Chapter 2

The promise of marine biotechnology: Benefits for people and the planet

Recent advances in our understanding of marine bioresources have enabled better understanding of the potential contribution of marine biotechnology to social and economic growth and prosperity. Governments investing in marine biotechnology have recognised the potential for marine biotechnology to help sustain the ecosystem services the ocean provides to the planet. This chapter discusses the potential socioeconomic contribution of marine biotechnology and the importance of marine biotechnology to environmental sustainability.

Food security: Securing a sustainable food supply for a growing population

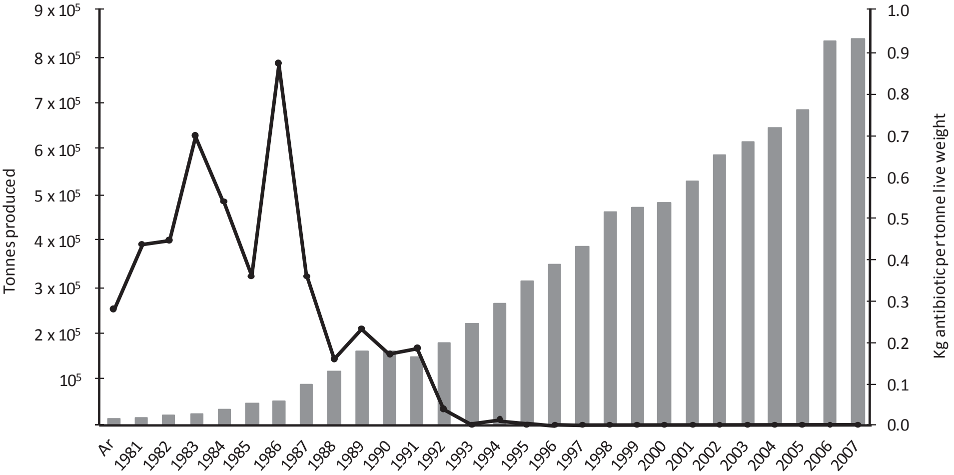
As the global population increases, demand for food and for new sources of protein is projected to grow, challenging existing food production systems. To feed the 9 billion people predicted in 2050, food output must increase by 70%.[1] This will be difficult. The reasons include climate change, urbanisation, changes in consumer tastes, scarcity of natural resources such as land and water, biodiversity issues, and the scale of the investment required to transform food production systems. Globally, consumption of animal protein is expected to double in the first half of this century. The strongest growth is expected in farmed fish and chicken, which also seem to be the sources of animal protein with the smallest carbon footprint (Nutreco, 2010).

Over 1 billion people worldwide rely on fish as their primary source of protein. Rising demand is driving innovation in fish production, as 75% of capture fish stocks[2] are depleted from overfishing. Aquaculture now produces 50% of the world's food fish (Browdy et al*.,* 2012; FAO, 2011); it is also the fastest-growing food production sector, providing new opportunities for food production from the sea and on land and reducing pressures on wild fish stocks. So great are the productivity increases in aquaculture that it is referred to by some as a "blue revolution" that promises to transform food production as the "green revolution" in agriculture did a century earlier (FAO/NACA, 2012).

The benefits arising from the rapid growth in aquaculture have been accompanied by serious environmental, social and production challenges.[3] Reliance on fish feeds remains an issue in most countries as they are often derived from scarce wild resources. The social impact of aquaculture is multi-faceted: it creates new job opportunities but can also mean the end of traditional jobs and socially valued skills. There are also constant challenges in terms of fish health, rearing and containment. To grow and fulfil the promise of a blue revolution, aquaculture will need to balance its long-term environmental sustainability with its present goal of growing large fish rapidly.[4] Marine biotechnology may help to achieve and reconcile these two imperatives.

Marine biotechnology, in the form of new vaccines and molecular-based diagnostics, has already helped to increase production, reduce the use of antibiotics and improve fish welfare (Sommerset et al*.,* 2005). In many places, the use of antibiotics has plummeted. In Norway 99% of farmed salmon are produced without the use of antibiotics (Figure 2.1). In other countries, however, especially developing countries without access to molecular-based tools and technologies, use of antibiotics remains widespread (Cabello, 2006).

Figure 2.1. The decline of antibiotic use in Norwegian salmon farming



Source: Petter Arnesen (Marine Harvest ASA) at the OECD Global Forum on Marine Biotechnology: Enabling Solutions for Ocean Productivity and Sustainability, held in Vancouver, Canada, 30-31 May 2012.

The application of new genomic knowledge and technologies to the practice of aquaculture is termed “molecular aquaculture” to help to distinguish it from the more production-oriented activities in aquaculture such as improved feeding systems, cage design and husbandry.[5] Molecular aquaculture is characterised by the incorporation of new “omic” knowledge, high-throughput genomics technologies and recombinant DNA technology. These technologies have facilitated selective breeding for economically important traits such as body shape or disease resistance.

Whole-genome knowledge arising from genome sequencing projects (such as for cod or Atlantic salmon) is providing new inputs for marine biotechnology and new opportunities for aquaculture and wild stock management regimes. Genomic knowledge is being used to study species which are not currently the focus of large-scale cultivation efforts in order to identify new species for culture. Genomics is improving understanding of these species – their life cycle, nutritional requirements, pathogen susceptibilities – and providing a basis for developing improved feeds (e.g. less reliant on fish oils), production methods and fish health tools.

Genomic and related technologies have also been used to create new DNA-based vaccines for economically important diseases (e.g. Apex®-IHN, Novartis, for the treatment of infectious hematopoietic necrosis in farmed salmon) and highly sensitive specific tools for disease detection (Cunningham*,* 2002).

More controversially, recombinant DNA technology has been used to modify fish genetically. Like genetically modified (GM) crops, fish may be modified by the inclusion of genes from other species to improve productivity traits. This may prove to be a way forward in at least some jurisdictions. In the United States, the Federal Drug Administration (FDA) is moving closer to approving the first GM salmon, which contains a growth hormone gene from a related species which allows the salmon to grow to market size in half the normal time.

Molecular aquaculture holds great potential for increasing sustainable food production to meet anticipated increases in global demand through the culture of species such as salmon, tilapia, shrimp and oysters. However, molecular aquaculture is developing and diffusing at different rates in different countries, potentially limiting the productivity gains and sustainability of the endeavour. Developing countries face challenges for accessing new technologies and financial capital while more developed countries face challenges associated with public support and public-private partnerships. These challenges will need to be addressed if molecular aquaculture is to reach its potential.

Health: Biomedical, pharmaceutical and nutraceutical applications of marine biotechnology

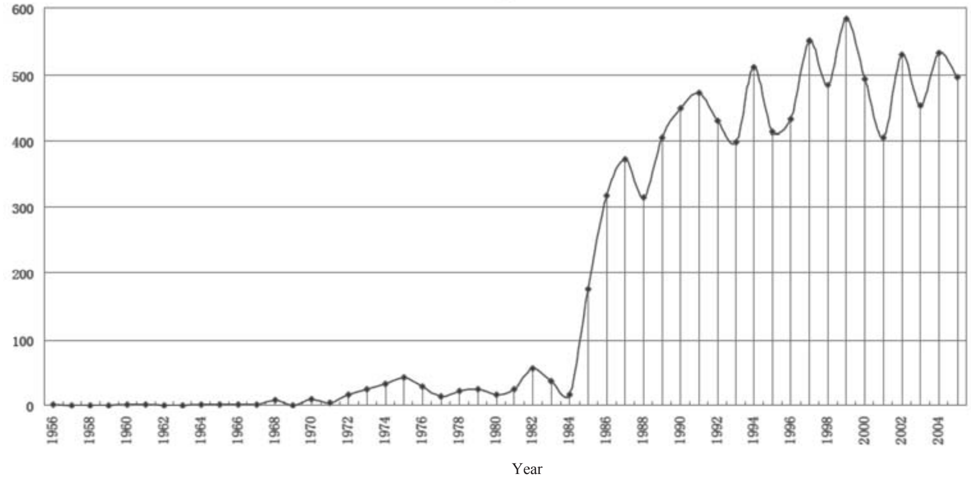
Countries' grand challenges in terms of health and well-being vary (Varmus et al., 2003; Daar et al., 2007; World Health Organization, 2012; http://grandchallengesgmh.nimh.nih.gov/). In developing countries, infectious disease and the cost of treatment and vaccination regimes are leading challenges, while developed countries must deliver appropriate services to ageing populations and face increasingly stratified disease and greater incidence of drug resistance. As the world's population is ageing and growing, these challenges will only increase, but pharmaceutical companies struggle to meet new demands. To improve the health of the world's citizens, there is a need for new and more effective drugs and natural products to support citizens' health and well-being.

Since the identification of bioactive nucleosides from marine sponges over five decades ago (Bergman and Freeney, 1950, 1951; Bergmann and Burke, 1955), well over 20 000 novel marine natural products[6] from marine organisms have been discovered (Hu et al., 2011). Some marine organisms contain, or produce, bioactive or structural compounds that can be used to manage pain or reduce inflammation, to treat cancer or other diseases, as new materials for dressing wounds, or to regenerate tissue. Marine sponges or symbiotic microbes have been used as sources of products, as have fungi and, increasingly, marine bacteria.

Chitin, obtained from the shells of crabs, lobsters and the internal structures of other invertebrates, has anti-bacterial, anti-fungal and anti-viral properties which make it attractive for use in medical materials such as wound dressings and surgical sutures (Jayakumar et al., 2010). Certain siliceous sponges are of interest because of their ability to form silica skeletons. Silica from these organisms and, increasingly, the blueprints for silica skeleton formation, are finding use in a range of biomedical applications such as coatings for metal implants used in surgery, adhesives for drug delivery, and microelectronic fabrication (Andre et al., 2012). Similarly, the agar derived from macroalgae is being used in drug encapsulation, and collagen-based marine sponge skeletons have potential uses in bone repair (Zheng et al., 2007).

The isolation of bioactive arabinonucleosides from the sponge *Tethya crypta* in the 1950s led to the development of two synthetic drugs, Ara-C (against leukaemia) and Ara-A (for treating viral infections). Despite this promising start, it was not until 2004 that the next marine-derived drugs, ziconotide (Prialt®), isolated from cone snails, and trabectedin (Yondelis®), isolated from sea squirt, were commercialised. The conotoxin in cone snail venom is usually lethal to humans, but in small quantities it can be a useful anaesthetic or analgesic or be used in drugs for conditions such as epilepsy and psychiatric disorders. Today, there is strong commercial interest in conotoxins, and 251 patents and patent applications have the term “conotoxin” in the title.[7]

Figure 2.2. Trends in novel products obtained from marine organisms (number of products)



Source: Hu et al. (2011), “Statistical Research on Marine Natural Products Based on Data Obtained between 1985 and 2008”, *Marine Drugs* 9(4): 514–525. doi: http://dx.doi.org/10.3390/md9040514.

Genomics are providing new insights into the genetic diversity of marine bioresources and revealing new sources of drugs (Trincone, 2011). As a result, the number of promising marine-derived compounds or secondary metabolites is increasing rapidly and some are already in the drug development pipeline (Figure 2.2). From 1998 to 2006, the pipeline included 592 marine compounds with anti-tumour and cytotoxic activity, and 666 additional chemicals with pharmacological activity (anti-bacterial, anti-coagulant, anti-inflammatory and anti-fungal, as well as effects on the cardiovascular, endocrine, immune and nervous systems) (Mayer et al., 2010).[8]

The marine-related pre-clinical pipeline for drug development is growing and becoming truly global; investigators from 32 countries were involved in 2007-08 alone. By 2010, there were over 36 marine-derived drugs in clinical development, including 15 for cancers. Close to half of all current anticancer discovery efforts focus on marine organisms. Two years later, seven marine derived drugs had received FDA approval, eleven drugs were in clinical testing and 1 458 were in the clinical pipeline.[9]

Marine microbes, and bacteria in particular, are the focus of much attention, as they are increasingly seen as a particularly rich source of bioactive compounds (Gokulkrishnan et al., 2011). This is due both to the complex nature of marine ecosystems and to estimates of undiscovered bacteria in the marine environment.[10] As most existing drugs are derived from terrestrial sources, marine resources, particularly marine microbes, are a largely untapped resource (Chin et al., 2006; Newman and Cragg, 2007).

Marine biotechnology may thus make significant contributions to the development of new antibiotics, anticancer and immune system modulators. Antimicrobial resistance due to widespread use of antibiotics for human health and agriculture is a serious health threat and is the focus of increasing public and government concern. The World Health Organization (WHO) has identified this as one of the three main threats to human health. The problem is likely to get worse as there are few new candidate drugs in development; bacteria are becoming resistant to antibiotics faster than effective replacements can be developed (Dwyer et al., 2009).

Pharmaceutical development relies more on exploitation of new compounds discovered through metagenomics and screening of marine biobank samples for bioactivity. The major bottlenecks in the marine pharmaceutical pipeline include insufficient funding for basic marine pharmacology and technical challenges for the characterisation of unknown taxa and gene functions. Several groups have R&D programmes to develop novel antibiotics through the isolation and characterisation of potent substances from the sea. In 2006, the Scripps Research Institute launched a programme of antimicrobial R&D running from initial discovery to development and testing to clinical trials.

Table 2.1. Functional food from marine biomass

Ingredient	Studies
Fish	
LC n-3 PUFA (omega-3 fatty acids)	The metabolic syndrome, cancer, Inflammatory diseases, brain function(dementia and macular degeneration / schizophrenia / depression), effects during pregnancy
Marine phospholipids	Therapeutic effect on brain, suppression of cancer
Vitamin D	Bone health, Inflammatory diseases, cancer, brain, pregnancy
Selenium (Se)	Immune system, viral infections, reproduction, thyroid function, mood, cancer, mammary gland (rats),colon cancer
Fish peptides and hydrolysates	High blood pressure, low immune response, cancer anaemia
Selected amino acids in fish	Atherosclerosis, blood lipids, inflammation, oxidative stress, diabetes II
Fish proteins	High blood pressure, lipid metabolism, obesity/metabolic syndrome, glucose and lipid metabolism, insulin sensitivity
Shellfish	
Chitosan and glucosamine	High cholesterol, infection, cancer, low immune response, wounds, Alzheimer's disease
Chondroitin sulphate	Osteoarthritis, obesity/weight loss, cancer, oxidative stress, neuro-related diseases
LC n-3 PUFA fortification	Preterm infants, term infants, fortification increases intake, lipid peroxidation
Seaweed	
Proteins, peptides and amino acids	High blood pressure, low immune response obesity/metabolic syndrome, glucose and lipid metabolism
Fatty acids	Heart diseases, inflammatory diseases
Polysaccharides Sulphated fucan Sulphated galactan	Oxidative stress, virus, cardioprotective
Metabolites Polyphenols Steroids	LDL cholesterol, valuable curative properties, anti-oxidant, anti-diabetic, anti-inflammatory
Vitamins Vitamin C Vitamin E	Oxidative stress
Pigments Carotenoids Chlorophylls	Cerebro-vascular diseases, metabolism, obesity, diabetes

Marine bacteria are, however, not the only potential source of new drugs. Other marine microbes, aquatic plants and larger marine organisms are also a focus of pharmaceutical research. The discovery and development of novel bioactives from marine sources is accelerating owing to recent advances in high throughput screening and metagenomic analysis, and compounds from harmful algal blooms are showing promise in pharmaceutical terms (Waters et al., 2010).

Nutrients, enzymes, metabolites and other compounds from marine bioresources are also contributing to nutraceutical applications and the development of functional foods. Macroalgae, fish and even bacteria are used as sources of essential fatty acids, including arachidonic acid (ARA) and docosahexaenoic acid (DHA). Vertebrates and shellfish are good sources of calcium or chitin (and derivatives such as glucosamine) which have found application as nutritional supplements or aids. Marine organisms also produce a number of metabolites and active compounds that can be incorporated in a range of nutraceuticals containing active ingredients such as antioxidants, essential oils and vitamins that support good health (Table 2.1).

As functional foods are largely biomass-based, they require relatively less investment and research intensity than pharmaceuticals. Documentation of the effects of functional foods/nutraceuticals is a neglected area but has the potential to add much value to these products. Functional foods have relatively strong market penetration and public acceptance, but their commercialisation will require the development of sustainable culture, capture or harvesting as well as appropriate extraction and preservation methods.

Fuel security: The use of marine organisms to produce sustainable and renewable energy

Most OECD and many non-OECD economies are committed to reducing their carbon footprint. Many OECD members are turning to renewable biomass to supplement, and perhaps eventually replace, some petroleum-based feedstock. For different countries, this move may be driven by issues relating to fuel security or economic vulnerability.

Biomass is a biological source of organic carbon (e.g. wood, plants, animal matter and a variety of organic solids including industrial and agricultural waste) which can be used directly or converted into energy products such as biofuel and biogas. Biomass is therefore a renewable source of energy, and conversion of biomass into biofuel is one instance of agricultural or industrial biotechnology.

First-generation biofuels, such as biodiesel made primarily from grains, seeds or commodities such as maize and sugar cane, are produced in many parts of the world. These biofuels have been criticised for diverting food sources away from the human food chain and for creating unsustainable patterns of land use.[11] Second-generation biofuels, also called advanced biofuels, are the same end product but are considered more sustainable. They are derived from sustainable sources (e.g. non-food crops and waste biomass) and/or have a lower carbon footprint than first-generation biofuel feedstocks. They therefore lessen the concerns raised by the latter. Although they raise fewer sustainability issues, they create development and commercialisation hurdles, largely owing to the difficulty of extracting the useful sugars locked in the fibrous biomass.

In 2008, the OECD published an economic assessment of second-generation biofuel support policies (OECD, 2008). It concluded that government support of biofuel production in OECD countries is costly, has a limited impact on reducing greenhouse gases and improving energy security, and has a significant impact on world crop prices. The report concluded that other forms of bioenergy, such as bioheat, biopower and biogas, would represent more economically viable and environmentally sustainable ways to reduce greenhouse gases.

To become economically and environmentally viable, biofuel production will need to address technical and commercial challenges such as treatment or disposal of by-products, carbon neutrality, production and capital costs, scale-up, and integration with existing infrastructure (Coyle, 2010). Algal biofuels, also known as third-generation or next-generation biofuels, may address some of these challenges and make biofuels more economically viable and environmentally friendly.

Algae biomass may be composed of either microalgae or macroalgae (seaweed). Algal biofuels result from the application of marine biotechnology to algae biomass to generate biodiesel, bioethanol, biogasoline, biomethanol, biobutanol and other biofuels. Algae biomass offers many of the advantages associated with first- and second-generation cellulosic biomass and lacks lignin, a plant material whose presence in cellulosic biomass presents significant processing challenges. This is the most technologically significant advantage of algal biomass for biofuels. Other advantages of algae biomass include the fact that its production is not geographically limited and its cultivation can avoid competition with food production. Adoption of algal biofuels can rely in part on investments and infrastructure developed to accommodate first- and second-generation biofuels.

The use of algae for biofuels is attractive for many reasons. Algae may produce more energy/tonne and may be grown more quickly (typically in 1-10 days) than conventional crops such as soybean or cotton (Potters et al., 2010). Theoretical calculations of biofuel production vary, yet production of ethanol from algae is widely considered to exceed production from terrestrial crops (Scott et al., 2010; Tan et al., 2011) (Table 2.2). Cultivation of microalgae may also have a smaller physical footprint than comparable land-based biomass. It has been estimated that no more than 39 000 km^2 of algae, an area corresponding to the Sea of Azov or to around 10% of the land surface of Germany, would be sufficient to replace all the petroleum fuel in the United States (Potters et al., 2010).

While algal biofuels require fertilisers or organic material, these can be carbon- or nitrogen-rich waste gas streams and provide an opportunity to biofix these greenhouse gases before they enter the environment (Mussatto et al., 2010; Ho et al., 2011). Algae can be produced using ocean and waste water, obviating the need for fresh water. Microalgae can also be produced on land, and algae are biodegradable if released into the environment as waste (Christenson and Sims, 2011).

Table 2.2. Theoretical calculations of biofuel production from different crops

Crop	Oil yield (l ha^{-1})	Land area needed [1] (M ha)	% of existing US cropping area
Corn	172	1 540	846
Soybean	446	594	326
Canola	1 190	223	122
Jatropha	1 892	140	77
Coconut	2 689	99	54
Oil palm	5 950	45	24
Microalgae[2]	136 900	2	1.1
Microalgae[3]	58 700	4.5	2.5

1. To meet 50% of all transport fuels needs in the United States. 2. 70% oil (by weight) in biomass. 3. 30% oil (by weight) in biomass.

Source: T. Tan, J. Yu and F. Shang (2011), "2.58 - Biorefinery Engineering", in *Comprehensive Biotechnology* (Second Edition), Vol. 2, pp. 815-828.

Microalgae may be grown in ponds or photobioreactors and may be used as feedstock for several renewable fuels. Marine biotechnology clearly has a role to play in the successful development of algal strains. The biochemical composition of algae may be modified by altering bioreactor-based growing conditions to produce valuable co-products such as proteins and residual biomass. Growth conditions and extraction processes need to be further developed before algal biofuel production will be commercially viable (Day et al., 2012). The economic feasibility of these processes needs to be addressed and a full life-cycle analysis is needed to study carbon dioxide production, the biofixation ability of microalgae strains, and the stability of these strains under production conditions (Brennan and Owende, 2010; Ho et al., 2011). Further applications of marine biotechnology, potentially including the genomic modification of algal strains to suit production scenarios or the harvesting of other bioactives in the fuel extraction process, will undoubtedly be required for commercialisation on a wide scale. Adaptation of the biorefinery concept to marine raw materials offers one approach to addressing these challenges.

Macroalgae-based biofuels present similar but slightly different opportunities and challenges. Macroalgae are a readily accessible source of biomass, their culture and production methods are well developed, and the supply chain is well established. However, the physical footprint of macroalgae is larger than that of microalgae and, because it is more amenable to growth in the ocean, there are challenges in terms of containment and interaction with facilities such as fisheries and wind farms. Challenges in terms of biofuel extraction and waste are being addressed. Bio Architecture Laboratories (BAL) has recently engineered a microbe to degrade and a pathway to metabolise alginate, the most abundant sugar in seaweed (Wargacki et al., 2012). Alginic acid/alginates constitute 20-30% of the total dry matter content of brown seaweeds. The BAL platform can convert seaweed carbohydrates into a renewable chemical intermediate that is scalable and can be used to produce both fuels and a variety of chemicals for green plastics, surfactants, agrochemicals, synthetic fibres and nutraceuticals.

Although currently more expensive than other biofuels, algal biofuels represent a novel marine biotechnology which has passed the proof-of-concept stage (Mussatto et al., 2010) and is now the focus of significant activity in the private and public sectors. Apart from the technical challenges noted above, commercialisation of biofuels and biochemicals faces two major challenges. On the investment side, the slow pace of decision making and the level of crossover among funding domains impede progress; on the market externality side, biofuel companies compete against 100 years of technology development and substantial government support in the oil and gas sectors.

Critical questions remain concerning the viability of using algae for large-scale biofuel production. A recent German report (Leopoldina, 2012), for instance, argued that the oceans are unsuitable as a source of biomass for large-scale biofuel production owing to the rapid turnover of unicellular phytoplankton as a result of grazing by zooplankton. To answer questions regarding viability will require a detailed life-cycle analysis (LCA) that provides internationally acceptable performance data. While algae have many advantages, a detailed analysis may reveal further problems. For example, the use of fertiliser releases nitrogen-based GHGs with a much higher global warming potential than CO_2, and the extent of the problem will depend on the rate of application of fertiliser.

Aside from the production of renewable biofuels, marine biotechnology may be used to make the extraction of fossil fuels more efficient. Extraction of fossil fuels is often relatively inefficient because of the porosity of the rock or the viscosity of the crude oil. Only a fraction of the oil in the oil fields tapped to date has been removed, and reservoirs with a large percentage of oil are often abandoned owing to the increasing difficulties of extraction as the reservoir is exploited. Marine microbes can be used to increase the efficiency of oil recovery by decreasing the viscosity of the oil or increasing the permeability of the rock material in the reservoirs. While microbial enhanced oil recovery (MEOR) is still controversial,[12] it is another way in which marine biotechnology can contribute to addressing the global challenge of energy security (Brown, 2010).

Microalgae, macroalgae and bacteria have also shown their utility in microbial fuel cells, i.e. systems that harvest the electricity generated by microbial metabolism (Reimers et al.*,* 2001; Girguis et al.*,* 2010).

Industrial processing: Applications in research, manufacturing, processing and other sectors

Pressures to reduce GHG emissions and improve environmental sustainability have prompted significant investment in the development of sustainable industries as a source of green growth. Tools based on marine biotechnology can be widely used in industrial processing and manufacturing and can play an important role in global green growth efforts. Many marine organisms, or their products, including several of those mentioned above, are good sources of novel enzymes, biopolymers and biomaterials. Bioactive molecules, compounds or enzymes can be cultured or harvested directly as feedstock from marine sources or used to synthesise analogues.

For example, in addition to their fuel potential, algae and other marine biomass represent largely untapped alternatives to so-called platform chemicals and even functional food products. Microalgae are rich in polyunsaturated fatty acids (PUFA), a vegetable alternative to fish oils and oils rich in omega-3 fatty acids. They may therefore find application in fish feed and products for human consumption prior to the esterification needed for biofuel production.

Chitin, a polysaccharide consisting of units of N-Acetyl glucosamine, is a marine resource that has found wide application (Jayakumar et al.*,* 2010). Obtained from the shells of crabs, lobsters, shrimp and the internal structures of other invertebrates, chitin and its d-acetylated form chitosan are used as stabilising agents in foods and cosmetics, to treat water for food preservation, and in antifouling applications.

Most of the 3 500 enzymes identified from microbial sources so far are from terrestrial sources. Those identified in the marine environment have tended to come from organisms living in environmental extremes and have a wide range of applications in industrial and agricultural processing.

Biosurfactants and bioemulsifiers are two important bioactive compounds derived from bacteria. These amphiphilic compounds display a range of surface activities that allow for the solubilisation of hydrophobic substrates. They are produced by a huge variety of bacteria and have a wide range of structural and functional forms. Depending on their form they have a range of potential industrial and environmental applications (e.g. emulsification, detergency, dispersion and solubilisation of hydrophobic compounds) which are of interest for replacing synthetic surfactants (Satpute et al., 2010).

Similarly, bacteria-derived exopolysaccharides,[13] high molecular weight polymers secreted by bacteria, are being considered as substitutes for synthetic or plant and algal gums (including marine-derived carrageenan). Bacteria-derived gums have properties similar to plant and algal gums and can be used for stabilisation, gelling, adhesion, thickening and many other industrial applications. For example, xanthan gum, from the bacterium *Xanthomonas campestris*, is widely used in foodstuffs and cosmetics. It is used in large quantities during drilling for oil, particularly in horizontal drilling, as a mud thickening agent with excellent rheological properties. Marine bacteria are expected to be a valuable source of new exopolysaccharides with diverse and useful functional and structural properties.[14]

Bacteria-derived silicas, in the form of novel biosilicas with unique electrical, optical and catalytic properties, also have great potential in nanomaterials. Marine-derived silica may be used as a carrier or stabiliser of manufactured products, can confer unique properties to adhesives or paints, and may be used as an insulator or filler of materials.

Marine biotechnology applications are also a source of new products for conducting biological research. Agar and agarase from macroalgae are stable for culturing, while polymerase enzymes such as *Thermus aquaticus* isolated from thermal vents in the marine environment are of use in the polymerase chain reaction (PCR) used to amplify small amounts of DNA. The bioluminescence compound aequorin and the fluorescent molecule GFP (green fluorescent protein) isolated from jellyfish have also found applications as probes and in imaging applications in life science research. Bioluminescence has a range of environmental applications as luminescent bacteria can be used to detect contaminants in wastewater and soil.

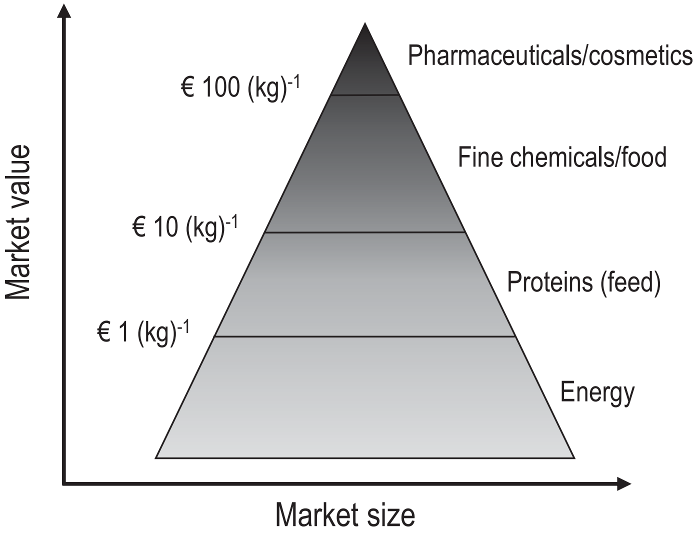
Other environmental applications of marine biotechnology cover environmental monitoring and bioremediation (discussed below) and biofouling. Biofouling can reduce the fuel efficiency of transport vessels; in aquaculture, it can reduce the functionality of nets and corrode and destabilise marine structures. Biofouling generates an economic expense, but attempts to overcome it may harm the environment. Paints designed to reduce biofouling and agents to clean biofouled materials (e.g. aquaculture nets) are often toxic and harmful to the environment. Marine biotechnology may lead to the development of naturally occurring marine organisms or derivatives that prevent biofouling. Rocks or crustaceans devoid of barnacles and other biofouling, often found in coastal regions, are an obvious source of such organisms. In addition to being eco-friendly, the products may be more effective than existing chemical products.

Marine biorefineries

There is considerable speculation regarding the business model and economics of biorefineries based on marine raw materials. The most attractive approach involves integration of all components in a global business model. In the integrated marine biorefinery, biofuel is one product but more valuable feed, food and other materials are also produced (Figure 2.3), and indeed may have to be produced to make the refinery financially viable. As in petrochemical refineries, profit margins on bulk production fuels are likely to be low, and higher revenues from high-value, low-volume materials make biorefining more attractive.

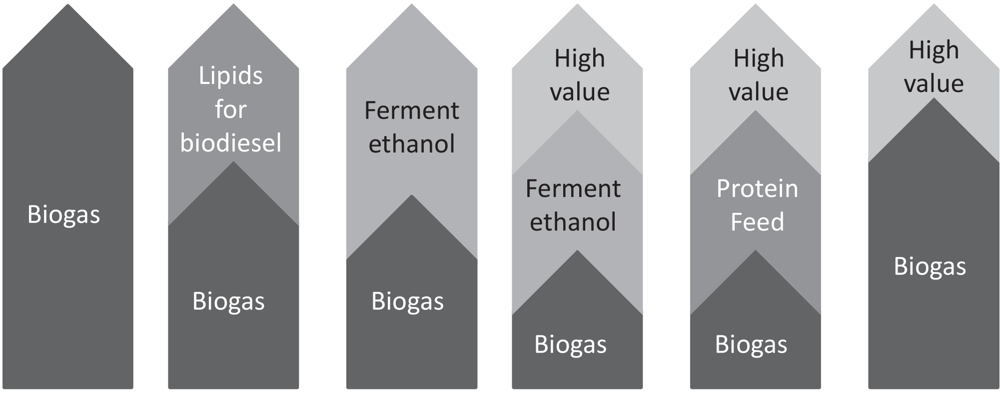
There are also opportunities for applying biorefinery-type processes to extract commercial products from microalgal biomass. Microalgal biomass cultivated for its lipid content for conversion to biodiesel offers several possibilities for obtaining additional commercial materials such as fermentation to obtain ethanol (low conversion rates) and biogas. It is also possible to produce protein-rich feed for animal and human consumption. Figure 2.4 shows some permutations of the integrated marine biorefinery concept. The design and engineering principles for marine biorefining are in their infancy compared to biorefineries for terrestrial crops.

Figure 2.3. Value pyramid for marine biotechnology products



Source: Sustainable Energy Ireland (2009), “A review of the potential of marine algae as a source of biofuel in Ireland”, *Sustainable Energy Ireland*, Dublin, February.

Figure 2.4. Permutations of the integrated marine biorefining concept



Source: Sustainable Energy Authority of Ireland (SEAI) (2009), “A review of the potential of marine algae as a source of biofuel in Ireland”, *Sustainable Energy Authority of Ireland (SEAI)*, Dublin, February.

Ecosystem goods and services from marine resources

Marine bioresources provide a number of important ecosystem goods and services for the planet and its inhabitants. Costanza et al. (1997) classified 17 different ecosystem services and estimated that marine systems contribute about 63% of value (USD 20.9 trillion a year), mostly from coastal systems. Marine organisms (microalgae, fish and invertebrates) are a source of food for billions of people and livestock. The oceans are well known as regulators of global temperatures and filters of pollution. They are also sinks for carbon and nitrogen, and a source of oxygen and food.

Living in the ocean's surface water, in easy reach of light, phytoplankton are estimated to produce half of the oxygen breathed by humans and animals. In addition, they have an important place in the food web and play a valuable role in carbon cycling by locking away carbon dioxide and nitrogen, which is eventually deposited on the ocean bottom, thereby slowing the impact of global warming. The ecosystem services provided by the marine environment are attributable to its vast size and to a large extent to its complex ecosystems and biodiversity.

However, the oceans' bioresources and biodiversity increasingly face direct and indirect threats (see Chapter 1) that could disrupt marine ecosystem services. It is therefore most important to preserve the marine environment and its bioresources. Marine biotechnology can play an important role in reaching these goals.

Marine-derived biosensors can help to monitor the marine environment. Biosensors are devices composed of a biological sensing component linked to a signalling component which can reveal the presence of an element, molecule or organism of interest. They can detect changes in analytical or biological parameters and may be useful for detecting quickly the presence of invasive species that can disrupt marine ecosystems and the habitats of marine or terrestrial organisms. In 2011, a team at the Virginia Institute of Marine Science reported the creation of a portable biosensor that could detect marine pollutants, including oil, much more quickly and cheaply than current technologies (Spier et al., 2011). If deployed near oil facilities, such sensors could provide early warning of spills and leaks and track dispersal patterns in real time.

Marine biotechnology can also contribute to the preservation of the marine environment and ecosystem services through the development of DNA-based monitoring tools (Bott et al., 2010). These tools have a range of applications; they enable the detection of genetically modified organisms and aquaculture escapees, validate the identity of species, and alert environmentalists to the presence of invasive species.

Beyond monitoring of the marine environment, marine biotechnology has a role in remediation. Researchers are screening naturally occurring microbial populations in the marine environment to identify bacteria that metabolise certain types of hydrocarbons. These bacteria can be used to break down pollutants without any danger to the ecosystem as they occur naturally in the environment.

Although bioremediation has seen some promising advances, there is room for improvement. It is often slow and may not perform consistently under different environmental conditions, such as variation in temperature and wave strength. Bioremediation is often boosted by additives that enhance the activity of endogenous microbes that degrade hydrocarbon compounds (biostimulation) or by the addition of new oil-degrading bacteria (bioaugmentation). Biostimulation was used successfully during the Exxon Valdez oil spill, through the application of fertiliser to more than 120 km of oiled shoreline (Bragg et al., 1994). However, such processes may not be suitable under all circumstances and their effectiveness may vary depending on the form of hydrocarbon, volume of spill, and wind and sea conditions. Indeed, they may cause further damage to fragile marine environments. Genetic manipulation of these bacteria and/or identification of new bacteria with appropriate remediating abilities are now a focus of marine biotechnology research.[15]

Conclusions: Marine biotechnology for people and planet

The outlook for marine biotechnology has changed profoundly over the last decade in large part owing to advances in science and technology, in particular the "omic" sciences. These advances provide new insights into marine bioresources and improve the ability to access, manipulate and develop these resources to address some of today's grand challenges. Ocean bioresources are no longer viewed solely as a source of food but more as a vast reservoir of a diversity of organisms and genes with virtually unlimited potential for development and exploitation. Under the right conditions, marine biotechnology may provide new foods and food production methods, new health products, sustainable renewable energy alternatives and new sustainable industries.

The application of marine biotechnology to marine biomass – fish, shellfish, macroalgae and microalgae, related waste – provides new opportunities for improved and expanded food production, development of sustainable biofuels and new natural products for health and well-being. Perhaps the biggest challenge to biomass-based development is the need to harvest biomass in a sustainable manner. A number of contemporary examples of overfishing (e.g. cod fisheries in Newfoundland, anchovy fisheries off the coast of Peru) illustrate the economic, social and ecosystem damage that can be done by unsustainable harvesting of marine biomass. Marine biotechnology can help to ensure the sustainable use of biomass through the development of new culture, production and processing techniques and practices.

The genetic diversity of marine bioresources, in particular of marine microbes, provides a wide array of opportunities and challenges for marine biotechnology. It holds significant potential for discovering new bioactive compounds with wide applicability in drugs and in greener, more sustainable industries. The need to develop marine resources in a sustainable way remains, but, for marine microbes, it is prefaced by the need to access and characterise these genetic resources in a complex and dynamic ecosystem. Here the need is to sift through and translate huge amounts of data in order to understand and develop these resources effectively. Genomics and related tools are providing a means to access and characterise these resources, but this work will clearly become more efficient and effective with greater understanding of the complexity of marine bioresources.

Marine resources are crucial for the survival of the planet and the quality of these resources can be affected positively or negatively by the actions of many countries. Because marine bioresources are inextricably linked to the ecosystem services the ocean provides to the planet and its inhabitants, it is essential to preserve their integrity and biodiversity. Marine biotechnology can provide a means of monitoring and even remediating the marine environment through biosensor and bioremediation applications. Such applications are essential for understanding and predicting changes in this environment and for conserving and managing the coastal and marine resources that are critically important to a bioeconomy.

While the potential for marine biotechnology is clear, delivering on its promise may require the attention of governments, policy makers and others. Put simply, the challenge is to extract value from resources that are spread widely across a complex marine ecosystem while maximising the integrity and sustainability of that ecosystem for future generations. Policy work to ensure the protection and appropriate development of shared marine resources is a global imperative and actions are most likely to be effective if they are harmonised across countries.

Notes

1. www.fao.org/wsfs/forum2050/wsfs-forum/en/, and www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf.
2. www.fao.org/fishery/topic/3380/en.
3. Many OECD countries have recognised the importance of sustainable aquaculture (e.g. OECD Workshop on Advancing the Aquaculture Agenda: Policies to Ensure a Sustainable Aquaculture Sector, April 15-16, 2010).
4. The development of environmental performance standards for aquaculture sites and the development of integrated multi-trophic aquaculture are helping to improve the situation (Chopin, 2010).
5. Introduced by the Co-ordinated Working Group on Marine Biotechnology under the KBBE-net, 2009, http://ec.europa.eu/research/bioeconomy/pdf/cwg-mb_to_kbbenet_report_final.pdf.
6. Chemical compound or substance produced by a living organism in nature.
7. www.espacenet.com, accessed August 2012.
8. See *The Global Marine Pharmaceuticals Pipeline* at http://marinepharmacology.midwestern.edu/.
9. www.oecd.org/sti/biotechnologypolicies/Session%204%20Mayer.pdf.
10. Products such as the polyketide bryostatin-1 first isolated from *Bryozoa* are now known to be a secondary metabolite from associated bacteria (Waters et al., 2010).
11. Brazilian biofuels derived from sugar cane waste escape the negative press coverage accorded first-generation biofuels.
12. MEOR is a controversial practice: there have been many claims of success but also failures. There is no defined standardised technology, and field trials, often using dubious products, have varied widely in quality. Trials may not have been conducted on the most appropriate wells and reservoirs, and monitoring the operations can be very time-consuming and costly. Further, the trials are often conducted during routine oilfield operations so that it is difficult to gather robust data. Nevertheless, interest in MEOR persists as it may offer an inexpensive option for EOR, and improved recovery of even a few percent can amount to large

quantities of oil and profit over the extended working life of an oil reservoir.

13. Marine plants and macroalgae are also a good source of exopolysaccharides which are used in a number of industrial applications.

14. For example, some *Bacillus* species produce exopolysaccharides with antimicrobial properties.

15. The OECD worked on bioremediation technologies as early as the 1990s, and the 2010 Rimini workshop on Environmental Biotechnology also addressed hurdles to successful uses of such applications.

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