should be consulted individually for each country in question. While governmental information is often difficult to find and obtain, many of the reports are carried out by key researchers in the field on a consultancy basis and are published in the peer-reviewed literature.

Although biofouling is a major concern to shellfish aquaculturists and can have drastic impacts on the quality of product, most issues are associated with marketing products of reduced aesthetic quality. Biofouling does not impact the safety of the product for human consumption.

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