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Review

From aquaculture production to consumption: Freshness, safety, traceability and authentication, the four pillars of quality

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ABSTRACT

Farmed aquatic products are among the most widely traded commodities and one of the sectors with the fastest growth in the last years. However, aquaculture is still affected by negative connotations in comparison with other agroindustry sectors. Markets, consumer preferences and concerns about food safety and sustainability are influencing the growth of the sector and are forcing the implementation of quality management systems. Modern management systems help to minimize the environmental impacts and the distribution of unsafe or poor-quality products, thereby reducing the potential for bad image, liability and recalls. This article presents a comprehensive overview of the status, relevance, and impact of the quality management systems in the development of marine aquaculture, with the focus on four of the most important criteria associated with these systems: freshness, safety, traceability, and authenticity.

1. Introduction

Aquaculture production is steadily increasing every year, while capture production has almost stabilized in the last 20–30 years, meaning that aquaculture represents enormous potential to supplement the quantities from the catch while alleviating the pressure on natural stocks. In 2014, an important milestone was reached, for the first time 50% of the fish, for human consumption (excluding non-food uses such as fishmeal or fish oil), was from aquaculture production (FAO, 2016). In 2016 the value for human consumption was 53% while considering the total global fish production aquaculture represented 47% (FAO, 2018). It is expected that world aquaculture production becomes higher than that of capture fisheries by 2025 (Ottinger et al., 2016).

Regional or local supply no longer limits the retailers' and food industries' response to market demand. Technological improvements have altered the production, trade, and distribution in the seafood industry, allowing it to source their products from all over the world, transforming the industry in an interconnected system with a large variety of complex relationships (Leal et al., 2015). As consequence, the inherent complexity of seafood supply chain, allows the opportunity for the development of "obscure paths" that leads to illegal, unreported, and unregulated (IUU) activities, that also implicates quality control failures (*e.g.*: heavy metals), seafood fraud (*e.g.*: mislabelling), unsustainable fishery (*e.g.*: overfishing and pollution), and human rights (*e.g.*: unfair payment) (Borit and Olsen, 2012; He, 2018).

Even though aquaculture has clear benefits in several domains, such as social (*e.g.*: employment, price stability), environmental (*e.g.*: bioremediation, habitat structure) or product quality (*e.g.*: freshness and security), negative perceptions or assumptions about the sector still exist (Claret et al., 2014; Conte et al., 2014; Klinger and Naylor, 2012). Consumer attitudes, and perceptions, regarding aquaculture or fisheries, can impact the success and acceptance of new food products (EUMOFA, 2017; Vanhonacker et al., 2011).

Consumer decisions about a food product do not depend solely on the associated pleasure or on its organoleptic properties (Kole et al., 2009; Matos et al., 2017). It depends on many personal expectations that differ from consumer to consumer as well as with the culture or geographical localization in which the product is marketed (Conte et al., 2014). Even though seafood products seem to be safer than ever before, from a technical point of view and due to several quality control programs, the awareness and concerns of consumers are increasing and further redefining industry quality parameters (Claret et al., 2014; Kole et al., 2009; Ghisi and de Oliveira, 2016).

The increasing interest in fish quality in all parts of the seafood

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chain is particularly true for aquaculture, in which the products and production processes have several specific characteristics that influence the product safety and quality assurance throughout all production chain. Factors include product variation, production yields, and shelf-life, which are influenced by, *for example*, weather conditions, biological variation, cooling facilities and hygienic measurements (Cataudella et al., 2005;). Some other specific hazards exist in the production and distribution of seafood, such as the sources of raw materials and the incorporation of many participants. In the last case, the large number of formal and informal relationships during captures, processing and transactions, as their multitude of specific activities and common practices, increase the difficulty of regulatory agencies and governments to control and oversee the sector (Cataudella et al., 2005; Iles, 2007; Trienekens and Zuurbier, 2008). National and international authorities are responding to this by implementing new legislation and regulations to ensure safe and animal-friendly production, sustainability and lower pollution levels (Tacon et al., 2010; Trienekens and Zuurbier, 2008). Similar principles from the livestock industry are being adapted to aquaculture: 1) ensuring food safety and quality; 2) improving processing technology; 3) adding value to products; and 4) expanding supplies and markets. These topics are closely interconnected and focused on ensuring quality for the consumer and on helping businesses to prosper (Ene, 2013). The application of these principles in the aquaculture supply chain, besides being voluntary, is also becoming a common requirement for the main importer countries, in order to safeguard public health and demonstrate that the product originates from legal and sustainably managed aquaculture according to codes of best practices (Leal et al., 2015). A complete understanding of the relationship between fish product attributes, social/ethical problems, environmental impact and issues underlying food traceability and authentication is very relevant in this context, not only to consumer quality judgments and perception of product value but also to all players in supply chain (Cataudella et al., 2005; Kole et al., 2009). Therefore, the purpose of this review is to present an overview of the application of quality management principles in the aquaculture sector, giving relevance to important quality management attributes such as freshness, safety, traceability, authenticity and how they interact with each other in final products quality perception.

2. Defining quality and its attributes for evaluation

It is generally known that seafood products are one of the most vulnerable and perishable food items. For seafood benefits to be fully realized, it must have to be produced and maintained in secure conditions and remain as fresh as possible to the point of purchase by the consumer.

According to Bremner (2000), the term “quality” in the food science literature is often misused, creating some confusion between the terms employed for conceptual discussion and the ones used for the practical report of measurable data. The problem with ‘quality’ definitions is that they do not clearly indicate which attributes or indicators should be measured, to assess quality in any particular production situation, the types of raw materials used, or in the final products (Bremner, 2000). In this regard, quality is defined by the International Standard Organization (ISO) as “the totality of features and characteristics of a product that bear on its ability to satisfy stated or implied needs”. In addition, quality can be defined as “conformance to requirement”, “fitness for use” or, more appropriately for foodstuffs, “fitness for consumption” (Bremner, 2000). Thus, quality is also described as the requirements necessary to satisfy the needs and expectations of the consumer (Aung and Chang, 2014).

In the food industry, quality is frequently defined using terms related to nutrition, microbiology, physicochemical characteristics or consumer acceptability (Hassoun and Karoui, 2017). These terms should be analysed through an integrated vision since all of them contribute to quality assessment in different steps of the supply chain (Hassoun and Karoui, 2017). To overcome such undefined terminology, Bremner proposed a hierarchial approach that encompasses all the aspects (concepts, criteria, specifications of the criteria and methods to provide values for the criteria) (Bremner, 2000). The same methodology is proposed to be applied to other similar generic terms such as freshness and safety (Barbosa et al., 2002; Bremner and Sakaguchi, 2000). Although there are many different formulations of this concept, it is commonly agreed that quality can be generally categorized as: search qualities (*i.e.* attributes perceived before purchase); experience qualities (*i.e.* attributes only perceived when consuming the product); or credence qualities (*i.e.* attributes not readily perceived without explicit clues) (Matos et al., 2017). Essentially, food quality is associated with a proactive policy and the creation of requirements to maintain an efficient and secure food supply.

In this work, the term “quality” will have the same meaning as defined by ISO - “the totality of features and characteristics of a product that bear on its ability to satisfy stated or implied needs”. The chosen criteria to evaluate quality in the aquaculture sector will be freshness, safety, traceability, and authenticity.

2.1. Freshness

Freshness is a major basic contributor to quality and safety of fish and fishery products. The term ‘fish freshness’ is a concept that sums up many factors, (similar to quality as explained in section 2) and should be carefully described. According to Oehlenschläger “*Freshness is an ideal of perfect condition or state, when fish properties are close to the ones it had while living or immediately post-capture or harvest*” (Oehlenschläger and Sorënsen, 1997). In fact, different stages of fish freshness can be described using multiple properties, that are known to be associated with the progression of fish spoilage (Matos et al., 2017). Besides evaluating its optimal condition (after slaughter), it is possible to estimate its capability to retain those sets of characteristics until the time it is processed, cooked, presented, eaten or all of these, following capture (Matos et al., 2017; Nollet, 2012; Rehbein and Oehlenschläger, 2009). These properties are commonly referred as “freshness indicators”, and where described by Bremner and Sakaguchi, as” *that measurable entity that should provide a monotonic response, which can be used to describe one or more of the post mortem changes that have occurred*” (Bremner and Sakaguchi, 2000). In this case, monotonic response refers to the ability of the analysed parameter to provide specific data results, that are associated with one or more stages of freshness loss. For example in the case of the measurement of total volatile biogenic amines (TVB-N), where the data results increase with the progression of time and is possible to associate a specific value to determine an acceptable condition of the fish for consumption. The most common studied indicators are associated to four specific fields:

- *Sensory* – *e.g.*: appearance, odour, taste, touch;
- *(Bio)chemical* – *e.g.*: volatile compounds, proteins, lipids, amino acids and adenosine triphosphate (ATP);
- *Physical- e.g.*: muscular structure and colour changes;
- *Microbiological* – *e.g.*: microorganisms' growth and identification (Ashie et al., 1996; Olafsdóttir et al., 1997).

Three main *post mortem* processes that influence these parameters are enzymatic autolysis, oxidation, and microbial degradation. All of them are responsible, to some extent, for the development or transformation of specific substances that contribute to alterations in the previous parameters, characteristic of spoiled fish (Ghaly et al., 2010). Therefore, their evaluation through measurable indicators is a direct measure of time expired since catch and death under the prevailing circumstances (Bremner and Sakaguchi, 2000). According to Huss (1995), the mentioned changes occur more or less simultaneously but are more important in certain periods that can be divided into four phases, as shown in Fig. 1.

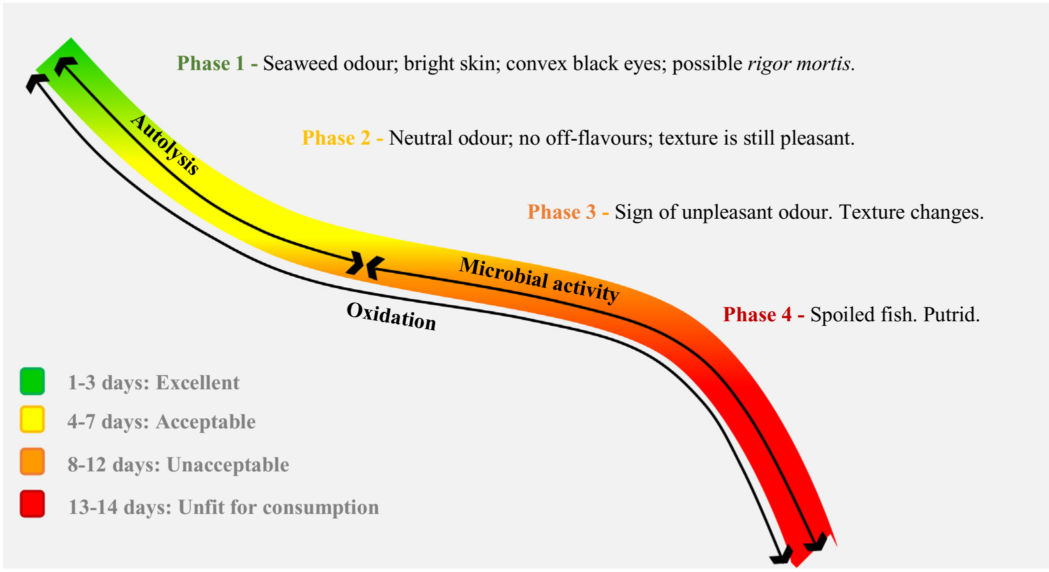

Fig. 1. Stages of fish degradation. Progression of fish degradation process, principal changes, common time frame and consumer acceptance, based on Huss (1995).

The shelf-life investigation is another research area, that shares some common principals with freshness. This area of investigation faces the same problems related with definitions as described previously for quality and freshness (Barbosa et al., 2002). The term shelf-life is related to methods used to delay the impact of *post mortem* processes on seafood characteristics, extending its storage time and consequently its suitability for human consumption. Several techniques are already in use and have been extensively reviewed (Ashie et al., 1996; Ghaly et al., 2010; Wang et al., 2017), involving the use of chemicals (acids, sulphites, oils), modified atmosphere packaging, temperature or pH changes.

2.2. Safety

Safety, as quality criteria, is difficult to perceive. A product can appear to be of high quality standards, but safety hazards may be hidden or go undetected (pathogenic organisms, toxic chemicals or physical hazards), until the product has been consumed. If detected, serious food safety threats may result in market access exclusion and major economic loss or costs (Aung and Chang, 2014; Trienekens and Zuurbier, 2008). Nowadays there is a consensus among specialists that safety is a very important quality pre-requisite. Since food safety hazards directly affect public health and economies, achieving proper food safety must always take precedence over achieving higher levels of other quality criteria (El Sheikha and Xu, 2017).

The links between safety and quality can be established in the following ways: quality and safety are both interrelated and linked to trust/confidence. Quality is seen to lead to taste, health, care, and pleasure. Similarly, safety is seen to be the consequence of control, origin, best before date and excellence, while resulting in health and a feeling of calm (Aung and Chang, 2014). On the other hand, food quality is primarily an economical issue decided by the consumer, while food safety is a governmental commitment to ensure that the food supply is harmless for consumers and meets regulatory requirements (Aung and Chang, 2014).

Seafood safety is based on conformity to not exceed predetermined levels of contaminants or freedom from foodborne pathogens (*e.g.*: *Salmonella spp; Vibrio spp; Anisakis spp*); metals (*e.g.*: Hg, Cd, Pb), toxins, pesticides, food additives, preservatives, physical hazards and spoilage (Cole et al., 2009; Sapkota et al., 2008). As the product moves through the supply chain, safety can also be defined as the style of production, harvesting, preparing, handling and storing, to prevent infection and to help ensure that the food maintains its nutritional value for the consumer (Cataudella et al., 2005). In order to reduce directly or indirectly the presence of hazards, the European Union (EU) has elaborated several regulatory proposals. They stipulate limits in which different hazards can be present in the products and in the environment, restraining the proliferation of emerging diseases or exotic pathogens in the natural ecosystems of receiving countries (*e.g.:* Council Decisions - CD No 2010/221 (EU), CD No 2011/187/EU; Regulations - Reg. No 1143/2014, Reg. (EU) No 324/2011, Reg. (EU) No 350/2011; Council Implementing Decisions – 2014/22/EU, 2013/706/EC, 2012/31/EU), (Long, 2016; Oidtmann et al., 2011a). In this context, food safety is a responsibility shared by producers, processors, distributors, retailers, and consumers.

2.3. Traceability

Consumers demand verifiable, authentic and traceable information as evidence of food excellence and safety. Therefore, there is an increasing need for transparent information on the entire food chain, supported by modern traceability methods.

While food safety is an intrinsic part of food quality, traceability systems are an essential component of food safety and quality management systems (Aung and Chang, 2014; Dalvit et al., 2007; El Sheikha and Xu, 2017). Traceability systems neither produce safer/high-quality products nor determine liability. Traceability is not a type of information; it is the means by which information is retrieved and hence also stored and arranged (Olsen and Borit, 2013). Traceability systems can efficiently collect data and provide information about whether control points in the production or supply chain are operating correctly or not. The more precise the system, the faster a producer can identify and resolve food safety or quality problems (Aung and Chang, 2014).

Traceability could answer the questions of "who (*i.e.*, actor/product), what (*i.e.*, actor/product information), when (*i.e.*, time), where (*i.e.*, location) and why (*i.e.* cause/reasons)" with regard to food safety, quality and visibility (Aung and Chang, 2014). In addition, depending on the direction in which information is recalled, supply chain traceability can be defined as tracing or tracking. Backward traceability or tracing is the ability, at every point of the supply chain, to find the origin and characteristics of a product based on one or several given criteria. Forward traceability or tracking is the ability, at every point of the supply chain, to find the product's localization from one or several given criteria (Bosona and Gebresenbet, 2013). It is important for an

Table 1
Most representative private certification schemes for aquaculture (adapted from Potts et al., 2016).

Name	Species scope	Global scope	Consumer label
Aquaculture Stewardship Council (ASC)	Abalone, bivalves, freshwater trout, pangasius, salmon, shrimp, tilapia	Asia, Africa, Australia and Oceania, North America, South America, Central America and Caribbean; Europe	
Naturland	Carp, salmonids, whitefish, mussels, shrimps, tropical freshwater fish, perch like fish, jack like and cod like fish; and macro algae	Asia, Africa, Australia and Oceania, South America, Central America and Caribbean; Europe	
China G.A.P	All species with specific control points for eel, crab, croaker, flounder, shrimp, tilapia.	China	
Friends of the Sea (FOS)	All species of fish, abalone, bivalves, crustaceans	Asia, Africa, Australia and Oceania, North America, South America, Central America and Caribbean; Europe	

(continued on next page)

Table 1 (*continued*)

Name	Species scope	Global scope	Consumer label
Global Aquaculture Alliance Best Aquaculture Practices (GAA BAP)	Barramundi, catfish, golden pompano, jade perch, mussels, pangasius, rainbow trout, salmon, shrimp, tilapia, trout	Asia, Africa, Australia and Oceania, North America, South America, Central America and Caribbean; Europe	
The Global Partnership for Good Agricultural Practice (GLOBAL G.A.P.)	35 species of finfish, crustaceans and molluscs (hatchery-based and passive collection of seedlings from the planktonic phase for molluscs)	30 countries from North, Central and South America; Europe; Asia; Australia and Oceania	None (business to business)
International Federation of Organic Agriculture Movements (IFOAM)	All species for aquaculture	Asia, Africa, Australia and Oceania, North America, South America, Central America and Caribbean; Europe	None
Generic food quality and safety standards	HACCP	Systematic approach to the identification, evaluation and control of steps in food manufacturing that are critical to product safety.	
	ISO	International standards to achieve uniformity and to prevent technical barriers to trade throughout the world. Focuses on management.	

information system to support both types of traceability, as the effectiveness for one type does not necessarily imply the effectiveness for the other (Aung and Chang, 2014). Also, the efficiency of a traceability system can be characterized by breadth (*i.e.* the amount of information collected), depth (*i.e.* how far back or forward the system tracks the relevant information) and precision (*i.e.* degree of assurance to pinpoint a particular movement of a food product) to be able to balance cost and benefits (Bosona and Gebresenbet, 2013).

It is worth noting that since traceability is based on systematic recordings and record keeping, there is no guarantee that the recordings are true. Both errors and fraud may lead to untrue claims with respect to the properties of the food product (Olsen and Borit, 2013).

Nowadays is not enough to have ecolabels or references to sustainable productivity. Consumers are perceiving it as marketing strategies and higher levels of food chain transparency are required in order to gain their confidence (Iles, 2007). In this case transparency means, allow to the public/organisations access to information perceived as relevant for them, such as about, sustainability practices, supplier's information or product production, which is something that companies may not be prepared to do, due to concerns about of competitiveness loss and costs (Iles, 2007; Westerkamp et al., 2019).

2.4. Authentication

Authentication can be defined as the act of establishing or confirming something (*e.g.*: food of animal origin) as authentic, that is, the claims made by or about the subject are true (Fontanesi, 2010). The main objectives for authenticity assessment includes i) protection against fraud, to safeguard fair trade; ii) ensure correct labelling of products following EU regulations (EC 104/2000); iii) protect endangered species; and iv) support customs examinations (Alasalvar et al., 2011; Rasmussen and Morrissey, 2008; Rehbein and Oehlenschläger, 2009). In addition, the legislative protection of regional foods strengthens the importance of authenticity testing as a quality criterion for food and food ingredients. This might involve confirming the identity of a product (*e.g.*: which species), its geographical origin (*e.g.*: from which farm) and discrimination between production methods (*e.g.*: farmed or wild) (Danezis et al., 2016). Food authenticity testing does not serve only consumers but also the stakeholders who are seeking the opportunity to assure their food products labelling compliance and branding (Danezis et al., 2016).

3. Application of quality attributes in aquaculture

Quality in fish products relates to attributes that fish posses, among distinct species, as well as in the same species. Such attributes vary due to interactions of endogenous factors (*e.g.*: age, proximate composition) as with environmental, nutritional and rearing conditions (Hassoun and Karoui, 2017; Matos et al., 2017). The most common key attributes associated to consumer conception of food quality and their associated decisions, are related with organoleptic characteristics (*e.g.*: taste, odour, flavour); marketable traits (*e.g.*: freshness, size); safety (*e.g.*: parasites, hygiene) and nutritional value (*e.g.*: vitamins, fatty acids) (Matos et al., 2017).

However, in aquaculture production, to evaluate quality, specific characteristics have to be considered. Pre-harvesting, harvesting and post-harvesting factors will influence the main quality criteria (freshness, safety, traceability, and authentication). Operational parameters like quality of hatcheries that supply the juveniles, rearing conditions, feed quantity, food formulation ingredients, slaughter method and, product manipulation and storage, must be considered and controlled (Cataudella et al., 2005). Nowadays, quality is increasingly being associated to Certification/Standards schemes, in order to: 1) control origin (*i.e.*, wild/farmed) and processing conditions (fresh/frozen, thawed fish); 2) ensure the product's safety; 3) ensure that food products are correctly labelled in terms of which animals are actually processed for consumption; and 4) recognize traceability systems from fish to fork (*e.g.* geographical origin) (Aung and Chang, 2014). The adoption of quality standards/certification schemes (summarized in Table 1) offers systematic approaches to incorporate the concept of continuous improvement and can be applied to any process in the food chain. This implies more emphasis on freshness and safety control, on traceability of food products, on environmental issues and animal friendliness (Potts et al., 2016). Also, to achieve higher compliance with regulatory and customer requirements, it could be necessary to shift from the basic product control at end of the line, to control all steps in the supply chain (Potts et al., 2016; Trienekens and Zuurbier, 2008). This also means control from the feed constituents, hatchery quality, carbon footprint, sustainable and economic performance (Biomar, 2018).

Adaptation of such schemes has to be correctly executed from the beginning since all these aspects are critical for the best maintenance of the original fish product excellence. In the following sections quality attributes, previously defined (section 2), will be described giving emphasis to aquaculture production and products.

3.1. Product freshness

Several methods and techniques have been developed to determine and evaluate the alterations of fish freshness. Some of these methods have been extensively reviewed (Cheng et al., 2015; Hassoun and Karoui, 2017; Olafsdóttir et al., 1997) and are summarized in Table 2. Briefly, classical indicators to characterize freshness are related with the four groups of parameters: sensory, chemical, physical and microbiological. In recent years, the development of new techniques was focused on the fusion of several of the traditional methods. The aim is to develop sensors (Venugopal, 2002), spectroscopic techniques, computational methods (Rehbein and Oehlenschläger, 2009) and/or mathematical models (Giuffrida et al., 2013), to allow simultaneous analysis of different indicators to overcome the disadvantages associated with classical methods (*e.g.:* time consuming; specialized personal; high amount of sample). However, even with the emergence of these technologies, they face some obstacles to be accepted, such as price, recognition as international standard methods or industrial applicability (Hassoun and Karoui, 2017). This means that some of the older methods still prevail in laboratories and companies.

Several works related to fish freshness analysis contributed to clarifying the impact of aquaculture common procedures on fish, leading to improvements on the methods utilised by the aquaculture producers. Examples are the analysis of capture methods (Huidobro et al., 2001a, 2001b; Tejada and Huidobro, 2002; Zampacavallo et al., 2015) product processes like washing and gutting (Bosco, 2010; Cakli et al., 2007), storage conditions (Barbosa and Vaz-Pires, 2004; Bogdanović et al., 2012; Freitas et al., 2019; Wang et al., 2017) and diet formulations (Alexi et al., 2017; Fountoulaki et al., 2009; Nasopoulou and Zabetakis, 2012). Also, such studies contributed to clarify that time-temperature reference (Akkerman et al., 2010), by itself, does not perfectly describe the fish freshness state (Bremner and Sakaguchi, 2000). This means that low temperatures are not the only influence on fish freshness. Other factors, such as pre-harvest, harvest, slaughter, and post-slaughter techniques affect every major property of fish flesh (*i.e.*: texture or appearance) in the first few days of storage, contributing to initial freshness state condition and its duration. The inclusion of procedures like, starvation period, slaughter in ice:water mixtures and temperature control, contributed to a much slower rate of change in properties of fish from aquaculture. As a consequence, no direct or indirect measure of any of the properties can provide a measure of 'freshness' unless the peri-mortal circumstances are known (Bremner and Sakaguchi, 2000).

Besides temperature control methodologies (*e.g.*: chilling, superchilling, and freezing) (Claussen, 2012) other methods were developed to reduce fish spoilage with minimal impact on sensory, physicochemical and nutritional value contributing for seafood shipment over large distances and extended periods of time (Wang, 2019). Such

Table 2
Summary of the principal methods used for fish freshness determination.

Method	Sensory			Microbial	Chemical				Physical		Spectroscopy
	QIM	Torry scheme	EU scheme	TVC	Volatile compounds	Protein analysis	Lipid oxidation	K-value	Texture Devices (*e.g.*:Torrymeter)	Colour Measurements	UV, VIS NIR; FTIR, Raman spec.; NRM.
Advantages	Human senses. Non-destructive Low cost for industry.			Detection and quantification of microorganisms.	Result of fish decomposition. Detect spoilage molecules. Most used in analytical laboratories.				Fast. Not destructive Suitable on field. Experience not required.	Non-destructive. Fast.	Rapid data acquisition. Parameters simultaneous determination.
Disadvantages	Trained personal. One species one scheme. Torry scheme is destructive.			Time consuming Not all organisms are detected.	Time consuming. Expensive for industry. Specialized personal and equipment's. Influence of diverse variables.				Not used in: thawed fish or chilled seawater. Limited for: fillets, high salt content and damaged fish	Lack standardization. Expensive.	Lack standardization. Relatively expensive.
References	(Rehbein and Oehlenschläger, 2009)			(Gram and Dalgaard, 2002)	(Cheng et al., 2015; Olafsdóttir et al., 1997)				(Cheng et al., 2015)		(Hassoun and Karoui, 2017)

examples are: processing methods (*e.g.*: drying or smoking) (Sampels, 2015); packaging (*e.g.*: vacuum, modified atmosphere, smart packaging) (Fletcher, 2012; Kerry, 2012); surface decontamination (*e.g.*: high pressure, irradiation, natural antimicrobials) (Wang, 2019); edible films (Janes and Dai, 2012); chemical methods (Skåra et al., 2012) and transportation (Hansen et al., 2012; James, 2019).

All the produced knowledge leads to a variety of methodologies to choose, enabling companies to adapt their production methods according to their objectives and/or client demands. The preferable targets for such studies are the most profitable and produced species, like salmonids. Other species have been studied, as they gain relevance in the market, also contributing for diversification of aquaculture production (*e.g.*: *Dicentrarchus labrax* (Mokrani et al., 2018), *Sparus aurata* (Alexi et al., 2017), *Seriola dumerili*, *Pagrus major* (Bosco, 2010) and *Boops boops* (Bogdanović et al., 2012)).

3.2. Safety in the aquaculture sector

Although aquaculture has the potential to feed millions of people, improper facility management (*e.g.*: inappropriate stock density, cage location, and feed excess) may severely degrade aquatic ecosystems and pose health risks to consumers, through contamination with natural and man-made hazards (Grigorakis and Rigos, 2011). Also, several pathogenic agents that can be found in the aquatic environment, in some cases can affect only aquatic life but in others also affect humans. Consequently safety control in the aquaculture sector is basic precondition of adequate quality of the fish, through quality management of the facilities and fish health management plan (Sitjà-Bobadilla and Oidtmann, 2017), (for occupational health and safety hazards see Guertler et al., 2016; Holen et al., 2017 or Moreau and Neis, 2009). These control plans will further impact the overall quality conception of the final product, on the consumer perspective (as explained in section 2.2).

In a broader analysis, as in the case of aquaculture quality, the preconditions for safety can be linked to sustainability, environmental concerns, and product consumption security. In recent years, the risk of propagation of infectious or toxic agents and the occurrence of disease outbreaks have increased (Fèvre et al., 2006). The principal reasons for disease risk increment are related with: i) consumption of raw or minimally processed fish; ii) international transactions of aquaculture products and their derivatives; iii) diagnosis methodologies; iv) changes in ecological balance; v) pollution and climatic changes (Brugere et al., 2017; Daszak et al., 2001; Semenza and Menne, 2009). To some extent, all contributed to alterations on the dynamics of the relationship between individual animals, infectious agents, and people, influencing pathogen rates of replication and proliferation, broadening transmission times, geographic distribution and host species (Brugere et al., 2017).

In the following subsections, these themes will be discussed, giving emphasis to facilities management and fish diseases control (subsection 3.2.1), as to safety in seafood consumption (subsection 3.2.2.)

3.2.1. Facilities management and disease control

The occurrence of disease outbreaks of aquatic origin has become one of the most important safety concerns in aquaculture production in the last decades (Bayliss et al., 2017). The occurrence of contamination/infection of fishes or humans, due to bacterial, viral, parasitic or biotoxin infections, have been responsible for the interruption of the production cycles, heavy losses and unsustainable activity development (Rigos and Katharios, 2010).

Fish and other aquatic animals live in symbiosis with their environment which makes them especially sensitive to many substances found in water, both natural and anthropogenic (Boyd, 2017). Disease development in aquaculture can be a multifactorial occurrence that can be explained by the conceptual model of disease triangle (Fig. 2), a classic pathology concept (Gurr et al., 2011; Scholthof, 2007). This

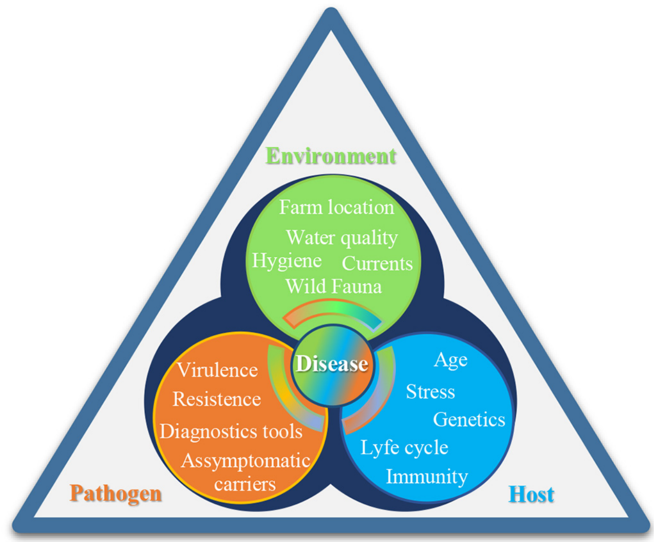

Fig. 2. Aquaculture disease triangle. Description of common parameters for evaluation of pathogen, host and environment interactions, based on Sitjà-Bobadilla and Oidtmann (2017) and Scholthof (2007).

model examines the interactions between the environment (Beveridge, 2004; McNevin, 2017; Svobodova et al., 2017), the host (Boyd, 2017; Mateus et al., 2017; Thompson, 2017) and the infectious (or abiotic) agent (Bricknell, 2017; Oidtmann et al., 2011b, 2013), to understand how epidemics might be predicted, limited or controlled (Scholthof, 2007). The relationship between the three are complex, as the presence of a pathogen does not necessarily lead to the development of disease (Sitjà-Bobadilla and Oidtmann, 2017). Sitjà-Bobadilla and Oidtmann (2017) adapted this concept to aquaculture and resumed it in 13 factors (divided through host, pathogen and environment) that intervene in the emergence and spread of diseases in the aquaculture industry (Fig. 2).

Controlling the factors of one of the triangle vertices could impair the disease development, reducing the impact of the outbreak in the production (Scholthof, 2007). Most common fish pathogens are presented in Tables 3, 4 and 5, addressing virus, bacterial and parasitic diseases, respectively. The tables give a general overview of each type of infectious disease (causative agent, occurrence, symptoms) common in marine aquaculture. Other diseases that affect important economically species like salmonids (viral haemorrhagic septicaemia (VHS); infectious hematopoietic necrosis (IHN); infectious salmon anaemia (ISA); Koi herpes virus (KHV); epizootic hematopoietic necrosis (EHN); epizootic ulcerative syndrome) are not addressed in the tables. Specific information about them can be found at the European reference laboratory (www.eurl-fish.eu), world organization for animal health (www.oie.int).

Even with accumulated knowledge on pathogenic agents, many others will remain undescribed to science or will pass undetected, due to the vast number of fish species and diversity of pathogens that can infect them, but also due to lack of resources to carry out the necessary studies (Bricknell, 2017). In recent years there was greater attention on the implementation of management, production, and biosafety regulations, with the aim to reduce the impacts of aquaculture in the ecosystems (Oidtmann et al., 2011b; Vendramin et al., 2016). This implies control of the rearing conditions, the susceptibility to disease or pathogen occurrence and environmental degradation, avoiding in this context, an overall reduction in performance (*e.g.*: growth) (Jeney, 2017). The measures needed to mitigate these occurrences are well known both by policy makers as by aquaculture sector, throughout not only adequate technical equipment installation (Beveridge, 2004) but also good quality water, well-balanced feed, and good aquaculture practices (Cole et al., 2009; Jensen and Greenlees, 1997). The

Table 3
Common marine viral diseases in fish species other than salmonids.

Disease	Occurrence	Clinical signs	References
Lymphocystis disease	22 and 27 °C, Younger fish are more susceptible. Incubation time is 10 days at 25 °C. Detectable for at least 4 weeks after the fish recover. Surviving fish are apparently immune to reinfection	Macroscopic clusters of hypertrophic dermal fibroblasts (whitish, greyish or darker)	(Crane and Hyatt, 2011; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)
Viral encephalopathy and retinopathy	Juvenile and larval Adults chronic asymptomatic carriers Elevated temperatures Incubations time 4–30 days	Neuro invasive eyes and brain. Impaired coordination, loss, whirling swimming, blindness swim bladder hyperinflation, and hyper excitability in response to noise and light.	(Crane and Hyatt, 2011; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)
Red sea bream iridoviral disease (RSID)	When water temperature is > 20 °C	Lethargy, anaemic, haemorrhagic petechial in the gills and splenomegaly. Formation of inclusion body bearing, basophilic, hypertrophic cells within infected organs.	(Crane and Hyatt, 2011; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)
Viral haemorrhagic septicaemia (VHS)	Disease rarely manifests above 16 °C. Juvenile and adult fish under stress conditions Temperatures changes Wide species range	Lethargy, moderate exophthalmia. Haemorrhagic in the ocular tissue, skin and fin bases	(Crane and Hyatt, 2011; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)

implementation of these measures, as well as the development of protocols to monitor the aquaculture activity and its environmental impacts (Halide et al., 2009; Sitjà-Bobadilla and Oidtmann, 2017), are essential for detecting and alerting for relevant changes for the commercial activity (Yazdi and Shakouri, 2010). The data generated can also be an important part, to be integrated into traceability management systems, contributing to the overall quality perception of the consumer and transparency (Iles, 2007; Westerkamp et al., 2019).

Most of these surveillance measures are prophylactic, since the treatment of outbreaks in marine aquaculture are not compatible with the environment (*e.g.*: antibiotics or chemicals), are economically unsustainable and are frequently not practical (Jeney, 2017; Sitjà-Bobadilla and Oidtmann, 2017). The epidemiological challenges to an effective surveillance system are related to rapid detection, representative reporting and accurate diagnosis (Frans et al., 2008). This lead to the development of sensitive techniques for monitoring and diagnosis, prompted by the rapid growth of the aquaculture sector. A summary of these methodologies advantages and disadvantages are present in Table 6.

The implementation of surveillance systems, in which the maintenance of biosafety is preferred in all aspects of the activity, helps to reduce and control the incidence or spread of diseases. Risk based surveillance systems (Cameron, 2012; Oidtmann et al., 2013) or integrated pathogen management strategies (IPMS) (Sitjà-Bobadilla and Oidtmann, 2017), will also enable the readiness of measures to be applied in case of contamination before becoming a significant problem to the farm (Adams and Thompson, 2011; Oidtmann et al., 2011b). It also provides relevant information that can be used by entrepreneurs or governments to sustain national and international protection laws (Brugere et al., 2017; Oidtmann et al., 2011b).

In primary production (*e.g.*: aquaculture), farmers are responsible to assure their product safety. Consequently, control of environmental hazards or the ones with an animal occurrence at the time of catch is important. Therefore, implementation of disease surveillance and quality systems, in aquaculture primary production, will also help in the preparation of processes to control hazards that are directly associated with seafood consumption risks (section 3.2.2).

3.2.2. Seafood consumption risks

The incidence of foodborne illness or zoonosis involving farm-raised fish species as vectors (Gauthier, 2015) will differ from region to region and from habitat to habitat and will vary according to the method of production, management practices and environmental conditions (Cole et al., 2009; Fèvre et al., 2006; Jensen and Greenlees, 1997; Reilly and Käferstein, 1998; Sapkota et al., 2008).

Seafood related illnesses can be divided into three types: infectious, toxic and allergic, (Butt et al., 2004b). The causative agents associated with foodborne illness are: bacteria; parasites; toxins and chemicals. Tables 7 and 8 summarize the causative agents, most common symptoms, risk factors, and are divided into infectious and toxic/allergic agents, respectively.

The degree of risk differs for seafood eaten raw and those cooked before ingestion. Taking this into consideration, seafood can be classified into three main risk categories (Amagliani et al., 2012; Mizan et al., 2015):

1) High risk – fresh or frozen, molluscs and raw fish.
2) Medium risk - fresh or frozen crustaceans and fish, to be eaten after cooking.
3) Low risk - lightly preserved products (*e.g.*: marinated, fermented or cold smoked); semi-preserved fish (*e.g.*: caviar); heat-processed (*e.g.*: pasteurized; sterilised);

Shellfish are one of the main sources of foodborne diseases due to its nature. Being filter feeders, they concentrate pathogenic agents inside to levels that are harmful to humans (Vidaček, 2014). Fish products contamination by infectious pathogenic agents occur mainly on the skin and the gut. Muscle contamination in the case of infectious agents occurs by mishandling the product or in the case of toxins and chemicals due to the accumulative effect (Vidaček, 2014).

However, in some cases, infection agents (*e.g.*: parasites, bacteria, and viruses) with origin on the environment or processing plants, pose a lesser risk for human health, if seafood product is properly handled, stored or cooked before consumption (McCoy et al., 2011). In the case of presence of toxins or chemicals since they are difficult to remove from the product and can be heat resistant, more restrict control is necessary (*e.g.*: mandatory label information, chemical routine analysis) once the majority of times they are only perceived after ingestion and when symptoms are presented (Grattan et al., 2016). Therefore depuration (in case of shellfish), environment quality control and compliance with certified quality programs (*e.g.*: HACCP) are of outmost importance, in reducing the occurrence of seafood borne diseases (Vidaček, 2014).

Table 4
Common marine bacterial diseases in fish species other than salmonids.

Disease	Causative agent	Occurrence	Clinical signs	References
Vibriosis	Vibrionaceae family	Facultative pathogens Cold-water vibriosis occurs below 10 °C. Also, at temperate and warm waters	Systemic haemorrhagic septicaemia Lethargy, skin darkening, corneal thickening, anaemic gills, internally, congested visceral blood vessels, intestinal haemorrhage,	(Buller, 2014; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)
Photobacteriosis or Pasteurellosis	*Photobacterium damselae* ssp. *piscicida*	Temperatures above 25 °C increase the probability and severity of the outbreaks. Young fish more susceptible. At lower temperatures, mortality may decrease, but fish become carriers. Pathogen can enter a viable-but-not-cultivable state and survive in the water column for long periods	Splenomegaly Granulomatous-like lesions in the spleen and kidney at more advanced stages appear darkened and in some cases petechiae are visible on the head, gills, operculum and fin bases.	(Buller, 2014; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)
	Photobacterium damselae ssp. *damselae*		Skin ulcers or systemic disease	(Buller, 2014; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)
Pseudomonas infections	*Pseudomonas* spp	Associated in several occasions with the "winter syndrome". The optimum temperature for disease outbreaks is below 16 °C and outbreaks in the Mediterranean area consequently occur during the winter months.	External signs: moderate abdominal distension and keratitis. Occasional petechial haemorrhages on skin and liver. Histopathologic ally, a granulomatous inflammation of connective tissues surrounding the skeleton/cartilage of the head region is observed	(Buller, 2014; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)
"flexibacteriosis", "gliding bacterial disease", "eroded mouth syndrome" and "black patch necrosis"	*Tenacibaculum* spp.	Opportunistic pathogen. Wild and cultured fish of any size can be affected, more severe in younger fish. Prevalent and severe in temperatures above 15 °C. Various stressors and skin abrasions. More frequent during summer than in winter	The mouth appears eroded and haemorrhagic, lesions may open in the skin, fins and tail appear frayed, and foci of gill rot may develop. A yellow pigmentation at the edges of the lesions is often seen due to an accumulation of *T. maritimum*	(Buller, 2014; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)
Epitheliocystis	Obligate intracellular prokaryotes related to the genus Chlamydia	Heavy infections and mortalities occur mainly in juvenile fish. Bluegill showed increased epitheliocyst at 12 °C compared with temperatures above 20 °C	Formation in the host gills and skin, of spherical or ellipsoid "cysts". Flared opercula and respiratory distress	(Buller, 2014; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)
Mycobacteriosis	*M. marinum* and *M. salmoniphilum*	The use of un controlled fish feed. Horizontal transmission from wild-living fish. Invasion through damaged skin or gill tissue.	Skin ulcers and granuloma formation in the form of greyish-white nodules in kidney, spleen and liver, with haemorrhaged in musculature.	(Buller, 2014; Woo and Bruno, 2014)
Streptococcosis	*Streptococcus iniae* *S. parauberis, S. agalactiae, Lactococcus garvieae*	Have both a sporadic and epizootic character. transmission from wild fish to farmed fish fresh trash fish used in the fish diet	Lethal septicaemia. Fish become sluggish. Whirling, spiral, or erratic movements reveal (meningoencephalitis). Exophthalmos with hyphaemia. Superficial haemorrhages. Pale liver and dark red spleen	(Buller, 2014; Woo and Bruno, 2014)
Edwardsiellosis	*Edwardsiella tarda*	Opportunistic pathogen	Skin ecchymosis and ulceration, fin and tail erosion; pale and inflamed gills. Internal organs appear haemorrhagic and oedematous. The kidney appears enlarged.	(Buller, 2014; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)

Table 5
Common marine parasites in fish species other than salmonids.

Disease	Causative agent	Occurrence	Symptoms	References
	Ichthyophonus hoferi	Feeding fish with untreated fish is a main route for transmission	Cutaneous ulcers and granulomatous lesions in internal organs. Occurrence of creamy white nodules on the heart as the most predominant lesions	(Lima dos Santos and Howgate, 2011; Woo and Bruno, 2014)
	Exophiala spp.	Temperatures of 12–14 °C	Fish dark and lethargic, erratic and whirling swimming behaviour. Dermal nodules. round yellow to white granulomas in visceral organs	(Lima dos Santos and Howgate, 2011; Woo and Bruno, 2014)
Kudoa thyrsites.	*Kudoa spp.*	Transferred from native wild populations to infect introduced cage-farmed stocks.	The muscle of the infected fish gets very soft, almost liquefied, during storage	(Lima dos Santos and Howgate, 2011; Pavlidis and Mylonas, 2011)
Enteromyxosis	*Enteromyxum spp*	Transmitted directly from fish to fish, through host ingestion of excrement containing vegetative developmental stages	Inducing severe, chronic desquamate enteritis, emaciation, poor growth, bloated abdomen, sunken eyes and death.	(Lima dos Santos and Howgate, 2011; Pavlidis and Mylonas, 2011)
Protistan ectoparasites	*Trichodina* *Brooklynella Uronema*	Occurring on the skin and gills of fish cosmopolitan, opportunistic pathogens with a tendency to proliferate on stressed or debilitated hosts.	Cause irritation, leading to mucus hyper production and hyperplasia. Gills damage	(Lima dos Santos and Howgate, 2011; Woo and Bruno, 2014)
amylodiniosis (‘velvet disease’)	*Amyloodinium ocellatum*	Presence of these organisms on cage cultured fish suggests that the cages have been deployed in water too shallow		(Lima dos Santos and Howgate, 2011; Woo and Bruno, 2014)
Cryptocaryonosis white spot disease	*Cryptocaryon irritans*		Pinhead-sized whitish vesicles, mucus hyper production, epithelial hyperplasia, corneal cloudiness, skin discoloration, and, with the disruption of the gill lamellar structure, severe respiratory distress.	(Lima dos Santos and Howgate, 2011; Woo and Bruno, 2014)
Protistan endoparasites	Microsporidians	Transmitted directly between fish through ingestion of infective spores	Causing hypertrophy of the host cell and forming a xenoma or pseudotumor.	(Lima dos Santos and Howgate, 2011; Woo and Bruno, 2014)
	Apicomplexans		Wide range of cell types and target organs are invaded.	
Sea Lice and other parasitic crustaceans	*Copepoda & Isopoda*	Copepod on fish has rarely been associated with mortalities, can proliferate and spread to epizootic proportions. Wild species can act as vectors. Some found paired, attached to the buccal and branchial cavities.	All cause irritation, infiltration of macrophages and lymphocytes and induce epithelial proliferation. Damaged in gill filaments. Skin erythema and haemorrhage typically in heavy infestations.	(Lima dos Santos and Howgate, 2011; Pavlidis and Mylonas, 2011)
Flat worms	*Turbellaria.*	Mostly free-living organisms, capable of horizontal transmission.	Shallow pouches in the host's gills or body wall	(Lima dos Santos and Howgate, 2011; Pavlidis and Mylonas, 2011)
	Digenea	Endoparasites Transmission from fresh not treated feed.	Inflammation on internal organs. Found on intestinal tract, peritoneum, swim bladder. Can proliferate in circulatory system.	(Lima dos Santos and Howgate, 2011; Woo and Bruno, 2014)
	Monogean *Polyopisthocotylea*	Hematophagous and principally stationary		(Lima dos Santos and Howgate, 2011; Pavlidis and Mylonas, 2011; Woo and Bruno, 2014)
	Monopisthocotylea	Fins and body surface, juvenile fish; characteristically motile	Hyper melanosis, lethargy, anorexia and weight loss	

Table 6
Principal methods used for diagnostic and surveillance of fish diseases.

	Classical methods	Immuno & Serological methods	Nucleic acids based methods	Commercial kits
	Histopathology; cell Culture; morphological, phenotypic, or biochemical characteristics.	ELISA and its variants	PCR based methods; LAMP; DNA arrays; Restriction enzymes	
Advantages	Fundamental in development of new diagnostic method. Detected new diseases with no other methods for detections are available. Used as confirmation when no other methods are available.	Versatility, simplicity, speed, and possibility to quantify the target pathogen.	Very Specific & sensitive. Allow differentiation to subspecies level; fast comparing to classical methods. No need to cultivate pathogens	Availability of tests Easy application
Disadvantages	Phenotypical close bacteria differentiation difficult Depend on competent (taxonomical) expertise Time-consuming and labour intensive. Ability of the organism to be cultured *in vitro* culture medium, cell lines (for viruses). Needs pure isolation of the pathogens	Difficult to obtain specific and sensitive antibodies antiserum for detection of a pathogen. Expensive to obtain antibodies.	Necessary previous knowledge of the DNA sequence of target species in order to develop primers. Prone to contamination with other DNA molecules	Cost per unit. Number of individuals needed for a relevant degree of trust
References	(Adams and Thompson, 2011)	(Adams and Thompson, 2011; Frans et al., 2008)	(Altinok and Kurt, 2004; Fernández et al., 2008)	(Adams and Thompson, 2011)

3.3. Tracing and tracking in aquaculture

Traceability is a tool for achieving different objectives, such as: assuring food safety and public health, (identify hazards, manage safety warnings, product recalls); to provide reliable information to consumers (protection against fraud; ensure fair trade; prevent unfair competition, environmental performance) and to improve process and product overall quality (stock management; costs reduction) (Ene, 2013; Iles, 2007; Westerkamp et al., 2019).

In aquaculture production, it could be applied the same group of six basic principles for an integrated agro-food chain traceability, they are: 1) product traceability; 2) process traceability; 3) genetic traceability; 4) inputs traceability; 5) disease traceability and 6) traceability of measurements (Bosona and Gebresenbet, 2013; Ene, 2013). All these principles required adequate knowledge on multiple seafood properties, as traceability systems can be composed by multiple datasets related to each of the six principles. According to Olsen and Borit (2013), there are two major definitions of traceability related with the type of information recorded. One is related with the online location tracking system, for food products and all their ingredients; the other is the accurate analysis of all analytically verifiable properties a food sample may have (Olsen and Borit, 2013). The first definition is related to paper documentation and more recently the electronic traceability and condition monitoring using RFID (Radio Frequency Identification) or WSN systems (Wireless Sensor Networks) (Badia-Melis et al., 2015; Musa and Yusuf, 2014; Parreño-Marchante et al., 2014). The second relates to the perishable nature and the variability of fresh food, like seafood. It involves measurement of parameters, typically physicochemical, genetic or microbiological, able to identify and discriminate products (Rehbein and Oehlenschläger, 2009). For each type of data, there is a diverse range of methodologies; Table 9 review their main advantages and disadvantages within the aquaculture sector. Utilization of limited or out of date traceability methods (*e.g.*: paper records) hinders the efficiency of traceability in the supply chain, because they could difficult the communication between participants (*i.e.*: bureaucratic barriers), interaction with other systems and lack of transparency (Appelhanz et al., 2016; Iles, 2007; Westerkamp et al., 2019). In comparison, the incorporation of the most recent traceability methods will allow the integrations of the information on online platforms or blockchain applications, that consequently will improve traceability, transparency, and access to all participants (Appelhanz et al., 2016; Iles, 2007; Westerkamp et al., 2019).

Also accordingly to Dabbene et al., 2014, measurements of the parameters should be used to validate the information of the traceability system which is related to authenticity.

However, even with the large amount of information possible to gather using both approaches, there are aspects of "history, application or location" relating to a food product that it is not possible to get through tracking movement and instantaneous measurements. These include data on yield and economics, properties relating to ethics, sustainability, and legality (Olsen and Borit, 2013).

3.4. Fish product authentication

There is a clear need to verify the trueness of the records and claims gathered for the implementation of traceability methods. Authenticity is the field responsible for validating that information. Through the use of analytical methods and instruments to determine specific food properties, it is possible to relate them, for example, with specific geographical location, organism species or production method (Olsen and Borit, 2013). Therefore regulatory authorities are asking for an extended and updated list of the analytical methods to support law enforcement and confirm the authenticity of food products (Griffiths et al., 2014).

This is also related to the mislabelling of food products which is very common in the seafood sector, despite the clear set of regulations from

Table 7
Most common pathogenic agents associated with infections from seafood.

Origin	Causative agent		Common Sympthoms	Risk factor	References
Bacteria	*Vibrio spp*		Gastroenteritis; septicaemia; necrotising wound infection	Consumption of raw seafood from contaminated waters	(Amagliani et al., 2012; Austin, 2010; Butt et al., 2004b; Novoslavskij et al., 2016; Weir et al., 2012)
	Salmonella spp		Diarrhoea, abdominal pain, muscle aches, fever	Foodborne or waterborne. Environment of processing plants	
	Aeromonas spp		Diarrhoea; a chronic enterocolitis fever and vomiting, cellulitis, muscle necrosis, septicaemia	Raw seafood; fresh and brackish water; refrigerated food products with extended shelf-life	
	Plesiomonas spp		Diarrhoea; abdominal cramps.	Foodborne or waterborne. Cutaneous contact with infected materials, including fishing- related injuries	
	Listeria monocytogenes		Septicaemia and central nervous system infection; fever, myalgia, headache.	Production lines and the environment of seafood processing plants	
	Mycobacterium spp		Granulomatous inflammation of the skin and deeper tissues.	Exposure of wounds and skin abrasions to contaminated water; injuries contracted during seafood processing.	(Gauthier, 2015)
Virus	Caliciviruses (*e.g.* Norovirus);		Gastroenteritis	Sewage-polluted area; Shellfish consumption	(Butt et al., 2004b; Vasickova et al., 2005)
	Hepatitis A virus		Fatigue, myalgia, anorexia, nausea, abdominal discomfort., icterus and dark urine,	Consumption of raw seafood, water; person-to-person contact: foods *via* the faecal-oral rout.	
Parasites	Nematodes	*Anisakis spp*	Abscess or eosinophilic granuloma, epigastric distress, nausea	Seafood open marine waters eating raw, inadequately cooked, poorly salted or smoked	(Butt et al., 2004a; Chai et al., 2005; Lima dos Santos and Howgate, 2011)
	Trematodes	*Opisthorchis spp Metagonimus spp*	Abdominal pain, fever, diarrhoea, headache, nausea, and back pain; anaemia, dizziness; inflammation, ulceration and necrosis of small intestine;	Consumption of farmed freshwater fish and crustaceans; eaten raw, marinated or improperly cooked	
	Cestodes	*Diphyllobothrium latum*	Abdominal pain and diarrhoea and had eosinophilia	Seafood from cold water habitats; eaten raw, marinated, or undercooked	
	Protozoan	Cryptosporidium Giardia	Diarrhoea. Pulmonary and tracheal cryptosporidiosis; Nausea, chills, fever, epigastric pain, and foul-smelling diarrhoea.	Seafood from cold water habitats; eaten raw, marinated, or undercooked	

Table 8
Most common pathogenic agents associated with toxins and allergic reactions from seafood.

Origin	Causative agents		Common symptoms	Risk factor	References
Biotoxins	Amnesic shellfish poisoning		Abdominal pain, vomiting, disorientation, seizures, permanent short-term memory loss. Excessive respiratory secretions. Coma and death.	Molluscs and squid. Viscera of scallops, sardines, anchovies, crab,	(Grattan et al., 2016)
	Ciguatera fish poisoning		Diarrhoea, nausea vomiting, parathesia, reversal of temperature sensation; metallic taste, itching, dizziness.	Large, predatory tropical reef fish (barracuda, grouper, red snapper, amberjack); some types of eels; farm-raised fish feed with contaminated fish.	
	Diarrheic shellfish poisoning		Diarrhoea, vomiting, abdominal pain, headache, fever.	Mussels, oysters, scallops, clams, cockles, some species of crabs.	
	Neurotoxic shellfish poisoning		Consumption: diarrhoea, abdominal cramps, reversal temperature sensation; slurred speech, pupil dilation, overall fatigue, involuntary muscle spasms. Inhalation: allergen like; throat irritation, sneezing, coughing, itchy and watery eyes, burning of upper respiratory tract.	Mussels, clams, whelks, conch, coquinas, oysters, scallops; liver and stomach contents of some planktivarous fish; inhalation of toxin aerosolized by coastal wind and waves.	
	Paralytic shellfish poisoning		Parathesias, nausea, respiratory distress. Muscular weakness, drowsiness, incoherent speech.	Scallops, mussels, clams, geoducks, cockles, puffer fish, some fish, gastropods, crustaceans	
	Clostridium boutulinum		Vomiting, diarrhoea, blurred vision, muscle weakness, dysphagia, dysarthria, and hypoglossal weakness, respiratory failure.	Water sediment. Retail seafood products, depending on the processing and packaging methods	(Butt et al., 2004b)
	Staphylococcus aureus		Food-intoxication syndrome.		(Elbashir et al., 2018)
Chemicals	Veterinary drug residues		Antimicrobial resistance, carcinogenic agents.	Exceed the maximum level or cases where forbidden drugs have been found.	(Vidaček, 2014)
	Environmental	*e.g.*: mercury, cadmium, PCBs; dioxins	Neurobehavioral deficits, neuronal loss, ataxia, visual disturbances, impaired hearing, paralysis and death.	Accumulation in the tissues of marine organisms. Natural occurrence and from industrial and agricultural sources	
	Biogenic amines	*e.g.*: histamine	Allergy-like form of food poisoning.	Time-Temperature abuse or natural occurrence in fish muscle. Produced during bacterial growth	
	Additives	*e.g.*: nitrites	Cause hypersensitivity reactions, or food intolerances.	Processing treatments.	
	Allergens	*e.g.*: parvalbumins	Cause hypersensitivity reactions, or food intolerances.	Individual sensitivity.	
	PAHs; Nitrosamines		Carcinogenic agents.	Processing treatments (*e.g.*: smoking; salting, fermented).	

the EU for this topic (Jacquet and Pauly, 2008). The large numbers of participants throughout the seafood sector, the nature of the information transmitted and the supports used in supply chain transitions increase the possibility of errors and the risk of counterfeits (Fontanesi, 2010). In fact, it was only through the use of DNA based methodologies for identifying species that some recent food frauds were detected (Griffiths et al., 2014).

As in the meat industry, identification of fish species is important also to ascertain commercial frauds. Seafood authenticity is mostly based on morphological characterization. However, there are very similar species that are difficult to differentiate through morphology (Cutarelli et al., 2014). Another problem is related with replacing valuable species with others of lower value, especially in transformed foodstuffs (for example, breaded fillets) (Cutarelli et al., 2014). Therefore molecular methods are becoming one of the prospective standards in the near future to overcome the limits of the conventional labelling and analytical procedures (Lo and Shaw, 2018; Teletchea, 2009). DNA amplification by Polymerase Chain Reaction (PCR) is a very powerful technique to overcome traceability and authentication hurdles due to DNA properties since: i) it is present in all cells and tissues; ii) it is unique for each animal (except for monozygotic individuals); iii) it is stable for long periods and to physical treatments, and iv) it can be easily isolated and analysed (Fontanesi, 2010; Teletchea, 2009). Molecular based techniques have a very high degree of reliability to confirm or deny the origin, descent or strain of animals or products and can also be used as evidence in court (El Sheikha and Montet, 2016). Other techniques have also been applied to address the authentication of food products (Danezis et al., 2016; Luykx and van Ruth, 2008). Among the main fields of study are: genomic; immunology; proteomic; chromatography; isotopes; vibrational & fluorescence spectroscopy; sensory analysis & biomimetic sensors. The main techniques associated to each group are summarized in Table 10.

The selection of the most suitable approach for traceability or authentication depends on the question being addressed, in which part of the supply chain it is located, the amount and type of sample and available funds (Leal et al., 2015; Teletchea, 2009). In addition, multi-analytical capabilities are essential for food authentication studies providing more descriptors and facilitating better classification. However, the ability to manage and analyse these data are falling behind the ability to generate it. To overcome this, various chemometric or data analysis techniques are crucial for the successful development of models (Danezis et al., 2016). The perfect traceability and authenticity tool for seafood products should be fast, simple, cheap, reliable and be applied without major financial burdens or logistical restrictions (Badia-Melis et al., 2015; Luykx and van Ruth, 2008). Currently, while such a method has yet to be developed and validated, the best approach will be the combination of multiple tools that complement each other, therefore maximizing its accuracy and reliability. Future implementation of authentication protocols for traceability or certification should avoid past mistakes and capitalize on previous successes recorded in the implementation of similar methods (Leal et al., 2015).

4. Future perspectives

The principal paths suggested to achieve integrated aquaculture quality systems, are based on sustainable practises, product diversification and transparent traceability (Little et al., 2017). The ability of firms to internationalize, comply with environmental commitment and innovate will determine their survival capacity (Cordón Lagares et al., 2018). An integrated multi-disciplinary chain approach to food quality and safety is necessary, since in the future the most innovative systems, addressing technological, logistical, economic, environmental and organizational aspects, will probably vary with species, country, region and policies (Asche, 2017; Bush et al., 2019).

Several advances have been made in the reduction of the adverse impacts of the aquaculture sector. Most of them through various

Table 9
Common types of information that are part of traceability systems.

Techniques		Advantages	Disadvantages	References
Conventional	Bar codes RFID WSN	Simple to use and most are economic. High data input. Easy integration in present manage software.	Unreadable for damaged labels Absent or limited environmental information Prone to mislabelling and fraud	(Aung and Chang, 2014)
Analytical	NMR IR GC–MS HPLC CE	Analysis of physicochemical attributes. Chemometric provides the ability to detect compounds patterns, related with origins.	Physicochemical properties in fish can be affected by farming system, processing methods, environmental conditions and industrial procedures Stability of the nutritional contents affected by feeds supplied by international companies; Do not provide historical information	(Luykx and van Ruth, 2008)
Genetic	DNA RNA PCR qPCR	Stability of genetic under production and processing techniques. Very specific identification.	Farmed fish present high gene flow between populations in abundant and widely distributed marine fish species. Fish farmers of diverse locations may use the same maternity fish stock.	(Dalvit et al., 2007; Scarano and Rao, 2014)

combinations of technological developments, improvements in existing technology, better management practices and site selection, feed technologies and species development (Edwards, 2015; Klinger and Naylor, 2012). An example in other areas is the strategic utilization of aquaculture by-products to increase margins and improve the sustainability of the industry. Stevens et al. (2018) present a case study of the Scotland salmon industry for the implementation of such an approach. Aquaculture by-products could be applied to products such as protein powders and hydrolysates, oil supplements, collagen supplements, pharmaceutical or animal feeds (Stevens et al., 2018).

However, the principal driver of aquaculture industry development, will probably be related to quality-control based policies and a "farm/sea-to-table" policy (Badia-Melis et al., 2015). Due to globalization in the food trade, quality assurance in the food industry has become a reality. Food chain integrity not only includes concerns with production and product freshness but also origin, fraud, and safety (Aung and Chang, 2014). The high complexity of interactions between all participants, along the supply chain, demands an effective way to address quality demands. To achieve the full potential, it must be scientifically based and responsive to the changes in the seafood production chain (Cataudella et al., 2005). On the other hand, from the point of view of the producers/suppliers, the variety of assurance systems and the implementation costs arouse doubts about the effectiveness of such systems (Bergleiter and Meisch, 2015; Trienekens and Zuurbier, 2008). The limited global dissemination of the assurance, standards and certification schemes may imply the more difficult access to some of the biggest markets. The offer is diverse, and the choice should be done as to whether a given standard is "fit for purpose", rather than whether it covers all categories to the highest degree (Potts et al., 2016). Therefore, considering the risks involved in certification processes and maintenance costs, they could be offset by the benefits. Also, international standards, have to start considering regional specificities, such as traditional market dynamics characteristic of country or region. The lack of sensibility to those issues could impair its implementation, compliance or maintenance, of such schemes (Mialhe et al., 2018). There is a need for correct implementation of innovative technology, standardize quality schemes and protocols, as faster international agreements on methods for validating technologies.

In the case of complex supply chains, such as seafood, assuring high quality is a difficult endeavour. The efficiency of traceability systems is becoming more dependent on the level of transparency throughout the supply chain (Iles, 2007; Westerkamp et al., 2019). Digital technologies and platforms (*e.g.* Amazon and blockchain) open new seas into seafood trade and logistics, having a great capability to change dramatically value chains approach (Bush et al., 2019). They have the capability to decrease uncertainty and information errors between participants, as to satisfy customers' interest in resource origin or sustainability performance (Cook, 2018; Westerkamp et al., 2019). The prerequisite for the application of such technologies is trust between the supply chain intervenient. However, some barriers are related to willingness to provide confidential information and system costs distribution between participants (Appelhanz et al., 2016; Westerkamp et al., 2019). On the other hand is still necessary to debate issues that will arise in a more transparent world, more precisely accountability (*e.g.*: who is responsible to whom and over which time frame) (Iles, 2007).

Table 10
Principal methods for seafood authentication.

Field	Main techniques	References
Genomic	PCR based techniques (SSCP; DGGE; RFLP; RAPD; AFLP; SSCP; ISSR; SCAR; PNA; FINS; Multiplex; DNA fingerprinting; Real Time)	(Asensio Gil, 2007; Rasmussen and Morrissey, 2008)
	Isothermal nucleic acid amplification (LAMP; HDA; MDA; RPA)	(Gill and Ghaemi, 2008)
	Next generation sequencing (454 Pyrosequencing Technology,Roche Diagnostics; HiSeq 2000 Sequencer, Illumnia; Ion Personal Genome Machine System, Thermo Fisher)	(Lo and Shaw, 2018)
	DNA barcoding; DNA microarray	(Lo and Shaw, 2018; Pardo et al., 2018)
Immunology	ELISA; immuno- precipitation; immuno-diffusion; immuno-electrophoresis.	(Danezis et al., 2016; Lago et al., 2014)
Proteomic	Electrophoretic techniques (2-DE; CE; IEF; Urea-IEF; SDS-PAGE; DIGE)	(Lago et al., 2014; Ortea et al., 2016)
Chromatography	Separation techniques (GC; LC; HPLC; UHPLC).	(Danezis et al., 2016)
Non-chromatography	PTR-MS; MALDI-TOF-MS; DART-MS.	(Danezis et al., 2016)
Isotopes	Isotopic techniques (IRMS; MC-ICP-MS; TIMS)	(Danezis et al., 2016; Luykx and van Ruth, 2008)
Vibrational and fluorescence	NIR; MIR; NMR; Fluorescence; Atomic; ICP-MS; ICP-AES	(Danezis et al., 2016; Luykx and van Ruth, 2008)
Sensory analysis & biomimetic sensors	Organoleptic test panels; (e-tongue), (e-nose), (e- eye)	(Danezis et al., 2016; Luykx and van Ruth, 2008)

5. Conclusion

In conclusion, an integrated multi-disciplinary approach to aquaculture development can help reconcile the human and environmental objectives of sustainable development. In order to future changes, become effective in the aquaculture sector, is also necessary an alteration from a consumer-oriented demand for sustainability to an industry motivation and regulatory monitoring (Iles, 2007). The reasons for this are that in some cases, consumers may not be able to further generate meaningful impact for quality or sustainability. Other reasons are lack of motivation, willingness to pay premium prices, or how their change of habits translate into industry improvements (Iles, 2007). Market forces, consumer demand and government regulations all should converge to push a new level of supply chain visibility and sustainability intensification, further redefining the industry.

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Declaration of Competing Interest

The authors declare that we have no competing interests.

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