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Insight into Aquaculture's Potential of Marine Annelid Worms and Ecological Concerns – A Review

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Abstract

Polychaetes are marine annelid worms that can contribute to aquaculture diversification. Its culture has been viable, and commercially attempted, but intensive production has progressed only in few countries around the world. In the countries with no production, marine polychaetes are imported or harvested. A strong and sustained research investment provided to a better understanding of the nutritional requirements and reproduction of some species. Recent studies showed new technical improvements, which can lead to an important progress in productivity and give a new impetus to the polychaete production. Some marine worm species were identified as good candidates for integrated multitrophic aquaculture. The development of cost-effective aquaculture techniques for marine annelid worms is essential to ensure a balance between commercial interests and the preservation of ecosystems. The influence of polychaete aquaculture on the environment and *vice versa* raise important concerns related to ecological security and sustainability of this activity. This review focus on the main technical improvements and advances that have been made in areas as diverse as: aquaculture potential of polychaetes**,** reared species, main species used worldwide, and highlights biological and ecological concerns, important challenges and recommendations.

Key words: Live bait, *Hediste diversicolor*, *Marphysa sanguinea,* Polychaetes

1. Introduction

Marine annelid worms harvesting on sediment shores is an ancient activity and has been an integral part of global coastal life. Nowadays, this activity has been widely spread, since these organisms are a highly efficient bait. The bait collection for both recreational and professional fishing purposes represents a very important business in many regions of the world (Cunha et al., 2005; Carvalho et al., 2013; Watson et al., 2017). Several polychaetes families (such as Arenicolidae, Glyceridae, Lumbrineridae, Nereididae, Nephtyidae, Onuphidae and Eunicidae) are harvested on intertidal flats, in different sediment types, ranging from mud to coarse sand (Olive, 1994; Scaps, 2003; Cunha et al., 2005; Cancela da Fonseca & Fidalgo e Costa, 2008; Carvalho et al., 2013; Mosbahi et al., 2015; Sá et al., 2017; Font et al., 2018).

In the last few years, the trade of live bait has expanded, not only due to its importance as fishing-bait, but also due to its potential as a food supply for broodstock diets for aquaculture, promoting gonad maturation and spawning for a range of hatchery-reared species - *e.g.* soles, shrimps and crabs (Luis & Ponte, 1993; Luís & Passos, 1995, and references therein). Recent studies also indicated that polychaetes could provide a nutritionally correct balance of polyunsaturated fatty acids to crustaceans and finfish, mainly of the Soleidae family, being essential for the maturation and spawning of these species in captivity (Cardinaletti et al., 2009; Alava et al., 2017). Marine annelid worms are key prey species for aquatic organisms, including economically important fish (*e.g.* sole) and invertebrates (*e.g.* shrimps) (Olive, 1994; Dinis et al., 1999; García-Alonso et al., 2008; Garcês & Pereira, 2011; Arias et al., 2013). Polychaetes are also widely used for research, as model laboratory animal, for example in reproduction, ecotoxicology, bioremediation and environmental monitoring studies (Fischer & Dorresteijn, 2004; Pierri et al., 2006; Cardoso et al., 2008; García-Alonso et al., 2008; Gray & Elliott, 2009).

The increasing demand for marine bait boosted the aquaculture production of different marine annelid worms. Although economically viable, the current production cannot supply the market demand (Fidalgo e Costa et al., 2006a; Sá et al., 2017). However, bait harvesting, bait trade (Carvalho et al., 2013; Mosbahi et al., 2015) and non-indigenous species imports may conflict with the marine and estuarine habitat conservation (Font et al., 2018). Bait related activities are deficiently regulated worldwide, even though bait harvesting ecological impacts are considerable. The existing paradigm that bait fisheries are low-value fisheries, of very limited extent, temporally intermittent, that are only ancillary to traditional fisheries, associated with poor data availability, leads to great challenges in order to regulate and manage this activity. This review aims to integrate relevant information on the state and the potential rearing of polychaetes, core technical improvements and production advances, main used species worldwide and environmental concerns related to harvesting and dumping activities.

2. Polychaete's Potential for Aquaculture

There are a limited number of locations where marine annelid worms can be collected in and exploited in an economically sustainable manner and without causing environmental damage. Adding to this, other concerns such as the worm's quality and size, limited access to harvesting areas due to tides and seasonal variations and the problems associated to imports, as introduction of non-indigenous species must be considered. Although imports of non-native species are allowed for live wild harvested bait, aquaculture of non-native species is not legally permitted in some countries, including Portugal. Commercial rearing of native species is an attractive solution to reduce the overcome these problems (Gambi et al., 1994; Olive, 1994; Nesto et al., 2012; Santos et al., 2016). As suggested by Olive (1999), this production would fulfil different needs, such as to: i) reduce indiscriminate harvesting, ii) contribute to cut imports of non-native species, iii) promote the development of new aquaculture products, iv) enhance the species diversification in the aquaculture industry and v) contribute to the development of new markets.

The environmental benefits, which may be gained from increasing bait farming and reducing bait-digging activity, are considerable. Many anglers would prefer to purchase cultured bait rather than dig their own, if the supplies were of high quality and priced advantageously in relation to some of the worms collected from the wild (Olive & Cowin, 1994; Fowler, 1999). Furthermore, the demand for polychaetes has increased as a result of their use to feed other species in aquaculture. In this way, the culture of polychaetes could also provide a mean for supplying other sectors of the aquaculture industry. This is especially true, when marine annelid worms are used for the improvement of diets in hatcheries and larval rearing units, for both finfish and crustaceans. However, the production of polychaetes must be competitive in terms of price, quality and product diversity when compared to the available wild sources, as suggested by Olive (1999). Farmers have been carrying out commercial scale trials, feeding different species with reared ragworms containing special lipid and fatty acid profiles (Olive, 1994), in broodstocks conditioning studies (Meunpol et al., 2005; Cabrita et al., 2006; Cardinaletti et al., 2009) or to increase haematocrit and haemoglobin levels in sole juveniles (Kals et al., 2015). Therefore, there is strong evidence that polychaetes could play an important role as a protein and lipid source in fish and crustacean diets, either as a whole or as part of a compound meal, in some stages of their life cycles (Dinis et al., 1999; Meunpol et al., 2005; Alava et al., 2017).

Integrated multitrophic aquaculture (IMTA) can be a solution to improve the rearing of marine annelid worms in some countries and at the same time contribute to reduce the environmental impact of the sector. Usually, cultured organisms (as fish or shrimp) need frequent feeding of artificial extruded diets. Excessive feed and faeces, deposited on the bottom of the pond, can lead to organic accumulation. In this environment, some polychaetes do not require feed supplementation once they are omnivorous and able to adapt their feeding mode, depending on food source availability (Vedel and Riisgård, 1993; Pousão Ferreira et al., 1995; Carvalho et al., 2007). Organic matter brought in during sea water exchanges may be enough for marine biomass production and simultaneous treatment of mariculture wastewaters using sand filters, as suggested by Palmer (2010). Nevertheless, additional feed and organic debris could be helpful to achieve a faster growth rate and maintain a higher rearing density. Therefore, polychaetes can be cultured together with some species (that have complementary feeding habits and produce additional organic enrichment) or with the concentrated waste sludge containing not only fish faeces but also uneaten feed and bacterial biofilms (Bischoff, 2007; Fang et al., 2017). These species could include fishes, oysters, mussels, shrimps, or algae (Barrington et al. 2009; Bischoff et al., 2009; Bischoff et al., 2010; Brown et al., 2011; Bergström et al., 2015). These integrated rearing systems have environmental and economic benefits and could contribute to the sustainable growth of aquaculture, based on new production technologies and systems, which increase the quality of the effluents and reduce the impacts on the environment. Marques et al. (2017) have tested the integrated use of polychaete-assisted sand filters and halophyte aquaponics for the biomitigation of a super-intensive marine fish farm effluent. The integrated multi-trophic aquaculture system tested in this study showed a significant decrease of organic matter but also a substantial potential for mitigation of dissolved inorganic nutrients (67% decrease efficiency). In the last decade of the twentieth century, scientists manifested an increasing concern regarding these impacts (Troell et al., 1999) and more researchers have been developed their research with IMTA or "Sustainable Coastal Production Systems" techniques (Newkirk, 1996; Buschman et al., 2001; Giménez Casalduero, 2001) to promote the sustainability of the aquaculture production systems.

The growth and resulting nutritional composition of cultured *Alitta virens* (M. Sars, 1835), which was fed with waste from a recirculation system holding juvenile Atlantic halibut *Hippoglossus hippoglossus* (Linnaeus, 1758), were evaluated by Brown et al. (2011). The presence of highly unsaturated fatty acids (HUFAS) such as DHA (docosahexaenoic acid), EPA (eicosapentaenoic acid), and amino acids (AA), greatly enhanced the value of these worms as components for fish or shrimp diets. The fact that these nutrients could be recovered from fish wastes offered a significant benefit in co-culturing these polychaetes with marine fish in recirculation systems. Plus, the authors demonstrated that producting *A. virens* using fish wastes was highly effective. The authors concluded that *A. virens* is an excellent candidate for integrated aquaculture in land-based systems since it can grow rapidly on marine fish recirculation system wastes, converting them into valuable biomass, which in turn may be a source of food for other aquaculture species. The rearing of the polychaete *Hediste diversicolor* (O. F. Müller, 1776) fed with faeces from the carpet shell clam *Ruditapes decussatus* (Linnaeus, 1758) points to similar conclusions (Batista et al., 2003a). A recent study confirmed the potential of this species for the bioremediation of super-intensive marine fish farm effluents and highlighted its ability to retain high value nutrients (*e.g.* HUFA in general and EPA in particular, and to a lesser extent DHA) from fish feeds that would otherwise be lost from the production environment (Marques et al., 2018).

Other suggestions made by Fowler (1999) should be taken into consideration. This author advises that developments in the bait species aquaculture using locally caught broodstocks, also provide an important potential for the artificial restocking of the populations severely depleted by overexploitation. The emergence of systems for the intensive culture of these animals can provide a mean of alleviating the effects of unsustainable bait collection and should reduce the need for bait imports. It is essential that the emerging polychaetes rearing industry does not itself impose an unsustainable demand on the natural environment (*e.g.* for broodstocks). The closed cycle aquaculture of polychaetes is complete for some commercial species as *A. virens* but not totally controlled for other important species. Although the development of laboratory strains is possible, aquaculture species are usually genetically different from the wild species and increase environmental concerns about possible escapes or dumping from fishing activities. Closed cycle aquaculture of marine annelid worms can become independent of wild resources except for the occasional renewal that enhance the genetic variability of the stocks, reducing the environmental concerns in case of escapes or introductions.

The systems developed for the culture of these worms should, therefore, include the implementation of an effective breeding protocol, which includes: broodstock rearing to alleviate the need for inputs from natural populations, procedures for mass fertilization, production of larvae and juveniles, appropriate types of new diets, optimal densities, and optimization of biomass production (Olive, 1999; Prevedelli, 1994; Prevedelli & Zunarelli Vandini, 1998; Safarik et al., 2006; Nesto et al., 2012; Santos et al., 2016).

Polychaete aquaculture has been developed for several species but there are hurdles to develop this activity. Research that allowed knowledge to produce new native species can enhance the diversification of the bait produced, develop simple inexpensive systems for rearing juveniles (García-Alonso et al., 2013), extend of breeding season and/or cryopreservation of larvae to achieve larval supply all year round, develop appropriate breeding protocols (Nesto et al., 2018), optimize growth through control of nutrition with new diets (Santos et al., 2016), temperature and, if appropriate, photoperiod (Olive, 1999), all contributing to improve the production of polychaetes.

2.1. Farmed marine annelid worms

The aquaculture of polychaete worms, in Europe, began in the United Kingdom (UK) and Netherlands and has been further developed in the last few years. Farmed bait in Europe currently mainly comprises the polychaete *A. virens*, commonly known as sandworm or king ragworm. The commercial aquaculture of *A. virens* was initiated in 1984 in England and, almost simultaneously, similar developments took place in the Netherlands (Olive, 1999). An UK company specialized in the production and sale of *A. virens*, reached production values of 30 tonnes per year in the late 1990s (www.ukmarinesac.org/activities/bait-collection) and became the industry leader. In 2003, an USA company and an aquaculture research center developed the world's first indoor recirculating marine polychaetes worms farm. The rearing method to produce polychaetes can be of the intensive type, as the one adopted in the United Kingdom with *A. virens*, or a semi-intensive and integrated culture using residual waters from aquaculture, which are rich in pseudofaeces and in residues. The integrated aquaculture system has been adopted predominantly in Asia and Oceania for other species. This method produces a reasonable quantity of biomass with reduced environmental effects (Folke *et al.* 1998). Applied research has also lead to significant results in various non-European Union countries, such as Australia, China and Korea (Nesto et al., 2012). In

Qidong, Jiangsu (China) there is a company that produces mainly *A. virens* (Nesto et al., 2012). This reared worm is available either alive or preserved frozen. Another UK company produces, markets and develops raw materials from *A. virens* derived products which make up the oil and protein elements of aquatic animal feeds. The established industry of polychaete production has shown a sustained pattern of growth, and aquaculture has become an accepted mean of supplying the market.

In Australia, the main polychaete farm has been established since 1996. Besides *A. virens*, it produces other species, mainly *Diopatra aciculata* (Knox & Cameron, 1971). Scaps (2003) reported that *Perinereis brevicirrata* (Treadwell, 1920) is produced in Taiwan to export to Japan, and that small farms producing *Perinereis* spp. are also found in southern Japan.

The polychaetes production is based on adult specimens which are usually collected from their natural habitat when they are mature. According to Serebiah (2015), marine annelid worms can be kept at room temperature, in aerated tanks or aquaria, using artificial seawater. In some species, adults can be sexed according to the colour of their gametogenic parapodia. The same author refers that adult male and female worms are best kept in separate tanks to prevent premature spawning, although this is not easy to do with all the species. Separation is easier in tube dwelling polychaetes, once a longitudinal cut is quickly repaired by the worm. Larvae can be obtained naturally with males and females in the same tank (Santos et al., 2016) or with artificial fecundation (Serebiah, 2015). Nesto et al. (2018) evaluated the effectiveness of two fertilization conditions, *in vitro* and natural, using tissue homogenates or thermal shock. Percentages of fertilized eggs and number of larvae were higher using *in vitro* fertilization, while low rates of fertilization and hatching were observed when mature individuals were induced with thermal shock. These authors also suggested that male tissue homogenates can induce females to successful spawn with high fertilization and hatching rates.

Sediment should be used in the rearing tanks to simulate the polychaetes' natural environment in large concrete tanks, other type of tanks, polyethylene containers or in aquaria for experimental trials. These systems, are used for conditioning a broodstock or to grow juveniles, with a sediment layer of 6 to 15 cm high (Nesto et al., 2012; Santos et al., 2016). Sediments should first be washed, or frozen, to kill any organisms remaining. Kaba'ah (2015) evaluated the use of the polyethylene beads as substrates for rearing *A. virens*. The author concluded that artificial substrate materials did not enhance culturing and growth of this worm, compared to sand, and had significant negative effects on the productivity.

Concerning feeding, Serebiah (2015) suggested the use of concentrated liquid invertebrate food, diluted and broadcasted evenly over the sediment, once per week. Commercial fish meals used daily (Santos et al., 2016) or three times per week *ad libitum* (Nesto et al., 2012) were also mentioned as diets for marine polychaetes.

Aquaculture of marine annelid worms has potential to grow since polychaetes can be produced in a sustainable way, to fulfil demand needs at a competitive price when compared to the wild animals. Overall, the aquaculture success of these worms is determined by having optimal environmental conditions, but increased human activity along the coastline (Halpern et al., 2008) can increase the cultivation's risks.

2.2. New potential candidates

According to Pires et al. (2012) *Diopatra neapolitana* (Delle Chiaje, 1841) is the most abundant and widespread species of the genus *Diopatra* in Ria de Aveiro (Portugal) but *Diopatra marocensis* (Paxton, Fadlaoui & Lechapt, 1995) also has a well-established population at this estuarine system. These authors studied the reproductive cycle of this *D. marocensis* population and concluded that *D. marocensis* is the biggest species with direct development, with the highest number of eggs and larvae inside the parental tube. This species reproduces along the whole year, being the main reproductive period extending from April to September. This characteristic, associated with its high commercial value, makes *D. marocensis* a candidate with high potential for aquaculture purposes.

Giangrande et al. (2014) evaluated the growth of the polychaete *Sabella spallanzanii* (Gmelin, 1791) in rearing experiences with the purpose of using the biomass as a dietary supplement for fish nourishment. The growth of this species was measured in suspended plastic nets, in two sites with different trophic features, where the specimens were co-cultured with *Mytilus galloprovincialis* (Lamarck, 1819) within a long-line. The authors demonstrated the possibility of obtaining high-value worm biomass coupled with mussel biomass, in a completely non-fed culturing system, without increasing (presumably even reducing) the environmental impact. The polychaete *Perinereis* cf. *nuntia* (Lamarck, 1818) is a tropical endemic species in Thailand that was also cultured in captivity (Poltana et al., 2007). In addition, various studies and private companies have focused their attention on the onuphid *D. neapolitana* (Conti & Massa, 1998; De Murtas et al., 2003), the common ragworm - the nereidid *H. diversicolor* (Fidalgo e Costa et al., 2000; Batista et al., 2003a and 2003b; Masala & Piergallini, 2007; Nesto et al., 2012; Santos et al., 2016) and the rockworm - the eunicid *Marphysa sanguinea* (Montagu, 1813) (Prevedelli, 1994; Garcês & Pereira, 2011; França et al., 2016).

A strong collaboration between the scientific sector and the aquaculture industry is fundamental to develop polychaete production, since the full understanding and replication of the polychaetes life cycle in aquaculture, nutritional and zootechnical requirements are central questions for a competitive commercial activity. Advances and the potential rearing of two promising species, *Hediste diversicolor* and *Marphysa sanguinea,* are detailed in the following sections.

2.2.1. *Hediste diversicolor* (O. F. Müller, 1776)

The ragworm *H. diversicolor* (O. F. Müller, 1776) occurs in estuaries and lagoons located along the Atlantic coasts of North America and Europe and it has been commonly used as bait and as food for fish and crustaceans reared in aquaculture. *H. diversicolor* is widely used as sea angling bait in Italy (Gambi et al., 1994; Nesto et al., 2012), France (Scaps, 2002) and along the coast of Portugal (Fidalgo e Costa et al., 2006a; Carvalho et al., 2013; Sá et al., 2017). It can grow and reproduce in different types of sediments, since it is a semelparous species, with a high physiological tolerance to a wide range of environmental factors, such as salinity, temperature and dissolved oxygen (Fidalgo e Costa et al., 1998). In laboratory conditions, this worm can use different types of food, including a suspension of clam faeces, extruded diets, semi wet pellets or fish fillet (Fidalgo e Costa et al., 2000; Batista et al., 2003a and 2003b; Santos et al., 2014; Santos et al., 2016). Thus, *H. diversicolor* might be a promising species to be commercially exploited in indoor farming systems, with Recirculated Aquaculture System (RAS) or in IMTA with fish or shellfish productions.

Batista et al. (2003b) have shown that the optimization of the feeding rate of *H. diversicolor* may cause an early sexual maturation, leading to the production of fast growing organisms that breed at smaller size. Increased juvenile growth rate may affect the trade-off curve, which relates fecundity and the development period for ectothermic organisms (Sibly & Atkinson, 1994; Atkinson & Sibly, 1997), including nereidid polychaetes (Olive et al., 1997; Last & Olive, 1999; Prevedelli & Cassai, 2001). In the study performed by Batista et al. (2003b) the polychaetes were fed with a commercial dry diet developed for gilthead seabream *Sparus auratus,* and with a diet for ornamental fish. Notwithstanding, Machado et al. (2016) tried to reduce the lipid content of diets for sea bream and ornamental fish. They observed that a diet with high protein content (60%) and low lipid content (2%) could slow down the process of early maturation in the ragworm *H. diversicolor*. However, since this kind of diet can be expensive and new formulations or alternatives that ensure high protein and low lipid content should be considered.

The potential use of ragworms in aquaculture was suggested to reduce the organic matter of effluents and increase the reproductive fitness of reared animals, in the study performed by García-Alonso et al. (2008). Aquaculture produces huge amounts of sludge that can be ingested and recycled by *H. diversicolor*, maintaining their level of ω-3 polyunsaturated fatty acids, when compared to ragworms fed with commercial fish food or eel sludge. This can be useful in order to decrease the consumption of fish meal in the aquaculture industry. Batista et al. (2003a) conducted a study with *H. diversicolor* fed on faeces of the carpet shell clam *Ruditapes decussatus* during 65 days and observed that worms were able to grow using the clam faeces, in the presence or absence of sediment. However, the worms from the trials with sediment showed a higher survival rate and greater biomass production than those from the trials without sediment. These findings suggest that a suspension of bivalve faeces can be used for *H. diversicolor* rearing in integrated polyculture systems. Carvalho et al. (2007) highlight the reduction of organic matter content in ponds in which *H. diversicolor* have been introduced has a major result of their work, most likely related to the activity of this species on the sediment reworking. Bergström et al. (2015) examined the potential use of burrowing polychaetes in remediation efforts on sediment organically enriched by mussel aquaculture. Their results showed that the decomposition of freshly produced mussel faecal pellets was enhanced by the presence of *H. diversicolor*, either by direct consumption of the faeces or by bioturbation activity. Oxygen conditions are significantly improved after the addition of polychaetes at naturally occurring densities. However, these authors considered that further technological developments are needed in order to allow this approach to be used by the industry.

It is worthy to note that high-protein diets (commercial fish meals) allow higher growth rates. Nesto et al. (2012) reported that both growth and survival rates were higher at the lowest densities (300 ind.m^{-2}), whereas the processes of gametogenesis and sexual maturation were not influenced by density. According to the same authors, the choice of appropriate diet formulations and the modulation of stocking densities are of great importance to commercial sized organisms, within 3.5 - 4 months from hatching. Organisms maintained at a density of 1000 ind.m^{-2} and fed with high-protein food (66% protein) showed the highest values of daily biomass production. However, this kind of diet has also shown to start out earlier gametogenesis processes and earlier sexual maturity stages.

Bagarrão et al. (2014) evaluated the effect of salinity on juvenile's growth and determined the lipid composition of these organisms at different salinities. The fatty acid profile is an important characteristic when these polychaetes are introduced in aquaculture diets for fish species, like broodstocks collections. The experiment was conducted in a period of 60 days, during which three different salinities were tested (15, 20, and 25 psu). The individuals reached specific growth rates between 6.76% and 7.01%, and daily growth rate and final weight were higher in individuals submitted to salinities of 20 and 25 psu ($p < 0.05$), respectively. With this study, Bagarrão et al. (2014) concluded that a salinity of 20 psu may be the most suitable for *H. diversicolor* growth. Regarding the lipid profile, these authors concluded that salinity does not influence the fatty acid composition of this species. Therefore, it is expectable that the rearing of these organisms can be carried out at different locations in coastal zones, without changes in lipid composition.

There are still few studies regarding the fatty acids abundance and profile in ragworms. Luís & Passos (1995) investigated seasonal changes in lipid profiles and composition of wild *H. diversicolor*. Fidalgo e Costa et al. (2000) determined the growth and survival rates of juvenile common ragworms fed with six different diets in laboratory; each of them was analysed for organic matter, caloric and total lipid content and the fatty acid content of the worms was related to the specific diet. It is worthy of note that higher levels of DHA and EPA allow a higher incorporation of HUFA, which results in higher survival rates and better growth of worms. Santos et al. (2016) studied the effect of different diets on the growth of *H. diversicolor* juveniles, as well as the fat content, fatty acid profile, and protein content in their tissues, aiming to find an appropriate diet to be used in commercial aquaculture. Juveniles fed with commercial diet for seabream, had the highest final individual weight (0.89 ± 0.10 g) and the highest daily growth rate. This study showed that the total fat content of the diets was reflected in the fat content of the reared worms. Individuals fed with a commercial diet for sole had the highest fat content (2.25%), the ones fed with seabream dry feed showed similar results (2.18%) and the lowest percentage was observed with the mackerel diet (0.85%). Regarding the fatty acid profile, the major fatty acids found in juveniles fed with the three different diets were palmitic acid (C 16:0), with a higher value in the individuals fed with mackerel's fillets. Oleic (C 18:1 n9), eicosapentaenoic (C 20:5 n3), docosahexaenoic (C 22:6 n3) and stearic (C 18:0) acids were also higher in *H. diversicolor* fed with experimental diets. Marques et al. (2018) showed that *H. diversicolor* enables the recovery of HUFAs (*e.g.* EPA, DHA and AA) and palmitic acid into the tissues of these polychaetes. These FA can be reintroduced into productive systems through the potential of *H. diversicolor* to recycle these key ingredients available in different food sources originating from cultivated fish.

According to the previous studies, the use of *H. diversicolor* can possibly reduce the production of waste and be produced in integrated multitrophic recirculation systems. This species is able to switch its feeding behaviour (Scaps, 2002; Fidalgo e Costa et al., 2006b) and, thus, fish faeces, uneaten fish food and sediment borne bacteria are possible sources of nutrients to the worms. Investigation regarding the type of systems, new diets and “waste” resources is needed. In spite of all this research development in the last decades, *H. diversicolor* has not been adopted as a commercial species. A solution to promote the growth and biomass increase and, at the same time, delay the maturation is crucial to improve this species production in aquaculture, since this species is semelparous, with a single reproductive event before the death of the mature worms.

2.2.2. Marphysa sanguinea (Montagu, 1813)

Prevedelli et al. (2007) studied a population of *M. sanguinea* y in Italy and found that the first phases of larval development took place in the maternal tube, which constitutes the only protection system for the eggs. Larvae (trochophores) reach the surface and continue their development after they have a complete ciliature and the ocular spots become light-sensitive due to strong positive phototropism. Larvae are not very mobile, and the pelagic phase is very short, which generates an early need for substrate material.

Garcês & Pereira (2011) investigated the influence of salinity on the survival and growth rates of *M. sanguinea* juveniles. Their results showed that salinity changes produced an immediate and significant effect on growth. These authors recommended a salinity range between 25–35 psu, since the growth rates decreased beyond this interval. Salinities close to 15 or 40 psu seemed to be the lower and upper physiological limits, respectively, for this species.

Parandavar et al. (2015) evaluated three different densities of rockworm (500, 1000 and 2000 ind.m^{-2}) and showed that the *M. sanguinea* specific growth rates decreased with increasing densities. Nevertheless, daily biomass production in different density groups can vary between 6.28 g.m^{-2}.day^{-1} and 14.7 g.m^{-2}.day^{-1}, suggesting that this can be one of the most suitable species to be commercially exploited in a farming system. However, its production requires knowledge on reproduction and nutrition in order to develop protocols for the reproduction and appropriate rearing techniques.

França et al. (2016) analysed the influence of temperature and diet on the reproduction of *M. sanguinea*. Their results showed that a temperature range of 22 ± 1 ˚C and a diet with high protein levels (plus a low lipid content) originated a significantly higher density of new generation individuals than the other condition used (18 ± 1 ˚C and a diet with lower protein content).

Further research is needed, mainly in concerning the reproduction and nutrition of *M. sanguinea* and also regarding the density and growth potential with new diets. This research should provide support to understand if this species is suitable for a commercial exploitation in indoor or outdoor farming systems.

3. Main species used worldwide

There are several worm species that are specially used by sea anglers worldwide (Table 1). Some of those species are mainly supplied by Korea, China, Vietnam and USA, the major international market suppliers nowadays (Fidalgo e Costa et al., 2006a; Arias et al., 2013; Sá et al., 2017; Font et al., 2018).

Table 1 – List of the worm species that are mainly used by sea anglers worldwide.

Scientific name	Scientific authority	Common or trade name(s)
Alitta succinea	Leuckart, 1847	Pile worm, clam worm
Allita virens	M. Sars, 1835	Sandworm, king ragworm
Arenicola defodiens	Cadman & Nelson-Smith, 1993	Black lugworm
Arenicola marina	Linnaeus, 1758	Lugworm, blow lugworm
Arenicolides branchialis	Audouin & Milne Edwards, 1833	-
Arenicolides ecaudata	Johnston, 1835	Tail-less lugworm
Diopatra aciculata	Knox & Cameron, 1971	Tube worm
Diopatra cuprea	Bosc, 1802	Plumed worm
Diopatra neapolitana	Delle Chiaje, 1841	Solitary tube worm, casulo
Glycera americana	Leidy, 1855	American bloodworm
Glycera dibranchiata	Ehlers, 1868	American bloodworm, common bloodworm
Halla parthenopeia	(Delle Chiaje, 1828)	Llobarrero, minhocão
Hediste diversicolor	O.F. Müller, 1776	Common ragworm, mud worm, minhoca-da-pesca, tremolina
Marphysa sanguinea	Montagu, 1815	Rockworm, ganso
Namalycastis rhodochorde	Glasby, Miura, Nishi & Junardi, 2007	Nypa pal worn, nuclear worm, magic cord
Nephtys caeca	Fabricius, 1780	Large white ragworm, silvers
Nephtys cirrosa	Ehlers, 1868	White catworm

Nephtys hombergii	Savigny in Lamarck, 1818	Catworm
Nereis limbata	Ehlers, 1868	Cinder worm
Nereis pelagica	Linnaeus, 1758	Slender ragworm, red ragworm
Perinereis nuntia vallata	Grube, 1857	-
Perinereis aibuhitensis	Grube, 1878	Korean lugworm, Korean blue ragworm
Perinereis cultrifera	Grube, 1840	Ragworm, green worm
Perinereis linea	Treadwell, 1936	Korean ragworm
Perinereis nuntia	Savigny in Lamarck, 1818	-
Platynereis dumerilii	Audouin & Milne Edwards, 1834	Dumeril's clam worm
Scoletoma impatiens	(Claparède, 1868)	Teagem

There is currently a high market demand for bait, which is sold with high prices. For example, in the four most important Portuguese brackish water systems (Ria de Aveiro, Ria Formosa lagoons, Tagus and Sado estuaries) bait harvest yield an average of 4 million euros per year (unpublished data). In Canal de Mira (Ria de Aveiro, Portugal), the annual harvest of *D. neapolitana* exceeds 45 tonnes and is evaluated at over 325 000 € per year (Cunha et al., 2005). In 2003, a total of 16.87 million polychaetes were imported to Europe from China and USA, via Lisbon Airport, with a worth of 716 180 and 291 845 US $, respectively (Fidalgo e Costa et al., 2006a). Although recent data show a decrease on these importation numbers, they are still relevant with an annual mean value of 14.24 tonnes on the 2012–2015 period (Sá et al., 2017). Watson et al. (2017) estimated that 1600 tonnes of *A. virens* per year (worth £ 52 million) are landed in the UK, with approximately 121 000 tonnes of polychaetes collected globally, valued at £ 5.9 billion. These authors considered that these values are comparable to many of the world's most important fisheries. However, this data also proves that the current landings records for marine annelid worms are underestimated: The National Marine Fisheries Service (2015) recorded only 290 tonnes landed in 2014 for the USA (Watson et al. (2017) estimate a median of nearly 19 000 tonnes), whilst the FAO database has a global mean of only 439 ± 23.7 tonnes per annum from 2000-2012 (FAO 2014). According to Watson et al. (2017) it would be impossible to provide a direct global assessment of all bait collection with the resources and management frameworks available to fisheries agencies. However, where ancillary data are available, local data can be scaled resulting in the first assessments. The lack of reliable data and the non-existent fishery estimates leads to a highly significant gap in conservation management.

Many marketed polychaetes are caught from the wild or come from imports. Both activities carry negative impacts (e.g. risk of introduction of alien species, disruption of ecosystems), which in turn contribute to the growing interest of rearing these organisms. Clearly, not all the mainly used polychaetes could be produced in aquaculture, but advances with some potential species may contribute to the reduction of those negative impacts.

4. Ecological concerns

4.1. Bait importing and dumping

Importation and trade of non-indigenous worms are special concerning subjects, since they are sold as live bait worldwide (Font et al., 2018). Also, baitworms have been described as potentially invasive organisms. According to Çinar (2013), a total of 292 polychaete species, belonging to 164 genera and 39 families, have been transported around the world's oceans with human-mediated assistance. Some species imported and exported as fishing bait became established at non-native locations. The Mediterranean Sea (134 species), the coasts of the Hawaii Islands (47 species) and the Pacific coasts of USA (34 species) have been invaded by non-indigenous species of worms. This kind of introduction can be accidental or intentional. However, if they become dominant in their new environment, these organisms are referred to as “invasive” (NISC, 2006). For instance, Arias et al. (2013) reported that in the last few decades, the rate of biological invasion has increased in the Mediterranean Sea, leading to significant ecological and economic impacts. The risks associated to the introduction of non-indigenous species include, on one hand, the economic and ecological threatening of the coastal marine ecosystems well-being, and, on the other hand, the simultaneous transport of other associated hitchhiker species, which may act as vectors for parasites and diseases (Elliott, 2003; Çinar, 2013). Examples of other species that can be inadvertently inside the package are seaweeds and other organisms contained within or attached to it (Weigle et al., 2005; Yarish et al., 2009; Cohen, 2012; Haska et al., 2012; Arias et al., 2013). These organisms may impact the invaded ecosystem, extinguishing endangered species or causing mass mortality of native host; they are also a risk to public health (Cohen et al., 2001; Arias et al., 2013). The international trade of live bait entails similar risks to those caused by the ballast water of ships in international traffic, being responsible for most of the accidental introductions of non-indigenous worm species worldwide (Fidalgo e Costa et al., 2006a; Sá et al., 2017). Fidalgo e Costa et al. (2006a) reported that the Korean blue ragworm *Perinereis linea* (Treadwell, 1936) (cited as *Perinereis aibuhitensis* (Grube, 1878) has been successfully reared in a closed system in captivity, within the range of the environmental conditions existing in the Ria Formosa coastal lagoon (a Natural Park in the south of Portugal), both from wild imported specimens and from individuals born and grown in experimental circumstances. According to the preliminary results, this species also seemed to be able to reproduce in coastal lagoons and estuaries from the south of Portugal. Despite this, developments in the culture of non-native species should be monitored very carefully and actively discouraged.

Bait operations involve several risk factors, including the large number of imported species, lack of knowledge about the topic of marine invasions, the use of the common names instead of scientific names, and the discharge of untreated holding-tank water and unused products (Weigle et al., 2005). It is known that, for years, a significant percentage of recreational fishermen (approximately 40%) discarded the unused baitworms, wrapping seaweeds and their package into the water (Lau, 1995). Thus, the probability of introducing non-indigenous species increased with this practice (Haska et al., 2012; Saito et al., 2014; Sá et al., 2017; Font et al., 2018), especially because this likelihood is related not only to the number of individuals that are introduced (propagule pressure), but also to the number of release events (Allendorf & Lundquist, 2003). This is of special concern when considering that the numbers regarding the importation of wild bait to European countries are not well known (Fowler, 1999). Micael et al. (2016) reported that only polychaete species were identified as imported live-bait at São Miguel island (Azores, Portugal) and all specimens were identified as *P. linea*. In that study, responses to surveys conducted among 77 anglers showed that 31 % disposed of the remaining bait into the sea. Another field survey was developed at five sites where fishing rods are routinely used, to investigate if the non-indigenous polychaetes sold as fishing-bait were already established in the natural environment of the Azores archipelago. Three species of Nereididae were identified: the native *Neanthes nubila* (Savigny, 1822) and *Perinereis oliveirae* (Horst, 1889), plus the cryptogenic *Perinereis cultrifera*. Weigle et al. (2005) surveyed bait businesses in the Massachusetts region (USA) and observed that 60% of retailers, who imported non-indigenous worm species, received them packed with seaweed. A high percentage of these retailers noticed non-target species within the same package, associated with the imported organisms, within the same package. In addition, almost half of the surveyed retailers were not familiar with the economic and ecological impacts of marine invasive species. Similar conclusions were obtained by Font et al. (2018) to Catalonia. Contrastingly, Sá et al. (2017) examined several live bait boxes purchased at Portuguese stores and all of them were packed with synthetic materials (*e.g.* polyester fibre, sponge and paper pulp), sawdust and sand. The detailed observation of the packing materials indicated the residual occurrence of oligochaetes (*e.g. Enchytraidae*). Those results showed that the packing procedures of importers, such as transferring the imported species into water tanks and re-packing it using inert materials, might be important to reduce the risk of introduction of hitchhiker species.

Recently published, the European Code of Conduct on Recreational Fishing and Invasive Alien Species (Council of Europe, 2014) stated that recreational anglers must 'prevent the release, spreading and translocation of invasive alien species that can have significant impacts on native fish populations or the environment'; also they must 'use bait, particularly live bait, only in agreement with local or national regulations and use aquatic organisms only in the water body from which these were collected' and 'never transfer aquatic live bait from one water body to another'. As usual, the applicability of this code is very low until the different European countries have produced legal regulations to enforce it at the different national levels.

4.1.1. Recommendations for prevention and control

It is essential to educate local fishermen, sport anglers and retailers about the risks of dumping live baitworms, fragmented or as a whole, or even their packing boxes into the sea, and how these actions may have economic and ecological impacts, especially concerning to invasive species (Arias et al., 2013). Promoting the use of native baitworms, plus alerting to the disposal of the unused worms, seaweeds and their containing boxes in the trash (and not in the water), will help to prevent and control the introduction of non-native species (Balcom & Yarish, 2009; Arias et al., 2013; Font et al., 2018).

Haska et al. (2012) proposed the development of practice guidelines, to be used by wholesalers and retailers, and a system of certification, in order to introduce only "invasive-free" bait worm products in the market. Olenin et al. (2011) also made some recommendations, namely: conduct *in situ* continuous monitoring and sampling studies to assess bio-invasion risks; create an international operation to develop criteria defining which species are potentially invasive and which should not be imported and traded; quantify economic losses and compare them to any eventual benefits gained with the introduction of non-indigenous species; involve the general public in the monitoring and report of the existence of non-indigenous species in coastal environments; and use native species in aquaculture projects, whenever possible.

Furthermore, the detailed monitoring of the population dynamics of a species that was already introduced in a certain region, as well as the development of the System of Certification of Origin, with specific name, are options that will help control the problem and will surely be beneficial for the environment, economy and human health, as suggested by Arias et al. (2013).

In addition, it is necessary to implement prevention and control measures regarding the hitchhiker species. Sá et al. (2017) described the procedures adopted by the main Portuguese importer, which consists on a temporary storage of specimens in clean water tanks and their re-packing in new bait boxes with inert packing materials.

4.2. Gathering worms from natural environment

Usually, polychaetes are harvested from intertidal estuarine flats. To collect them, the most used method is bait digging, which consists on manually turning the sediment with a fork or a similar tool and removing the target organisms by hand (Fowler, 1999; Watson et al., 2007; Sypitkowski et al., 2009; Birchenough, 2013; Fidalgo e Costa et al., 2016; Sá et al., 2017). This activity occurs at mid to low tide, both during the night and the day (Fearnley et al., 2013). Watson et al. (2017) estimated that collectors removed on average 1.4 kg of *A. virens* per person per hour, walking a considerable distance across the intertidal sediment, to reach areas that were usually already dug. It is also common to harvest bait using dredges (Beukema, 1995; Sypitkowski et al., 2010). Bait dragging is a method used to collect polychaetes of the family Nereididae, in particular the king ragworm *A. virens* (Birchenough, 2013). This activity takes place at high tide and is conducted from a boat, using hooked metal drags (Dyrynda & Lewis, 1994; Fearnley et al., 2013). The impacts of this method received considerable attention, with studies investigating its effects on ecosystems (Beukema, 1995; Watson et al., 2007). The disturbance can be significant: Klawe & Dickie (1957) estimated that bloodworm diggers dug about 460 m^2 per tide in Nova Scotia, with a tidal amplitude that allows longer digging time per tide. In Maine, bloodworm diggers typically dug about 180 m^2 each tide, and so an average digger digs about 90 $m^2.h^{-1}$ for roughly 2 h each tide (Sypitkowski et al., 2009; Sypitkowski et al., 2010).

Harvesting activity of marine worms may affect the prey availability of target and non-target species, causing direct and indirect negative effects (*e.g.* McLusky et al., 1983; Ambrose et al., 1998; Dias et al., 2008; Birchenough, 2013). It is well known that commercial hand digging of baitworms can disturb the characteristics of the intertidal benthos, affecting intertidal communities, crustaceans, fish, and birds. There is also some evidence that digging releases nutrients and heavy metals from the sediment to the water (Howell, 1985; Milius, 1999; Shepherd & Boates, 1999; Falcão et al., 2006). The supervision of harvesting activities, as well as the policies and concerns on sustainable control of intertidal resources do not act properly. This undefined exploitation contributes to a parallel economy and directly conflicts with a sustainable and controlled activity. The bait exploitation in Portugal is allowed, using hand gathering or restricted gear by licensed persons, but in reality there are large numbers of non-authorised persons collecting bait (Cunha et al., 2005; Carvalho et al., 2013; Fidalgo e Costa et al., 2016; Sá et al., 2017). In Maine (USA), worms must be dug by hand and diggers must pay a nominal fee for a license, but there is no restriction on the number of worms that can be harvested. There are about 1000 licensed marine worm diggers per year and, despite this, the Maine Department of Marine Resources (DMR) does not differentiate worm licenses by target species (Sypitkowski et al., 2010). According to Watson et al. (2007) licences are unlikely to control the level of bait collection on the shore, or the frequency of collection visits, mainly because the variability in the frequency of visits, time spent and the difficulties in assessing what is an appropriate level of activity for a site.

4.2.1. Management measures

Despite the importance of polychaete fishery, which extracts significant biomass and has, consequently, considerable impacts on the environment, there are few regulations (*e.g.* Fidalgo e Costa et al. 2006a; Font et al., 2018). This means that this activity requires urgent governance, similar to the one that controls other fisheries. A considerable part of the polychaetes harvested for bait fishing comes from estuarine protected areas or natural reserves. Species conservation and maintenance of ecosystem functioning should be conciliated with the human interests and economic development. A number of management initiatives have been suggested to reduce conflicts or mitigate the effects of bait collection on the macrobenthic communities. Spatial or temporal zonation is often cited as a method to preserve bait stocks, reduce the impacts on macrofauna and sediments, as well as a method of allowing damaged habitats to recover (Watson et al. 2007). In particular, a rotating system, where different parts of the site are closed, has gained support relying on the idea that these areas may act as sources of recruitment for the exploited species, as suggested by Fowler (1999). Nevertheless, some other macrofauna species suffer immediate impacts and may take many years to recover, even if bait collection is suspended. Permanent no-harvesting zones may be the best option for preserving these species, since it is unlikely that these areas, once subjected to bait collection, will regain the species lost. It is the continued disturbance that precludes their development. Ultimately, the ecological benefit of any management scheme must be tested scientifically before implementation. Naturally, it must also take into account a wide range of social, economic and other ecological issues to effectively manage the resource now and in the future (Watson et al., 2007).

Future prospects

The demand for wild-caught polychaetes could increase and aquaculture can play a key role supplying the markets. This has already led to new studies and to the emergence of a number of polychaete culture systems, advances in nutrition and reproduction techniques. However, more investigation is needed to enable the successful production of new marine worm species. The development of rearing techniques and grow-out procedures are central points. They will allow the culture of new polychaetes, possible in polyculture systems that can enhance aquaculture sustainability, reducing environmental risk and increasing profits.

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