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How can saline and hypersaline lakes contribute to aquaculture development? A review*

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Abstract A considerable part of the world's population is currently experiencing a severe scarcity of freshwater and nutrition. Inland aquaculture has the fastest growth in fresh waters, and this contributes to the eutrophication of freshwater bodies. The increase in freshwater aquaculture impacts on the increasing demand for fresh water. A way to overcome this is to develop aquaculture in saline lakes. This article discusses how saline and hypersaline lakes may contribute to overcome this problem and gives a list of fish and shrimp species that can be cultivated in saline lakes. Successful development of aquaculture depends on a healthy cultured stock of commercial fish and shrimps. A sustainable healthy stock of fish and shrimps can be only maintained using live food for the cultured fish larvae, fry and fingerlings. As well as *Artemia* spp. there are many other crustacean species with the potential for growing in hypersaline waters. At least 26 copepod species around the world can live at a salinity above 100 g/L with 12 species at a salinity higher than 200 g/L, and these all have excellent nutritional value. There is a high potential to use eukaryotic organisms of different taxa in saline / hypersaline aquaculture for food, agri-aquaculture, different industries and as food supplements.

Keyword: aquaculture; saline lakes; shrimps; fish; Copepoda

1 INTRODUCTION

The current world population of 7.6 billion is expected to reach 8.6 billion in 2030, 9.8 billion in 2050 and 11.2 billion in 2100 (UN, 2017). The growing population faces many challenges. Currently, a considerable part of the world's population is experiencing scarcity of freshwater and nutrition and these problems are among the most important challenges of the developing humanity (FAO et al., 2015; WWAP, 2015). Currently agriculture supplies about 97.5% of the total food mass production, wild fisheries more than 1.5%, and aquaculture about 1% (FAO et al., 2015). Usage of fresh water by agriculture, municipalities and industries has risen from less than 580 km^3 in 1900 to more than 3 900 km^3 in 2010, and agriculture consumes approximately 70% of the total freshwater consumption in the world (FAO, 2015). Human population growth leads to an increase in the demand for food and irrigation water for agriculture by 60% to 65%. In 1995–2015, the production growth rate for crops was 2.4% per year, for livestock it was 2.6%, and for aquaculture it was 13.7% (FAO, 2009, 2014, 2016). Total aquaculture production increased from about 20 million tonnes in 1995 to 73.8 million tonnes in 2014.

To meet the food demand of humankind there is only one way: to increase aquaculture production (Duarte et al., 2009; FAO, 2016). On a global scale, over the past decade, there has been no significant increase in marine aquaculture production (FAO, 2016). World aquaculture production in inland waters increased from 24.5 million tonnes in 2004 to 47.1 million tonnes in 2014 (Fig.1), and its share in total aquaculture production increased from 58% to 64% (FAO, 2009, 2014, 2016). Inland aquaculture has the fastest growth in fresh waters, and this contributes to the eutrophication of freshwater bodies (Findlay et al., 2009; FAO, 2016), thus reducing the reserve for

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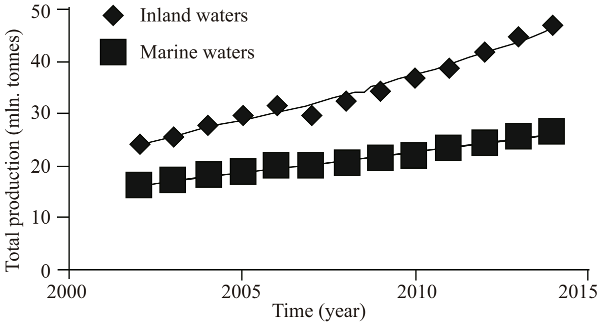

Fig.1 Changes of total marine and inland aquaculture production in the world, mln. tonnes

Based on FAO, 2009, 2014, 2016.

drinking water and other human needs. The question must be asked whether it will be possible for humanity to meet the food demands of its growing population by aquaculture development without damage to fresh water resources. The increase in freshwater aquaculture impacts on the problem of the increasing demand for fresh water. A way to overcome this is to develop aquaculture in saline lakes and cultivation of salt-tolerant crops around them without compromising the supply of drinking water (Rozema and Flowers, 2008; Shadrin and Anufriieva, 2016).

The use of aquaculture in inland saline waters may have great potential to be explored by the development of aquaculture trials in different inland saline waters. The first stage of such aquaculture development should be based on "learning by doing" (Holling, 1978). Conducting such experiments requires the integration of efforts by stakeholders who would include not only scientists, but also the users of lakes, aquaculture specialists, and environmental managers. The main goal of this paper is to stimulate cooperation between those stakeholders to explore the potential of saline and hypersaline lakes to contribute to aquaculture development.

2 THE WORLD DIVERSITY OF SALINE LAKES AND THEIR AQUACULTURAL POTENTIAL

Continental waters consist of both fresh and saline waters (defined as containing >3.0–3.5 g/L salt) (Williams, 1996; Zheng, 2014); their total global volumes are similar with 126 thousand km^3 of freshwater lakes and rivers and 104 thousand km^3 saline lakes (Hammer, 1986; Williams, 1996). Salt lakes are more varied in physicochemical features than freshwater lakes including ion composition. Some of them are closer to marine (thalassic) waters and others have very different dominant salts, for example soda and sulfate lakes (Zheng, 2014). In the lakes of varying salt composition there is often different faunal structure (Belmonte et al., 2012). Environmental filtering by salt composition, biotic interactions and stochastic factors together determine such faunal differences (Poff, 1997; Tolonen et al., 2018). Often it is difficult to separate the role of a single factor. Data from the long-term study (2000–2017) of the Crimean salt lakes shows that abundant species such as the anostracan *Artemia* spp. (Shadrin and Anufriieva, 2017), copepod *Arctodiaptomus salinus* (Daday, 1885) (Anufriieva and Shadrin, 2014a) and chironomid larvae *Baeotendipes noctivagus* (Kieffer, 1911) (Shadrin et al., 2017), which are possibilities for aquaculture, may reach high abundance both in marine and sulfate lakes under salinity range 30–250 g/L. Salt composition is an important factor but there is not enough published data in literature to comment on the role of salt composition in this paper. Saline lakes are widespread on all continents (Zheng, 2014); they played and still play an important role in the history of civilization (Adshead, 1992; Kurlansky, 2002). Salt is one of the essential products for humans; its extraction from salt lakes began more than 5 000 years ago and was widespread in the ancient civilizations of Asia, Europe, Africa and America with the oldest human settlements growing beside those lakes and becoming villages then towns (Lovejoy, 1986; Adshead, 1992; Williams, 1999; Kurlansky, 2002). The use of the therapeutic and cosmetic capabilities of the mud of salt lakes was known in the ancient world and currently lake muds are widely used for therapeutics and cosmetics in different countries (Ma'or et al., 1996; Du et al., 2006; Baschini et al., 2012). Aquaculture is a new potential way to use saline lakes which can generate profit in addition to salt production and mud use. There are good examples of such integrated sustainable use of saline lakes (Zheng, 2014; Shadrin et al., 2016; Shaalan et al., 2018). Most saline lakes are in arid areas (Zheng, 2014) and often people inhabiting those areas have very low incomes; aquaculture development in those areas may improve their economic situation (Jia et al., 2015a; Kavembe et al., 2016).

Due to global climate change and anthropogenic activity, salinity is increasing in natural and artificial water bodies in various regions of the world (Williams, 2001; Shadrin et al., 2015). There is also a high potential for aquaculture development using saline ground water (Shearer et al., 1997). Both freshwater and saline waters are used in continental aquaculture with successful examples of aquaculture in saline lakes in different countries (Jain et al., 2003; Kolkovski, 2011; De Los Rios-Escalante and Salgado, 2012; Jia et al., 2015a, b; Shaalan et al., 2018). However, saline waters are still used for this purpose in a lesser degree than freshwaters. This is not due to the low biological productivity of saline and hypersaline waters, since many of them are among the most productive aquatic ecosystems on the planet (Hammer, 1986; Shadrin et al., 2015). The reason is mainly the inertia of our thinking and activity patterns, traditions and habits. We need to change current aquaculture development priorities. Development of aquaculture in saline lakes must be among our main priorities (Shadrin and Anufriieva, 2016). Freshwater usage conflicts are common in arid countries or places where freshwater is pumped from groundwater or aquifers (WWAP, 2015). A way to overcome this is to develop aquaculture in saline lakes without compromising the supply of drinking water. Saline lake aquaculture may be one of the key elements of a new approach to environmental management of arid/semi-arid zones (Zheng, 2014; Jia et al., 2015a, b; Shadrin and Anufriieva, 2016).

For the development of aquaculture in saline lakes we must take into account the diversity of such lakes (Zheng, 2014). This diversity could provide different opportunities for aquaculture, which need to be considered. The conditions for the existence of organisms and the potential for aquaculture development in water bodies are determined by a complex interlacing of factors (total salinity, salt composition, pH, oxygen regimes, mixing regimes, temperature regimes, etc.). Classification of saline lakes according to their chemical composition (proportions between main ions) has been described many times (Kurnakov et al., 1936; Zheng, 2014; Schagerl and Renaut, 2016). For example, in Crimea, there are two chemical types of saline lakes—chloride and sulphate-chloride (Kurnakov et al., 1936) and there are differences in their biotic composition (Belmonte et al., 2012). The salinity regime of a lake is one of most important factors determining what kind of aquaculture can be developed in it (Williams, 1998; Khlebovich and Aladin, 2010; Shadrin, 2017). There are several classifications of water bodies based on salinity, which have minor differences (Williams, 1996; Zheng, 2014) and they will not be discussed here. Averaging these classification systems, all saline waters may be conditionally divided into hyposaline/brakish water (3–17 g/L), mesosaline/marine salinity (17–35 g/L) and hypersaline water/brine (>35 g/L). The yearly average salinity and also seasonal and interannual salinity fluctuations need to be taken into account to plan a strategy of aquaculture development in a lake. Every species is adapted to live in a certain salinity range (Khlebovich and Aladin, 2010). The halotolerance of the potential aquaculture fauna needs to be known to develop a strategy and technology for culture. Halotolerance of hydrobionts was mostly studied in chloride (chloride-sulphate) waters. Many commercially valuable fish and shrimp species can be successfully cultivated in saline / hypersaline lakes. The ranges of their halotolerance in chloride (chloride-sulphate) waters are given in Table 1. Currently only a small number of these are used in inland aquaculture. Not all species suitable for cultivation in saline lakes are listed in the table. Currently it is impossible to compile a full list because the aquaculture potential and halotolerance range for most species have not been yet studied. Based on the analysis of the literature and own field studies the author concludes that many species of fish and shrimp that are considered as freshwater organisms can be successfully cultivated in the salinity range 3–17 g/L. A salinity range of 17–35 g/L is a good prospect for cultivation of many species of marine origin. Inland Lake Qarun (Egypt) is a good example of this (Shadrin et al., 2016). However, there is a scarcity of studies in this direction. Only few shrimp and fish species can grow at salinity higher than 50 g/L; more such species may be discovered during further experiments. As an example, 71 fish species are found in the East Africa soda lakes, six of these species live at salinity up to 40 g/L, and three live at salinity up to 100 g/L (Kavembe et al., 2016).

Monoculture of fish and shrimps negatively impacts the natural environment and biodiversity (Xie and Yu, 2007; FAO, 2016). Polyculture of organisms of different trophic levels is a way to overcome or mitigate this problem. Now 'Integrated Multi-Trophic Aquaculture' (IMTA) is recognized as one of the main topics in aquaculture development (Alexander et al., 2015; Guerra-García et al., 2017). The IMTA approach allows simultaneously cultivating different species of two or more trophic levels in same pond / lake while the waste of one species is consumed as food by other species. Growth of cultivated animals can be co-limited by the supply of different biochemical essential components (PUFA, vitamins, etc.); a biochemically diverse food organism

Table 1 Common fish and shrimp species which can be cultivated in saline chloride (chloride-sulphate) lakes and ponds

	Min. salinity (g/L)	Max. salinity (g/L)	References
Fish			
Chanos chanos (Forsskal, 1775)	5	120	Jain et al., 2003
Chelon labrosus (Risso, 1827)		100	Hotos and Vlahos, 1998
Clarias gariepinus (Burchell, 1822)	0	12	Hecht et al., 1988
Ctenopharyngodon idella Cuvier and Valenciennes, 1844	0	12–14	Kilambi and Zdinak, 1980
Cyprinus carpio Linnaeus, 1758	0	12–15	Koehn, 2004; Shadrin and Anufriieva, unpubl.
Dicentrarchus labrax (Linnaeus, 1758)	3	40	Johnson and Katavic, 1986
Etroplus suratensis (Bloch, 1790)	10	35 (40)	Jain et al., 2003
Heterobranchus bidorsalis Geoffroy Saint-Hilaire, 1809	0	15	Fagbenro et al., 1993
Lates calcarifer (Block, 1790)	10	40	Jain et al., 2003
Mugil cephalus Linnaeus, 1758	3	110	Hotos and Vlahos, 1996; Jain et al., 2003
Oreochromis mossambicus (Peters, 1852)	5	80	Sardella et al., 2004
Oreochromis niloticus (Linnaeus, 1758)	0	15	Likongwe et al., 1996
Rachycentron canadum (Linnaeus, 1766)	5	35	Resley et al., 2006
Solea senegalensis Kaup, 1858	12	35–40	Imsland et al., 2003
Solea solea (Linnaeus, 1758)	15	50	Imsland et al., 2003
Shrimp			
Macrobrachium nipponense (De Haan, 1849)	0	15 (20)	Wang et al., 2004
Macrobrachium rosenbergii (de Man, 1879)	0	20	Jain et al., 2003
Penaeus indicus H. Milne Edwards, 1837	5	45	Vijayan and Diwan, 1995
Penaeus japonicus Spence Bate, 1888	10	55	Dalla Via, 1986
Penaeus merguiensis de Man, 1888	5	25	Zacharia and Kakati, 2004
Penaeus monodon Fabricius, 1798	3	50	Jain et al., 2003;
Penaeus penicillatus Alcock, 1905	10	40	Chen and Lin, 1998
Penaeus stylirostris Stimpson, 1871	10–15	40	Briggs et al., 2004
Penaeus vannamei Boone, 1931	1	40 (60)	Briggs et al., 2004

composition should promote their consumer growth (Marzetz et al., 2017). As an example, consumption of different osmolytes synthesized by different bacteria and algae can significantly increase halotolerance of animals-osmoconformers (Anufriieva, 2015; Shadrin et al., 2017). In addition to fish and shrimps many eukaryotic organisms of different taxa can be cultivated in saline/hypersaline lakes/ponds to be used in agriculture and aquaculture, different industries and as food supplements, etc. In the wide salinity range up to more than 50–200 g/L, they include different species of filamentous green algae, Crustacea (Amphipoda, Isopoda, Mysida), and larvae of Diptera. For example, among amphipods there are halotolerant species which can live at high salinity (Bayly, 1972; Britton and Johnson, 1987; the author's own data): *Gammarus aequicauda* Martynov, 1931 at more than 150 g/L, *G. mucronat*us Say, 1818 at 50 g/L, *Parhyale inyacka* K. H. Barnard, 1916 at 90 g/L, *Grandidierella bonnieroides* Stephensen, 1947 and *Ericthonius punctatus* Bate, 1857 at 80 g/L. A review on a possible use of halophilic bacteria was published previously (Oren, 2010).

3 LARVICULTURE OF COMMERCIAL FISH AND SHRIMP AND A PROBLEM OF LIVE FOOD ORGANISMS

Successful development of aquaculture depends on healthy cultured stock of commercial fish and shrimps. A sustainable healthy stock of fish/shrimp can be only maintained while using live food for the cultured fish larvae, fry and fingerlings (Evjemo et al., 2003; Das et al., 2012). Artificial feed solely cannot meet all the elements required for their normal development and growth. Food organisms can be cultivated in a wide salinity range from 0 to 250 g/L (He et al., 2001; Kolkovski, 2011; Anufriieva, 2015; Shadrin et al., 2017). The focus of this paper is mostly on the highest salinity where commercial fish and shrimp cannot be grown, in hypersaline waters with salinity higher than 100 g/L.

When talking about food organisms, people generally remember only *Artemia* spp. (Anostraca), which are a key element of our current aquaculture practice (Das et al., 2012). There is a large potential for development of *Artemia* cultivation in lakes and ponds in arid areas (Kolkovski, 2011; De los Rios-Escalante and Salgado, 2012; Jia et al., 2015a, b). As well as for *Artemia* spp. there are many other crustacean species that can be grown in hypersaline waters. At least 26 copepod species around the world can live at salinity above 100 g/L; 12 species at salinity higher than 200 g/L (Anufriieva, 2015). The most halotolerant among them are: *Cletocamptus retrogressus* Shmankevitch, 1875 (Harpacticoida) at salinity 350 g/L, *Arctodiaptomus salinus* (Calanoida) at 300 g/L, and *Meridiecyclops baylyi* Fiers, 2001 (Cyclopoida) at 240 g/L (Anufriieva, 2015). Copepods have excellent nutritional value; they are rich in highly unsaturated fatty acids (HUFA) with a high omega-3 fatty acid (docosahexaenoid acid; DHA) content (Evjemo et al., 2003; Das et al., 2012). *A. salinus* also has a high content of the valuable carotenoid astaxanthin and is now harvested in some saline lakes (Anufriieva and Shadrin, 2014b). Some copepod species can reach a high abundance in hypersaline waters and produce thermo- and halotolerant resting eggs that can easily be cultivated (Jiménez-Melero et al., 2013; Anufriieva and Shadrin, 2014a; Annabi-Trabelsi et al., 2018). Among the Cladocera, *Moina salina* Daday 1888 is the most widespread halotolerant species that can live at salinity up to 220 g/L (Amarouayache et al., 2012). Currently some copepod, cladoceran and rotifera species are successfully cultivated in saline waters (He at al., 2001; Evjemo et al., 2003; Das et al., 2012; Reyes et al., 2017).

Crustacean groups of larger size such as Amphipoda, Mysida and Isopoda also have a potential for cultivation in saline waters as food organisms for fish and shrimp; they are cultivated in some countries (Herrera et al., 2009; Schmalenbach et al., 2009; Guerra-García et al., 2017). Chironomidae larvae are valuable food for fry, fingerlings and adults of fish and shrimps; cultivation of chironomid larvae was started in the USSR in 1940–1950 (Ivleva, 1969), and today it is developing in several countries and gives high profit (Shaw and Mark, 1980; Sahandi, 2011). The widespread *Baeotendipes noctivagus*, occurring in waters with salinity up to 280 g/L, and Australian *Tanytarsus barbitarsis* Freeman, 1961, reaching high abundance at salinity up to 177 g/L, are the most halotolerant chironomids in the world (Shadrin et al., 2017).

All the above relates to chloride and/or chloride-sulphate waters. Animal species richness in soda lakes is lower than in other saline lakes but animal abundance may reach the highest values (Mengistou, 2016; Schagerl and Burian, 2016). Some invertebrate species may be successfully cultivated as food organisms. For example, animals occurring in the East Africa soda lakes are: 1. Rotifera (*Brachionus plicatilis* (Müller, 1786), *Brachionus dimidiatus* Bryce, 1931) at salinity up to 100 and 70 g/L respectively; 2. Copepoda (*Lovenula africana* (Daday, 1910), *Afrocyclops gibsoni* (Brady, 1904), *Eucyclops serrulatus* (Fischer, 1851), *Mesocyclops* sp.) at salinity up to 40–50 g/L; 3. Cladocera (*Diaphanosoma excisum* G.O. Sars, 1885, *Moina* spp.) at salinity up to 40 g/L; 4. Chironomidae larvae (12 species) at salinity above 40–60 g/L; 5. Diptera (*Ephydra* spp.) at salinity up to 160 g/L (Mengistou, 2016; Schagerl and Burian, 2016).

4 CONCLUSION

To develop aquaculture in inland saline waters we need to take into account that there is no one best strategy, design and technology. The optimum strategy and design should be based on the environmentally and economic conditions prevailing in the locality. While learning from experiments a sustainable, environmental friendly and ecosystem-based aquaculture must be developed. Sustainable and ecosystem-based aquaculture is independent of the biomass produced by natural ecosystems and includes representatives of all trophic levels in reasonable proportions. This means that aquaculture farms / production facilities must be diverse and include algae, small invertebrates, shrimp and fish.

Every lake / water body has its own individuality, with its abiotic and ecosystem peculiarities. To develop a sustainable strategy of aquaculture development we need to take the lake's individuality into account. Lakes are dynamic, and can transit from one state to another, shifting from one aquacultural potential to a different one (Shadrin, 2014). This must be taken into account for the long-term strategic development of an aquaculture farm/production facility in every lake. To do this we need deeper and wider knowledge of saline lakes, their ecosystems and objects of cultivation. The keystone for successful development of aquaculture in saline inland waters must be a strong social order and effective cooperation between science and lake user stakeholders.

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