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Microencapsulated diets to improve bivalve shellfish aquaculture for global food security

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ABSTRACT

There is a global need to sustainably increase aquaculture production to meet the needs of a growing population. Bivalve shellfish aquaculture is highly attractive from a human nutrition, economic, environmental and ecosystem standpoint. However, bivalve industry growth is falling behind fish aquaculture due to critical problems in the production process. Feed defects, disease, and quality issues are limiting production. New advances in microencapsulation technology have great potential to tackle these problems. Microencapsulated diets could efficiently deliver high-quality nutrients, disease control agents, and quality enhancers to bivalves. Microencapsulation has the potential to drive improvements in bivalve production, reduce production costs, enhance human nutrition and minimise impacts on the environment.

1. The global importance of bivalve shellfish aquaculture

1.1. Bivalves a strategic food source to sustainably feed a growing global population

Over 800 million people worldwide are hungry, one billion have inadequate protein intake, and an even greater number suffer from nutrient deficiencies (FAO, 2015). By 2050 these and 2.5 billion additional people will need access to nutritious food ("United Nations Population Division. World Population Prospects," 2017). Consequently by 2050 both total food demand and animal protein demand are expected to double (Jennings et al., 2016). Terrestrial meat production has tripled over the last 40 years to keep pace with demand (Stoll-Kleemann and O'Riordan, 2015). But this growth is unsustainable; terrestrial meat production is a major driver behind humanity exceeding safe biophysical thresholds for the planet, and already uses 70% of agricultural land and 30% of freshwater, and causes 18% of greenhouse gas emissions and 30% of biodiversity loss (Campbell et al., 2017; Stoll-Kleemann and O'Riordan, 2015). Expanding aquaculture is seen as a possible solution and has been identified as a critical component in securing food for 9.8 billion people by 2050 (Godfray et al., 2010; Troell et al., 2014; Waite et al., 2014).

Globally over 3 billion people depend on aquaculture for at least 20% of their dietary protein (Troell et al., 2014). Over the last decade animal aquaculture production has grown at 5.6% per year to 78 million tonnes, was worth US$ 160 billion in 2015, and is the world's fastest growing food sector (FAO, 2017; Jacquet et al., 2017; Tacon and Metian, 2013; Troell et al., 2014). However, like terrestrial meat production aquaculture is currently expanding in an unsustainable way (Godfray et al., 2010; Jacquet et al., 2017). Production quantity of carnivorous species such as salmon, catfish, and shrimp has ballooned, growing 84% over the last decade, and today salmon is the largest single commodity in aquaculture (FAO, 2017, 2016). Production of these species is reliant upon fish meal and fish oil from wild-caught fish, with 5 kg of wild-caught fish required to produce 1 kg of farmed salmon (Bostock et al., 2010). Wild fish stocks are suffering; 31% of stocks are overfished and a further 60% fished to their biological limit (FAO, 2016). Total capture of wild fish has been static since the 1980s despite increased fishing effort (FAO, 2016).

To sustainably provide food for a growing global population, there is a great need for aquaculture to focus on species lower in the food web that require little or no fish as feed (Jacquet et al., 2017) (Godfray et al., 2010). Bivalve molluscs offer one of the most attractive options for meeting this sustainability need. In 2015 14.8 million tonnes of bivalves were produced globally, and if bivalve aquaculture was to grow at the same rate as predicted for carnivorous fish aquaculture over the next decade, an extra 13.1 million tonnes of bivalves would be produced per year, feeding nearly twice as many people as bivalves do today (FAO, 2017).

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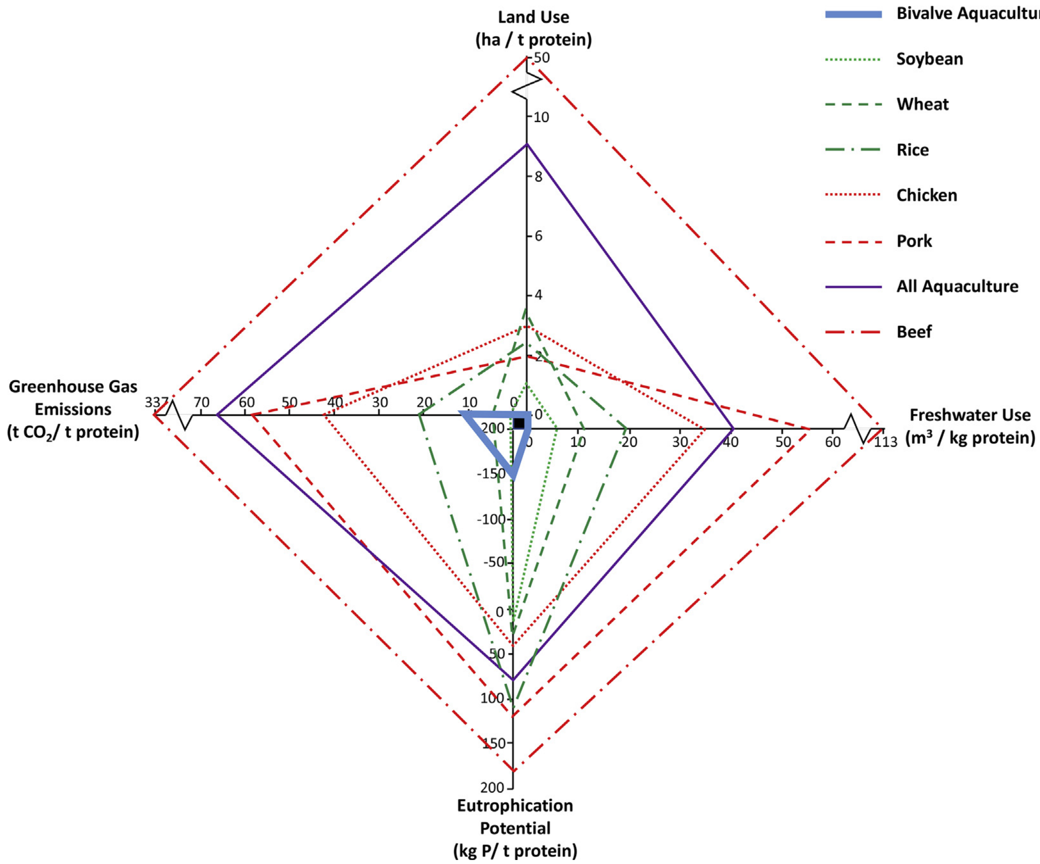

Fig. 1. The lower environmental footprint of bivalve aquaculture compared to other plant and meat food sources. Raw data for animal meats from (Waite et al., 2014). Freshwater consumption data for plant crops from (Mekonnen and Hoekstra, 2014) and converted from tonnes food to tonnes protein using ("USDA Food Composition Databases. United States Department of Agriculture Agricultural Research Service," 2017). Greenhouse gas emissions, land use, and eutrophication potential data for plant crops from (Clark and Tilman, 2017). Note the broken axes due to high values for beef.

1.2. Nutritional, economic and environmental benefits of bivalve aquaculture

Bivalve shellfish aquaculture is highly attractive from a human nutrition, economic, environmental and ecosystem standpoint and deserves a concerted research-led industry focus to increase production. Bivalves have a higher protein content than beef (140 vs 85 mg protein $kcal^{-1}$), and are a rich source of essential omega-3 fatty acids including docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), needed for infant development, cognitive function and cardiovascular and neural disease prevention (Adarme-Vega et al., 2012; Tacon and Metian, 2013). DHA and EPA levels in bivalves (1.76 and 2.12 $mg\,g^{-1}$ respectively) are comparable with oily fish (2.61 and 2.27 $mg\,g^{-1}$) and far exceed that of terrestrial meats (0.02 and 0.03 $mg\,g^{-1}$) (Tacon and Metian, 2013). Bivalves are highly affordable, with a global average farm gate price of \$1.10 kg^{-1}, compared to \$4.70 kg^{-1} for salmon and \$2.10 kg^{-1} for aquaculture in general (Waite et al., 2014).

The environmental footprint of bivalve aquaculture is also far lower than all other forms of meat or fish production and many arable crops, in terms of greenhouse gas emissions, land use, freshwater use, and eutrophication potential per unit protein (Fig. 1). To help appreciate just how significant this is, if just 25% of carnivorous fish aquaculture was replaced with an equivalent quantity of protein from bivalve shellfish aquaculture, 16.3 million tonnes of CO_2 emssions could be saved annually, equivalent to half the annual emissions of New Zealand (Waite et al., 2014; "World Bank. CO2 Emissions," 2017). An area of land larger than Wales (2.7 million ha) could be spared from conversion to farmland, 11.8 billion litres of freshwater could be saved each year, and a net 21.1 million kg of P could be removed from eutrificated waters globally (Waite et al., 2014). Bivalve farming also provides a wide array of marine ecosystem benefits, including the provision of nursery habitats for fish, filtration of the water column, enhanced denitrification rates, coastal protection, buffering against harmful phytoplankton blooms, and even restoration of coastal and estuary ecosystems (Gallardi, 2014; zu Ermgassen et al., 2013). Caution should of course be taken when expanding bivalve aquaculture to avoid some of the potentially deleterious environmental effects; species native to a region are best selected for aquaculture to avoid ecosystem damage caused by the introduction of non-indigenous species, and the potential risks of increased sedimentation from bivalve excrement should be assessed case by case (Branch and Nina Steffani, 2004). With careful planning, a concerted effort to increase bivalve production could make up an invaluable component of global goals to provide nutritious and sustainable food to people over the coming decades.

1.3. Global bivalve aquaculture production, management, distribution and consumption

The bivalve shellfish sector is an important growing global industry. Production quantity has grown at 2.7% per year over the last decade and in 2015 14.8 million tonnes of the major bivalve species (oysters, clams, mussels and scallops) were produced with a farm gate value of US\$17 billion (Fig. 2) (FAO, 2017). Over 93% of bivalve production occurs in Asia, and over 90% of Asia's production is in China, with the remainder in coastal areas of Europe, the Americas, and Oceania (Fig. 2) (FAO, 2017). Production *per capita* varies significantly between countries and is highest in New Zealand at 16.8 kg *per capita* (FAO, 2017; "World Bank. Total Population," 2017). Historical farming

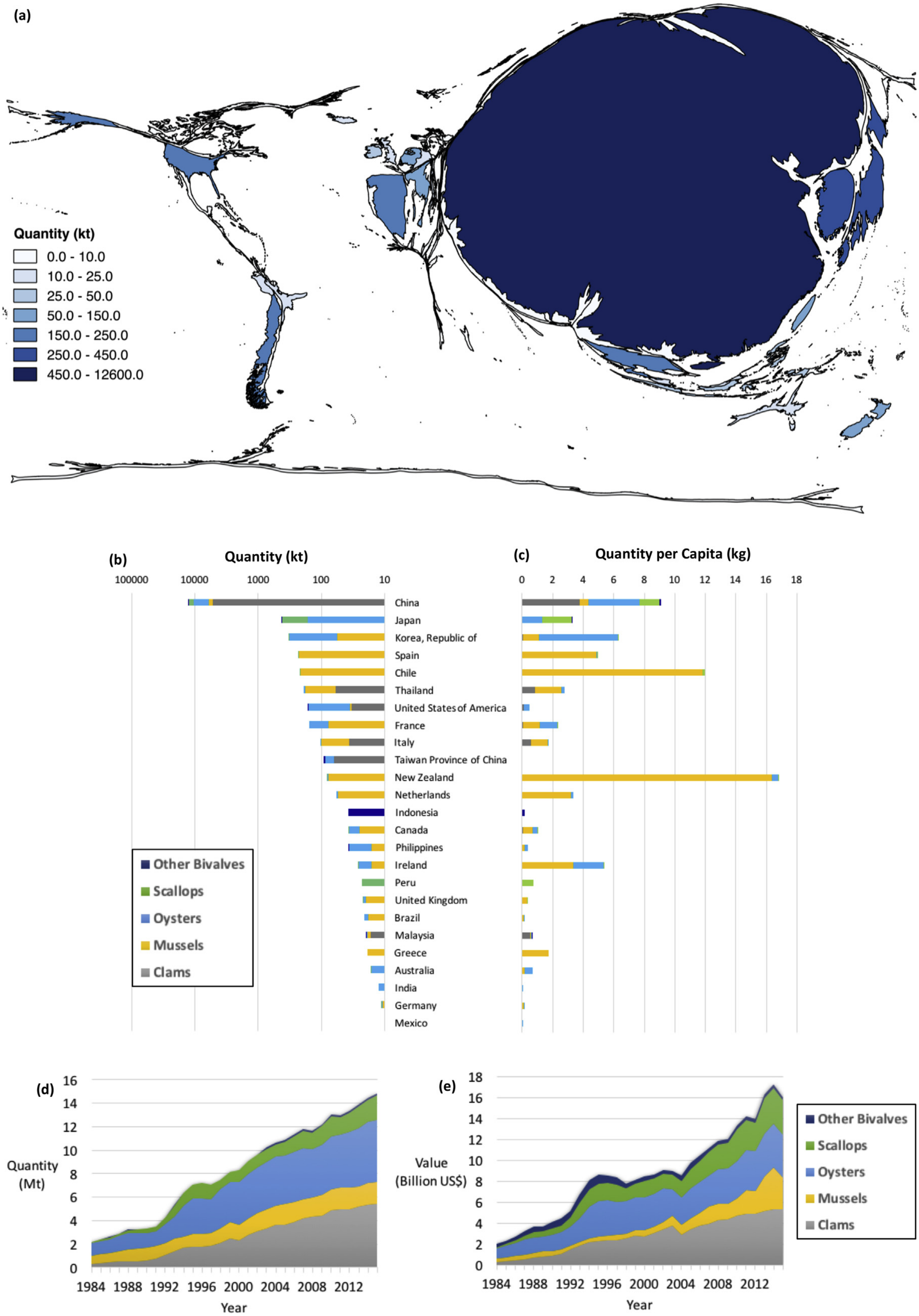

Fig. 2. A synthesis of the global production of bivalves, highlighting the importance of Pacific and western European nations. The total quantity of bivalves produced in 2015 by country is shown on the cartogram in (a); the relative size and shading of countries is scaled according to production quantity (Andrieu et al., 2008). A breakdown of bivalve production quantity by species for the top 25 countries is shown on a logarithmic scale in (b), and the production quantity *per capita* for these countries in (c). The global growth in bivalve production quantity and value is displayed in (d) and (e) respectively. Raw data from (FAO, 2017; "World Bank. Total Population," 2017).

Fig. 3. Shandong: a major shellfish production centre in China. The flow diagram provides an overview of the production value chain in China. Raw statistics from (Baluyut, 1989; FAO, 2017; O'Connor et al., 2012; Schneider, 2012).

culture and species site preferences strongly influence the range of species farmed within a given region, for example in Asia clams are the primary farmed species and in Europe mussels (FAO, 2017; Gosling, 2015). In China Shandong Province in particular is a highly productive region and produces 68% of the world's bivalves (FAO, 2017). A case study on shellfish production in China, where bivalve consumption has increased nearly 7-fold over the last 25 years, is provided in Fig. 3 (FAO, 2017).

Worldwide the bivalve shellfish industry has a distinctive structure with fragmented hatcheries and grow-out operators, overseen by regional and national governing bodies covering the value chain. The production process starts with bivalve juveniles (‘spat’, ‘seed’) which are hatched, reared and fed in hatcheries on land before being grown out in the sea (Duthie, 2012). Hatcheries are small-scale, and continue to operate mostly by ‘feel’ rather than by ‘science’ (Duthie, 2012). On a local level strong relationships exist between hatcheries and grow-out operators. Worldwide the producer industry remains fragmented and grow-out operators commonly farm bivalves as a sideline to other aquaculture species, in China represented by 20000 privately operated farms and 1200 state run farms (Baluyut, 1989) (Fig. 3). In China the state-run Chinese National Fisheries Corporation oversees the entire value chain from production to retail. In Europe and Oceania the European Commission on Fisheries, the Australian Fisheries Management Authority and the New Zealand Ministry for Primary Industries oversee production, and in the United States and Canada large vertically integrated shellfish businesses and governmental departments link hatchery and grow-out operations.

Bivalves are mainly consumed domestically providing an inexpensive food for millions of people (FAO, 2014). Less than 5% of world production is traded. Currently suboptimal transportation pathways and a desire for bivalves to be consumed fresh are a technical constraint, but long distance distribution is possible, and typically used for the small proportion of higher value bivalves sold in quality restaurants (FAO, 2017, 2014; Gosling, 2015). The market price varies widely, averaging \$1.10 kg^{-1} across all bivalve species in China, whilst in Europe the average is \$3.36 kg^{-1} (2017). This is significantly less than fish such as salmon at \$8.00 kg^{-1}, although in Europe some oyster species can fetch \$6 - 22 kg^{-1} (FAO, 2017; Josupeit et al., 2017). In Asia bivalves provide millions of people with an inexpensive source of food rich in amino acids, essential fatty acids, essential minerals, and vitamins (Joy and Chakraborty, 2017). In the developed world where over 2 billion consume too many calories but do not get the nutrients they need, bivalves provide an affordable healthy food (Joy and Chakraborty, 2017; WHO, 2017).

2. Factors limiting industry growth in bivalve aquaculture

2.1. Production problems are a major driver to the falling share of bivalves in global aquaculture

Growth in the bivalve industry growth is falling behind the rest of aquaculture. Of the 78 million tonnes of animal aquaculture produced globally in 2015, bivalve shellfish made up 19%, down from 25% in 1990, and production has increased just 2.7% per year over the last decade, compared to 8.4% for carnivorous fish aquaculture (FAO, 2017). Lower growth rates have a number of probable drivers, in which consumer taste, consumer access and marketing, food processing, distribution, supplier fragmentation, expertise and research and development investment all have a part to play (Duthie, 2012; Waite et al., 2014). However, it is clear that today several major problems specifically in the bivalve production process are contributing to low industry growth, outlined in Fig. 4 and explained below (Duthie, 2012).

2.2. Microalgae feed problems

Multiple defects in live microalgae feed increase costs and reduce bivalve growth and maturation rates yet so far no solutions or satisfactory alternatives have been found. Growing live microalgae to feed bivalves in hatcheries and nurseries takes up 50% of production costs at \$160–400 per kg biomass (Gui et al., 2016b; Knauer and Southgate, 1999). The microalgae produced are of highly variable and often poor quality, and susceptible to frequent contamination and population crashes (Gui et al., 2016b; Luzardo-Alvarez et al., 2010). Even the highest quality microalgae do not have the optimal nutrient composition for all stages of bivalve development, so multiple genera and cultures have to be grown on each site (e.g. *Isochrysis, Tetraselmis, Chaetoceros, Thalassiosira, Nannochloropsis*) (Adarme-Vega et al., 2012; Becker, 2013). To ensure reasonably consistent culture quality, microalgae have to be grown in controlled indoor environments, creating an expensive and major bottleneck limiting bivalve production (Knauer and Southgate, 1999). Since 1990 commercial and research bivalve hatcheries worldwide have repeatedly identified a strong need for alternative diets to replace live microalgae, but to date no satisfactory product has been developed (Gui et al., 2016a; Helm and Bourne, 2004;

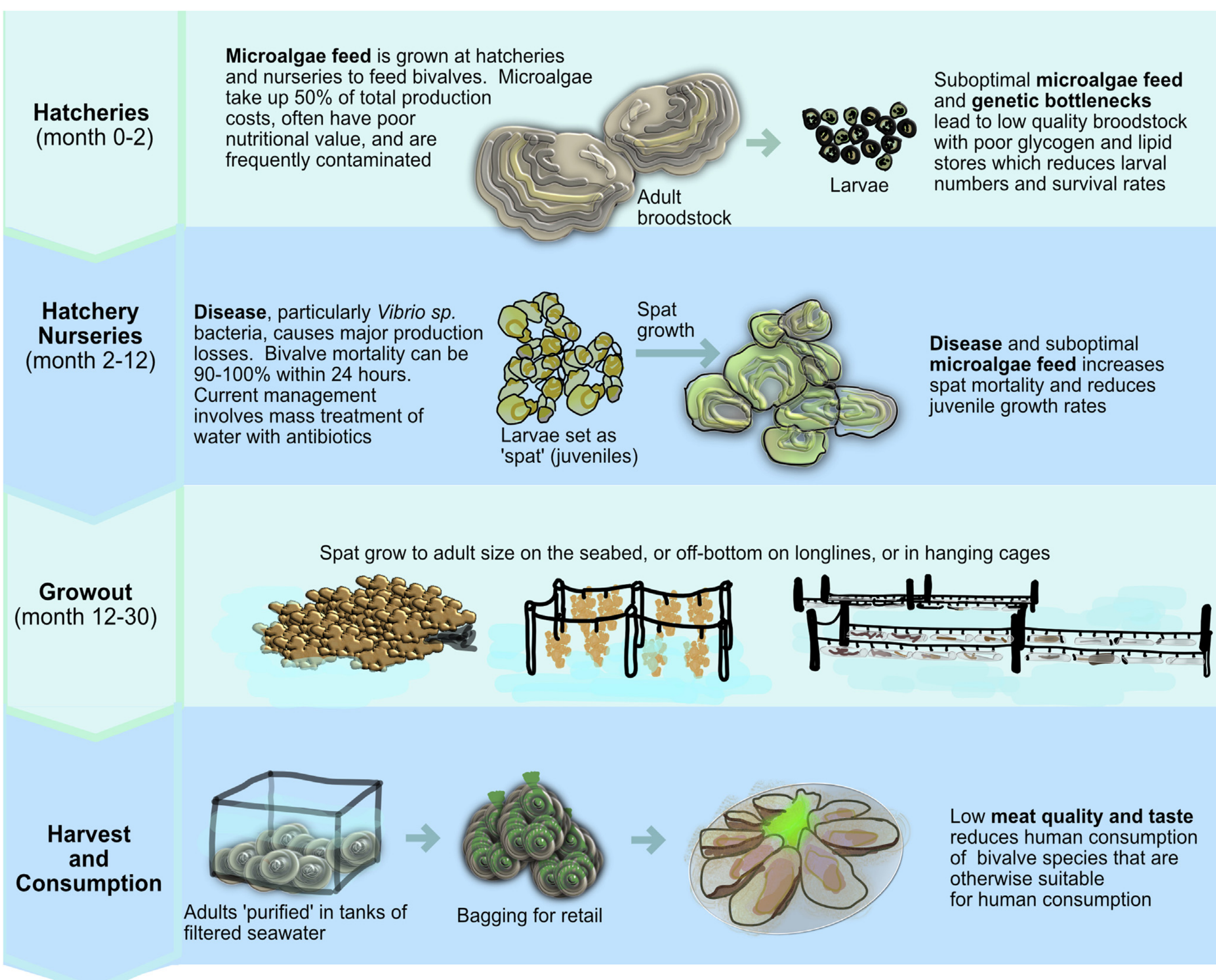

Fig. 4. The four key stages in bivalve production, illustrating the primary factors limiting yields.

Table 1
How new microencapsulated diets could tackle bivalve production problems. Numbers represent relevant sections in the main text.

Characteristic of Microencapsulated Diet	Problems Addressed				Potential Outcomes		
	Microalgae Feed Problems	Disease	Genetic Bottlenecks	Meat Quality and Taste	Increased Growth	Reduced Costs	Improved Bivalve Quality
Physical characteristics optimised for maximum uptake and cost efficiency (3.3)	✓	✓			✓	✓	
Optimal formulation of high quality cost effective nutrients (3.4)	✓		✓	✓	✓	✓	✓
Targeted delivery of disease control agents including antibiotics and probiotics (3.5)		✓	✓		✓	✓	✓
Quality enhancers including flavourings (3.6)				✓			✓

Knauer and Southgate, 1999).

2.3. Disease losses in the hatchery

Disease causes significant losses, prevention is costly and often it generates environmental damage and human health risk. Complete bivalve batches including juveniles and breeding adults are often lost, leading to hatchery closure (Prado et al., 2010). *Vibrio sp.* bacteria are the major disease problem; mortality of infected bivalves can be 90–100% within 24 h and industry losses are typically 60% (Dubert et al., 2017; Elston et al., 2008; Prado et al., 2010). Contaminated algal feeds are a major vector of *Vibrio* sp and current disease management is primarily dependent upon chemotherapy in the form of antibiotics (Beaz-Hidalgo et al., 2010; Dubert et al., 2017; Prado et al., 2010). Streptomycin, penicillin, florfenicol, erthromycin, and chloramphenicol are routinely applied to and circulated around hatchery water supplies to prevent and treat disease (Dubert et al., 2017; Prado et al., 2010). This is inefficient, and the economic costs can be equal to the cost of bivalve stock (Prado et al., 2010). More importantly, far from optimising the success of larval and juvenile bivalve cultures, this level of widespread antibiotic use is driving the proliferation of antibiotic resistant *Vibrio* in hatcheries (Dubert et al., 2017). Furthermore, water effluents and bivalve exports then act as a delivery mechanism for resistant bacteria to different geographical locations or aquatic environments (Dubert et al., 2017). There is a need for alternative solutions to manage disease, or at the bare minimum a more efficient delivery mechanism of antibiotics to bivalves to reduce overall antibiotic usage (Beaz-Hidalgo et al., 2010; Dubert et al., 2017; Prado et al., 2010).

2.4. Genetic bottlenecks

Genetic bottlenecks and inbreeding depressions are occurring in adult bivalve broodstock due to the selective breeding of 'high quality' adults in hatcheries, reducing yield. Declines in performance characteristics including yield, growth rate, and survival have been documented across bivalve species, alongside reduced disease resistance and adaptability to environmental changes (Gosling, 2015; Hargrove et al., 2015; Zhong et al., 2016). Dietary intervention can improve gonadal nutrient reserves and gamete quality, quantity and viability in bivalve broodstock without a need for selective breeding (González-Araya et al., 2012; Maneiro et al., 2017; Nevejan et al., 2008; Utting and Millican, 1997). Such intervention is needed in combination with improved breeding protocols that draw from a more diverse pool of individuals to improve broodstock quality without reducing genetic variation (Gosling, 2015; Zhong et al., 2016).

2.5. Meat quality and taste

There is a need to improve the palatability and quality of adult bivalves for human consumption. There remain consumer perceptions that bivalves do not taste as good as fish, and this has a negative impact on market value and demand (Waite et al., 2014). For some farmed bivalve species, highly nutritious flesh is even discarded while the shells are used for industrial applications and road surfacing (Rusch et al., 1988). Dietary supplementation to improve the nutritional quality and taste of bivalves is needed to increase consumer uptake of bivalves and reduce food waste.

3. Harnessing microencapsulated diets to solve bivalve production problems

3.1. An opportunity for industry growth

There is major potential for bivalve industry growth from solutions which tackle current problems in the production process. To date, bivalve aquaculture has not received the same levels of research or investment as fish aquaculture, and there is a great need for science to complement traditional knowledge and help the industry become more efficient (Helm and Bourne, 2004; Knauer and Southgate, 1999; Waite et al., 2014). Even modest increases in production could have a large impact; for example if just the United Kingdom were to increase its production *per capita* to the level of New Zealand, an extra 1.1 million tonnes of bivalves could be produced annually (FAO, 2017; "World Bank. Total Population," 2017). There is an opportunity to realise such increases in production by developing microencapsulated diets.

3.2. Potential from new advances in microencapsulation technology

New advances in microencapsulation technology offer great potential to tackle key problems in bivalve shellfish production (Table 1). A microencapsulated diet consists of a formulation of nutrients and agents surrounded by a digestable capsule. The concept of delivering microencapsulated artificial diets to aquatic filter feeders has been present since the 1970s (Knauer and Southgate, 1999). Since then a very limited number of studies have trialled the use of microencapsulated feeds including 'MySpat' (INVE Technologies, Dendermonde, Belgium) and 'Frippak' (Frippak Feeds, Basingstoke, Great Britain) to feed bivalves (Gui et al., 2016b, 2016a, Nevejan et al., 2007; 2008). These feeds are not directly representative of a natural bivalve diet; MySpat contains lipids originating from fish oils and protein from land vegetable origin, and Frippak is designed for shrimp and fish feeding (Langdon, 2003; Nevejan et al., 2007). Microencapsulated feeds are still yet to be adopted for large scale commercial use in the bivalve shellfish industry.

However new advances in microencapsulation technology could

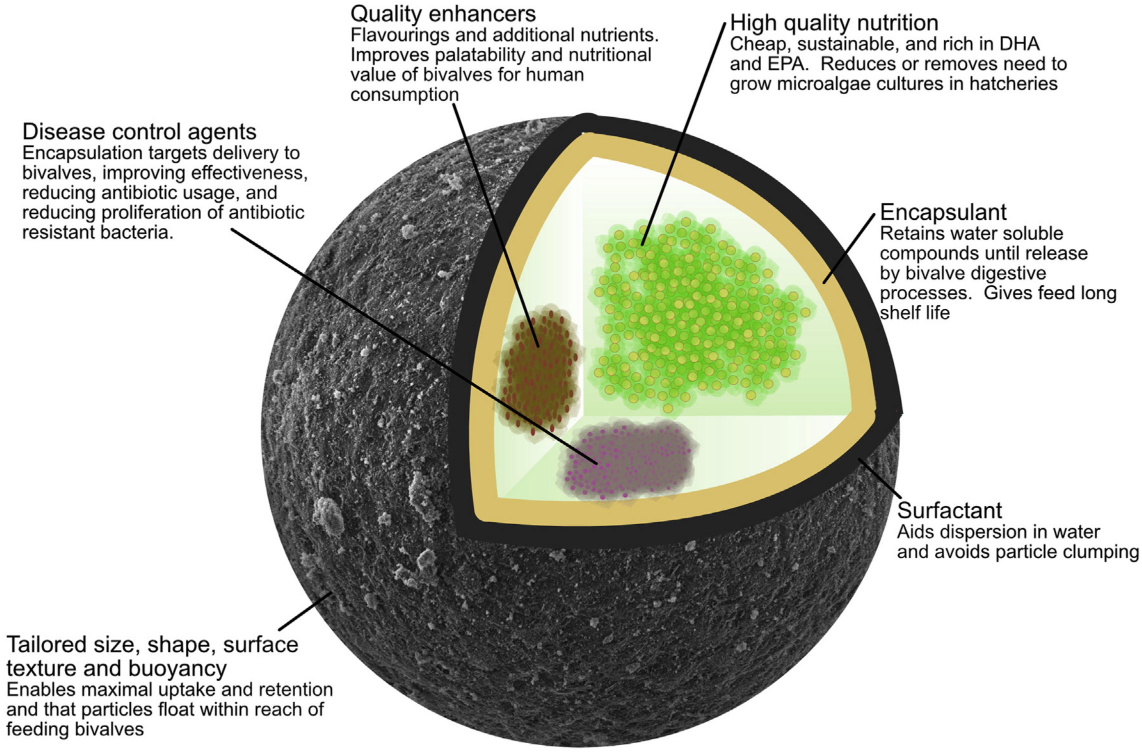

Fig. 5. Schematic of a microencapsulated food particle demonstrating the desirable characteristics that could result in enhanced commerciality of bivalves.

change this situation. A novel form of microparticles have recently been developed for the targeted delivery of chemical control agents to invasive bivalve species, and are known as BioBullets (BioBullets Ltd, Cambridge, UK) (Aldridge et al., 2006). To manufacture the particles, a slurry of lipid encapsulant and powdered diet is pumped into an ultrasonic atomising nozzle, before the particles form perfect spheres in specialised cooling chambers and are then coated in a proprietary surfactant to aid dispersion in water (Aldridge et al., 2006). A comparable encapsulation system is already being used at scale and is highly cost effective in other food sectors. It was recently demonstrated that the blue mussel *Mytilus edulis* could ingest BioBullets particles containing a formulated diet including *Schizochytrium* algae, opening a new direction for this emerging technology in feeding desirable products to bivalves (Willer and Aldridge, 2017). New microencapsulated diets offer many critical advantages over alternative strategies that could be used to tackle production limitations, and offer a solution to tackle problems with bivalve feed, disease, and quality (Fig. 5).

3.3. Beneficial physical characteristics of microencapsulated feeds

The physical characteristics of microencapsulated feeds can be optimised for maximum ingestion by bivalves and cost advantage relative to algal cultures. Microparticle size can be tailored to bivalve species or life stage preferences to maximise feeding efficiency, and buoyancy can be optimised to ensure particles remain within reach of filter feeding bivalves (Luzardo-Alvarez et al., 2010). This is a key advantage over nutrient delivery systems such as freeze-dried algal powders, which tend to float on the water surface, and can clump into particles too large to be accessed by bivalves. Pre-ingestive nutrient loss can be minimised by using an encapsulant that allows particles to remain stable and retain nutrients in seawater, but also be rapidly digested on entry to the bivalve gut (Knauer and Southgate, 1999). Lipid coatings allow delivery of low molecular weight, water soluble compounds with minimal leaching to the surrounding water (Langdon, 2003). This is a significant advantage over non-encapsulated artificial diets, which tend to leach nutrients to the surrounding water, and could further reduce the small eutrophication risk that bivalve hatcheries can pose to marine ecosystems (Grant et al., 1995; Knauer and Southgate, 1999). The stability of the microparticles in air also enables cost efficient mass production and long term storage of feeds, for example in distribution centres or on hatchery sites (Luzardo-Alvarez et al., 2010). This is a major advantage over simply growing higher quality algal cultures; stored microparticles are more resistant to bacterial contamination than live algal cultures, and the costly process of synchronising microalgal feedstock with bivalve production is avoided (Knauer and Southgate, 1999; Luzardo-Alvarez et al., 2010). This could make small scale farms more economic, and reduce the need for skilled labour to grow algae.

3.4. Nutrient delivery

A single microencapsulated feed particle can contain an optimal formulation of high quality, cost effective nutrients to increase yield and growth rates. Powdering and encapsulation processes enable high quality natural food sources not traditionally used in bivalve aquaculture to be delivered to bivalves. This includes strains of algae that can be grown rapidly and efficiently under optimised mass production systems and that are incredibly rich in DHA and EPA. DHA can make up 50% of the algal lipid content of these strains, compared to $< 10\%$ for microalgae used in hatcheries today (Adarme-Vega et al., 2012; Becker, 2013; Hadley et al., 2017). This offers a far more cost efficient method to improve bivalve nutrition than trying to grow higher quality microalgae on each individual hatchery site (Adarme-Vega et al., 2012; Knauer and Southgate, 1999). Other nutrients can be added to the microparticles to tailor diets to specific bivalve species, or specific geographies where key nutrients are lacking, and even the lipid encapsulant itself can be of high nutritional value (Knauer and Southgate, 1999). Such microencapsulated feeds could improve bivalve broodstock quality; broodstock quality is influenced heavily by dietary DHA intake, and DHA supplementation increases broodstock glycogen and lipid reserves, egg size, egg quantity, larval growth rate, and larval survivorship (Hendriks et al., 2003; Utting and Millican, 1998; Waters et al., 2016). Juvenile growth could be improved; juvenile bivalves will grow more rapidly on diets high in DHA and EPA (Laing et al., 1987; Laing and Millican, 1986). Combining these improvements promises to result in greater total production volume in hatcheries.

3.5. Disease control

Encapsulation enables targeted delivery of disease control agents such as antibiotics or probiotics to filter feeding bivalves, to improve disease control, and reduce costs, environmental damage, and human health risk (Luzardo-Alvarez et al., 2010). Antibiotic encapsulation could improve effectiveness, reduce overall antibiotic usage, and reduce proliferation of antibiotic resistant bacteria; a considerable advantage over simply applying more antibiotics to hatchery water supplies to solve the disease problem. However, disease management in aquaculture using antibiotics in any form remains an environmental and human health concern (Santos and Ramos, 2018). Probiotics such as *Phaeobacter inhibens* and *Bacillus pumilus*, or antimicrobial peptides such as Tachyplesin are known to protect bivalves against bacterial infection and are a more sustainable disease management option than antibiotics (Destoumieux-Garzón et al., 2016; Simon-Colin et al., 2015; Sohn et al., 2016). Microencapsulation provides a more direct and protected mechanism to deliver probiotics to the bivalve gut compared to liquid treatment systems (Martínez Cruz et al., 2012). Microparticle components aside from probiotics can also be made sterile during production, mitigating the risk of introducing disease into bivalve cultures through feed (Knauer and Southgate, 1999). Recent studies demonstrate that mortality in juvenile *Ostrea edulis* oysters reared on microencapsulated sterile algal powder is up to 60% lower than in juveniles reared on live algae or liquid algal concentrate, and reduced disease is identified as the likely cause (Willer and Aldridge, 2019). With further research and development microencapsulated diets could enable reduced disease incidence in bivalve broodstock, larvae, and juveniles, increase production output and improve bivalve quality, while minimising risk to the environment and human health.

3.6. Quality

Quality enhancers such as flavourings can be incorporated into microparticles fed to bivalves, which could strengthen consumer demand for bivalves and encourage a diet-shift towards more sustainable seafood. Flavourings fed during the prurging stage (when bivalves are kept in purification tanks for a few days before retail) (Fig. 4) would persist within the gut tissue once the bivalves are harvested. This could improve the taste of some bivalves, and be a more effective method than flavouring the exterior of the tissue after harvest (Rusch et al., 1988). More importantly, flavouring could be a highly effective way of disguising a diet-shift away from high trophic level fish and towards more sustainable seafood. We know when marketing low trophic farmed seafood species to consumers, it is most effective to highlight attributes such as taste, affordability, and health benefits, rather than environmental sustainability (Waite et al., 2014). A resounding result could be improved consumer uptake of bivalves, at the expense of less sustainable forms of meat production.

3.7. Challenges for the future

Clearly new microencapsulated diets present an opportunity to improve bivalve aquaculture, but several challenges need to be overcome in order to make them a commercially viable option. The scalability of these new diets must be formally assessed; we know the microencapsulation technology is cost effective at scale in other food sectors, but not yet for bivalve aquaculture ("TasteTech Ltd," 2017). The physical characteristics of diets need to be optimised for long term storage in distribution networks and in hatcheries. The palatability, digestibility and composition of microencapsulated feeds needs to be tailored to specific bivalve species and growth stages (Willer and Aldridge, 2017). The environmental impact of using microencapsulated diets in bivalve aquaculture needs to be formally assessed. Researchers will be required to work collaboratively with industry partners to bring technological innovation into practice. Researchers also need to work with policy makers, retailers and the media to stimulate demand and change food preferences towards bivalves in place of less sustainable meat and fish products (Waite et al., 2014).

4. Conclusion

Increasing production of bivalves through aquaculture offers an important opportunity in meeting global food security. There is great potential for new advances in microencapsulated feeds to offer an efficient way to deliver replacement or supplementary diets to bivalves that can tackle problems with bivalve feed, disease, and quality, enabling increased quality production output, increased industry growth and reduced costs. New microencapsulated diets could be deployed in major areas of potential production growth including Asia, as well as high-value markets such as Europe. Resulting growth improvements in the bivalve shellfish sector could dramatically improve food supply, and within the next decade twice as many people could be fed by bivalves as today if we could enable bivalve aquaculture to grow at the same rate as predicted for fish aquaculture (FAO, 2017). If 25% of the protein we currently obtain from fish aquaculture was obtained from bivalves, we could spare an area of land larger than Wales, annual CO_2 emissions equal to half New Zealand's emissions, and annually 11.8 billion litres of freshwater (Waite et al., 2014; "World Bank. CO2 Emissions," 2017). There is now an open opportunity for research and industry to overcome remaining hurdles in microencapsulated feed development and to realise the great benefit improved growth in bivalve aquaculture can have for the global population and our planet.

Conflict of Interest

D.C.A. is a Managing Director of BioBullets Ltd.

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