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A short note on the copepods: A brief synthesis and trends

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Abstract
The subclass Copepoda is one of the most important animal groups in aquatic ecosystems. Ecologists, evolutionary biologists, and biotechnologists are continuously trying new approaches for the study of copepods as model organisms for a wide variety of fields in pure and applied science, from evolution and ecology, to their utilization as live feed for aquaculture, as biological control of mosquito larvae, and as bioindicators of water and sediment quality for environmental monitoring, and as a source of protein in local populations. Here we summarize some of the advances and trends in the study of copepods from different approaches. This article highlights the importance of copepods and the need to enhance and intensify the research on various topics related to copepods, some of them for local sustainable development.

Keywords: aquaculture, vector, climate change, bioindicators, nutrition, halotolerance

1. Introduction

Copepods are small aquatic and semiterrestrial crustaceans and one of the most successful animals on Earth. Their total biomass in the world's water bodies make copepods one of the most abundant metazoan groups on the planet [1]. They can be found in the benthos and plankton in a wide range of salinities, from freshwater to hypersaline, and can be found where sufficient moisture and organic matter are present [2]. Copepods are common in marine plankton samples, in estuaries and coastal systems, lakes, ponds, ground water, in artificial containers, and in a variety of cryptic habitats like damp organic soils, forest litter, moss and phytotelmata. They can also be found in a wide altitudinal range from high altitudes to the deepest trenches of the world's ocean. Copepods include free-living and parasitic forms associated to a variety of vertebrates and invertebrates [3-4].

The subclass Copepoda is composed of ten orders [5], with about 21000 species (both valid and invalid) [3]. The body length of most copepods ranges from 1 to 2 mm [3], but some — *Pennella balaenoptera* (Siphonostomatoida), a parasitic copepod of the fin whale— reaches over 32 cm total body length [6]. On the other hand, the smallest copepod known so far is the male of *Sphaeronella monothrix* (Siphonostomatoida), a parasite of marine ostracods, with total body length of only 0.11 mm [7]. The orders Monstrilloida and Siphonostomatoida are exclusively parasites and some species of the orders Cyclopoida, Calanoida, Canuelloida, and Harpacticoida are parasites of or are associated to a wide variety of organisms. The orders Platycopioida, Misophrioida, Mormonilloida and Gelyelloida are exclusively free-living [8]. Calanoida represents the most diverse and widely distributed group and is the dominant component in zooplankton samples [9].

Free-living copepods play significant roles in aquatic habitats and are beneficial in diverse ways. Both planktonic and benthic copepods are abundant and important in aquatic food webs, they graze on primary producers and are eaten by higher trophic levels [10-11]; copepods and their nauplii have high nutritional value [12], and are prey of a variety of other zooplankters and can be a food resource for fish larvae [13]; as they have high nutritional value, they are a potential food source for aquaculture and human consumption [14-15]; several cyclopoid genera and species prey upon mosquito larvae and have been used as a biological control of mosquito-borne diseases [16-17]; since the populations of copepods are very sensitive to climate change and anthropogenic impacts, they are a good subject of study in ecological and ecotoxicological surveys [18-19]. Whilst free-living copepods play a positive role in various ways, parasitic copepods mostly have a negative impact on higher trophic levels causing damage to their hosts [20-21]. Despite their key role in several regions, studies on the copepod fauna are still scarce in many regions and their potential in various fields is still poorly known. Here we summarize briefly the potential use of copepods and the trends in future studies for sustainable development. The names of all the species in this article were updated according to WoRMS.

2. Copepods as a potential biological control of algal blooms

Hypersaline environments have higher salinities than seawater and may even be salt saturated. Hypersaline environments are toxic to most organisms causing the loss of cellular water [22] and the life in hypersaline situations can be energetically demanding [23]. Interestingly, some species of copepods can be found inhabiting hypersaline ecosystems worldwide, and are able to survive at salinities over 300–360 g/L. Copepods are generally osmoconformers [24-25], and display osmotic adaptations at the cellular level increasing intracellular concentration of compatible organic osmolytes/solutes. Such increased concentrations of organic solutes are synthesized either in a cell or obtained from the environment [26-27]. These osmolytes and/or other solutes have four chemical categories, viz. small amino acids and derivatives, carbohydrates, polyols and derivatives, and methylsulfonium and methylamine compounds [27]. Some authors have shown that osmoconforming copepods in hypersaline waters cannot synthesize osmolytes itself to meet their energy expenditure and they acquire halotolerence through consumption of exoosmolytes contained in algal blooms [28-29]. Previous studies showed that the biomass of *Arctodiaptomus salinus* (Calanoida: Diaptomidae) and *Cletocamptus retrogressus* (Harpacticoida: Canthocamptidae *ncertae sedis*) across the hypersaline lakes of Crimea was intense during severe algal blooms of the green algae *Dunaliella* with concentrations reaching 6×10^7 cells/L and 60 g/m^3 [30-31]. Similarly, *Apocyclops* cf. *dengizicus* showed tolerance to hypersaline conditions during cyanobacterial blooms [32], suggesting that cyanobacteria may produce compatible osmolytes under high salinity conditions [26, 23]. Hence, halotolerance of copepods may be due to the consumption of exoosmolytes in microalgae, cyanobacteria and other resources. Several species of copepods displaying halotolerance have already been recorded worldwide [33]. The mechanism by which copepods achieve halotolerance is still poorly understood and the study functional genomics at the cellular and physiological level might shed some light on this phenomenon. The feasibility of the utilization of copepods as biological control of algal blooms [34-35] is a potential field that has not been tackled so far.

3. Copepods in the aquaculture

Aquaculture is the breeding, rearing, and harvesting of fishes, mollusks, crustaceans, and aquatic plants and is a strategy towards the sustainable development, equity, and resilience of interconnected socio-ecological systems [36]. The expansion of aquaculture has become important to meet protein requirements in human consumption, and the development of novel methods in aquaculture is urgently required [16]. The use of live food is very important for larval fish rearing in aquaculture and some invertebrates have been used as live food in aquaculture. For example, *Artemia* and rotifers can be produced massively for feeding fishes. Also, adult copepods and their eggs, larvae, and juveniles constitute alternative live feed for fish larvae because of their high nutritional value [37-38]. However, the utilization of copepods in aquaculture should be done with caution since some of them could be parasitic species that could infect the fishes [39]. The importance of copepods in aquaculture has long been recognized, especially in the rearing of larvae of several marine fish [40]. Calanoids, cyclopoids, and harpacticoids have been used typically as live feed for fish larvae and juveniles in aquaculture (table 1).

Copepods are good candidates as live food for marine fishes in aquaculture [41] and their utilization can improve the survival rate of various fish larvae [42, 16]. Although natural fish food consists of proteins and lipids, it is poor in carbohydrates [43], and cereals are commonly added to fish ponds as a supplementary diet [44]. However, feeding with such supplements may shift the fish diet away from natural food sources [45]. Since natural fish diet has some disadvantages, copepods are used as a potential feed for fish larvae because they have relatively low contents of dry matter (approx. 10%), and are easier to breakdown than dry food [46]. The amount of lipids, fatty acids and amino acids found in planktonic copepods can be highly variable, depending on the season or developmental stage [47-48, 43]. Among the three nutritional values, copepods are rich in fatty acids, which is essential for the development of fish. To improve copepod production with high nutritional value as per the requirement in the hatchery, copepods are fed with algae that are cultured in nutrient-rich medium with additional supply of nitrogen and phosphorus at different concentrations. The availability of nitrogen and phosphorus at different concentrations in the nutrient medium affects the algal quality for grazers, such as copepods [49-51]. Also, the nutrient medium of microalgae consists of micronutrients including copper, selenium, vitamin C, and vitamin E [52-54]. Copepods are picky palate and the traditional method of nutrient enrichment in copepods is not suitable for live food for fishes, and the alternation of nutritional composition in copepods is achieved through the change in dietary of algal nutrition. This can be further improved with extensive research in nutrition and cultivation of copepods for fish larval rearing for aquaculture.

4. Utilization of copepods for human consumption

Fisheries are important sources of food and other commodities worldwide. The demand for seafood and fish-based products have increased and has affected negatively the fish stocks worldwide [36]. Recently, researchers have focused their efforts on utilizing underexploited marine sources (e.g. zooplankton, crustaceans, and algae) to reduce the pressure of currently overexploited fisheries [66]. Zooplankton species supply higher trophic levels with the essential n-3 long-chain (LC) polyunsaturated fatty acids (PUFAs) that they have synthesized from primary producers. *Calanus finmarchicus* (Calanoida) is distributed in the North Atlantic from the Gulf of Maine to the Norwegian Sea and possesses a unique lipid composition, oil, proteolytic and lipolytic enzymes, wax esters, astaxanthin (carotenoid), and chitin [14, 67]. The presence of valuable nutrients in *C. finmarchicus* (Calanoida: Calanidae) and in the genus *Allodiaptomus* (Calanoida: Diaptomidae) has been suggested as potential supplement for human consumption [14, 68]. However, further studies are needed to evaluate the sustainability of direct catching, alternative methods of capture and harvesting at reduced costs.

5. Copepods as a biological control

One of the sustainable development goals is to ensure the health and to promote well-being for all ages [69]. Many diseases are transmitted by mosquitoes and comprise over 17% of all infections, including dengue fever, yellow fever, malaria, Zika, chikungunya, West Nile virus, Japanese encephalitis, Rift Valley fever, and lymphatic filariasis, which causes millions of deaths every year [70]. The best way to prevent and eradicate these diseases is through interrupting the life cycle of the vector using a biological control [71]. Freshwater free-living copepods are commonly utilized as biological control because they feed on mosquito larvae, which are the main vector of several infectious diseases.

For example, dengue is a widely spread mosquito-borne viral disease [70]. Dengue and hemorrhagic dengue have become one of the most important public health issues in Southeast Asia [72], causing the death to over 25.000 million people in the last decades in Vietnam. At present, there are no specific treatments available to treat dengue except a vaccine. Despite vaccine is available, prevention is one of the crucial steps to control this infection. Since copepods prey upon mosquito larvae [73, 17], they are used as biological control in artificial containers in Vietnam, Philippines, and Japan [74-75, 72]. Results of a large-scale mosquito vector project in Vietnam have shown that species of *Mesocyclops* (Cyclopoida: Cyclopidae) is a potential control of mosquito-borne diseases [76]. Although the evidence for the control of dengue is limited, it has been suggested as a sustainable approach to control dengue [77].

Omnivorous copepods of the order Cyclopoida are used as biological control against vector mosquitoes, being the genera *Mesocyclops*, *Macrocyclops*, *Megacyclops*, *Acantocyclops* and *Thermocyclops* the most used (see table 2). Amongst the species more frequently used (e.g. *Mesocyclops aspericornis*, *M. pehpeiensis*, *Macrocyclops distinctus*, *M. albidus albidus*, *Mesocyclops longisetus longisetus*, and *Megacyclops viridis* viridis) *M. aspericornis* and *M. longisetus longisetus* are the most popular given their wide distribution and strong mandibles that facilitate depredation [78]. Since copepods prey upon mosquito larvae, they may control several mosquito-borne diseases. The use of copepods as biological control is a strategy that reduces the use of pesticides, but it is important to have accurate taxonomic studies to identify the most suitable species of copepods. Overall, the use of copepods as biological control of vector mosquitoes may be an effective method, and future studies will help to implement sustainable methods for biological of mosquito-related diseases.

6. Impacts of parasitic copepods in aquaculture

Parasitic copepods belong to the order Siphonostomatoida —75%—, Poecilostomatoida —20%—, and Cyclopoida —5%— [79]. Parasitic copepods can be found in association with all major phyla of aquatic animals [80]. In general, parasitic copepods damage their hosts by attaching and feeding habits and infestation may result in loss of condition of the host [80-81]. Parasitic copepods feed on the host's mucous, blood, and tissues, and their attachment and feeding activities are responsible for any primary disease that develops. Parasitic copepods are one of the most important enemies of fish. The most commonly reported parasitic copepod belongs to the family Caligidae (Siphonostomatoida), also referred to as sea lice, and have been commonly reported in cultures of brackish and marine fish species throughout the world, accounting for approximately 61% of all reports [21]. Species of this family have been responsible for most of the documented disease outbreaks. For example, *Caligus stromatei* (Siphonostomatoida: Caligidae) infected the gills and gill cavity of *Acanthopagrus schlegelii schlegelii*, (blackhead seabream; Pisces: Sparidae) causing mucous proliferation and gill congestion [82]; *Lepeophtheirus salmonis salmonis* caused severe skin erosion and hemorrhaging on the head and back, and a distinct area of erosion and sub-epidermal hemorrhage has been observed in the perianal region in the Atlantic *Salmo salar* (Pisces: Salmonidae) [83, 20]; infection by *Alella pagelli* on black sea bream caused hyperplasia of the gill lamellae [84]. Parasitic copepods causing diseases in fishes are well documented from several parts of the world [21]. The disease outbreaks and subsequent mortalities in salmonid culture caused by sea lice are now under control due to the development of a variety of treatments. Nevertheless, a substantial amount of economic losses is still occurring as a result of indirect mortality, reduced feed conversion and growth, loss of product value, and treatment costs. Despite parasitic copepods have a huge impact on wild fishes, few studies on their diseases and treatments have been published. Further extensive studies on control methods to reduce the impact of parasitic copepods in aquaculture are required.

7. Copepods in ecological studies

Climate change along with anthropogenic disturbances are responsible of continuous changes in the natural habitats leading to serious problems in the global environment [85]. As our planet is changing, an intriguing challenge is to understand how ecological communities respond to global changes. The role of humans in disturbing the natural habitats throughout the world is increasingly evident and the understanding of the consequences of these changes for life on earth is relevant [85-86]. Such environmental changes can be monitored using bioindicators. Along with several meiofaunal animals, copepods also offer several advantages for the study of aquatic ecosystems, e.g. benthic copepods are very sensitive to hypoxic conditions comparing to other meiofaunal animals [87], they are also sensitive to changes in salinity [88], and pollution caused by oil spills [18], and the utilization of pesticides [89], bioaccumulation of microplastics [90] —the latter with severe impacts on higher trophic levels [91]—, and, in general to any change in aquatic environments due to human activities [92-93], they are also sensitive to thermal pollution, agriculture discharge, sewage, metal pollution, and several pollutants [94]. As copepods are sensitive to various stressors, they are considered as a good model in ecotoxicological studies [19]. They are used to detect variations in the environment either positive or negative, and their subsequent effects on human populations [95]. Overall, the study of the variations in community structure of copepods is a valuable tool in ecological and environmental impact studies.

Water is of vital importance for sustainable development since it provides a series of services that contribute to the improvement of the quality of life. It is essential for human health and wellbeing and is included in the sixth goal of Sustainable Development, which says: to ensure availability and sustainable management of water and sanitation for all [69]. Nearly 70% of the planet is covered by water, but only 2.5% is freshwater. Although 1% of freshwater is easily accessible with much of it trapped in snowfields and glaciers, only 0.007% of the planet's water is available for the world's population (7.7 billion people), and has never been available to all people on the planet. For example, only 93% of drinking water is available to the people in Latin America and the Caribbean region and over 34 million people do not have access to drinking water [96].

At present, the availability of water is being affected by the pollution of aquatic ecosystems due to the dumping of chemical products, solid waste, etc., from agriculture, livestock, etc. This, in turn, has led to the eutrophication of rivers, lakes, swamps, etc. Eutrophication can be defined as a process of deterioration of water quality, caused by the increase of nutrients, mainly phosphorus and nitrogen [97]. This process has a great impact on aquatic ecosystems since it leads to a change in the structure of the community [98], resulting in the loss of biodiversity. Eutrophication is a limiting factor for the settlement of some individuals, such as fish, having negative effects on fishing, and as a consequence, food security is put in risk. Likewise, the dumping of these chemical and biological end products can cause serious health problems in the population [99], being eutrophication a global environmental problem and one of the most serious hazards for aquatic ecosystems [100]. With regard to all the above, copepods have been used as biological indicators of pollution, water quality, and eutrophication of aquatic ecosystem [101].

Some species of the orders Cyclopoida, Harpacticoida and Calanoida respond to changes in water quality caused by natural or anthropogenic activities [101-102]. For example, *Metacyclops mendocinus mendocinus, Acanthocyclops robustus robustus, Mesocyclops meridianus, M. ogunnus,* and *Thermocyclops decipiens* are associated with eutrophicated ecosystems, whereas *T. inversus* and *T. minutus* are associated with oligo/mesotrophic aquatic ecosystems [103]. The use of copepods as bioindicators of pollution is an excellent strategy to identify the level and degree of contamination before its effects begin allowing to take rapid actions [104].

Table 1: Main copepod taxa used in aquaculture

Order	Genus	Species	References
Calanoida	*Acartia*	*A. tonsa*	Marcus (2005) [55]; Santhosh *et al.* (2015) [56]
		A. tsuensis	Ohno *et al.* (1990) [57]
		A. centrura	Santhosh *et al.* (2015) [56]
		A. erythraea	Santhosh *et al.* (2015) [56]
		A. clausi	Marcus (2005) [55]
		A. sinjiensis	McKinnon *et al.* (2003) [37]
	Bestiolina	*B. similis*	McKinnon *et al.* (2003) [37]
	Eurytemora	*E. affinis*	Santhosh *et al.* (2015) [56]
	Parvocalanus	*P. crassirostris*	Schipp (2006) [58]
	Paracalanus	*P. parvus parvus*	Marcus (2005) [55]
	Centropages	*C. hamatus*	Marcus (2005) [55]; Santhosh *et al.* (2015) [56]
		C. typicus	Marcus (2005) [55]
	Gladioferens	*G. imparipes,*	Santhosh *et al.* (2015) [56]
	Pseudodiaptomus	*P. euryhalinus*	Puello-Cruz *et al.* (2011) [59]
		P. annandalei	Santhosh *et al.* (2015) [56]
		P. serricaudatus	Santhosh *et al.* (2015) [56]
	Calanus	*C. finmarchicus*	Marcus (2005) [55]
		C. helgolandicus	Marcus (2005) [55]
	Temora	*T. longicornis*	Marcus (2005) [55]; Santhosh *et al.* (2015) [56]
		T. stylifera	Marcus (2005) [55]; Santhosh *et al.* (2015)[56]
		T. turbinata	Santhosh *et al.* (2015) [56]
	Pseudocalanus	*P. elongatus*	Marcus (2005) [55]
Harpacticoida	*Schizopera*	*S. elatensis*	Kahan *et al.* (1982) [60]
	Amphiascus	*A. parvula*	Santhosh *et al.* (2015) [56]
	Amonordia	*A. normani*	Santhosh *et al.* (2015) [56]
	Tisbe	*T. biminiensis*	Ribeiro and Souza-Santos (2011) [61]
	Tigriopus	*T. japonicus*	Fukusho (1980) [62]
	Amphiascoides	*A. atopus*	Santhosh *et al.* (2015) [56]
	Tachidius (Tachidius)	*T. discipes*	Santhosh *et al.* (2015) [56]
	Macrosetella	*M. gracilis*	Santhosh *et al.* (2015) [56]
Cyclopoida	*Pseudomyicola*	*P. spinosus*	Santhosh *et al.* (2015) [56]
	Dioithona	*D. oculata*	Hernandez-Molejon and Alvarez-Lajonchere (2003) [63]
	Apocyclops	*A. royi*	Piasecki *et al.* (2004) [64]
		A. panamensis	Piasecki *et al.* (2004) [64]
	Diothona	*D. rigida*	Vasudevan *et al.* (2013) [65]
	Acanthocyclops	*A. robustus robustus*	Piasecki *et al.* (2004) [64]

Table 2: Main genera and species of Copepod used as biological control

Genera	Species	Geographic distribution
Mesocyclops	*M. aspericornis*	Tropical and subtropical
	M. pehpehiensis	Palearctic region
	M. woutersi	Australasian and oriental region
	M. thermocyclopoides	Australasian and oriental region
	M. brasialianus	Neotropical region
	M. edax	Neotropical region
	M. ruttneri	Oriental region
	M. guangxiensis	Oriental region
	M. annulatus	Neotropical region
Macrocyclops	*M. albidus*	Neotropical region
	M. longisetus	Neotropical region
	M. distinctus	Oriental, Palearctic and Australasian region

Megacyclops	*M. viridis*	Cosmopolitan
	M. latipes	Cosmopolitan
	M. formosanus	Oriental region
Acontocyclops	*A. vernalis*	Neotropical region
Diacyclops	*D. navus*	Nearctic region

Conclusion

In this contribution we summarized the potential importance of copepods. The bibliographic summary on various aspects of copepods highlights their relevance and significance in ecology, human health, aquaculture, and food industries. Copepods might be a useful tool to understand the impacts of climate change, to assess water quality, as biological control against mosquito-borne diseases and probably controlling algal blooms, as live food in aquaculture, and also as a source of protein for human consumption. It is also crucial to understand negative effects of parasitic copepods in aquaculture and on natural populations. This clearly proves that any attempt to understand more about copepods is worthwhile, and will lead to implementation and development of sustainable and efficient methods in all areas of copepod research.

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