

Effect of a temperature rise on metal toxicity for the aquatic biota: a systematic review

Efeito da elevação da temperatura sobre a toxicidade de metais para a biota aquática: uma revisão sistemática

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ABSTRACT

Ecosystems are subject to various stress factors, such as temperature rises due to climate changes and metal disposal. Thermal stress can amplify or mask the effects of metals on aquatic organisms. This study aims to carry out a systematic review on the effects of temperature rises due to climate changes on the toxicity of metals for freshwater organisms. Searches were made in different electronic databases and article selection was based on the following inclusion criteria: concordance with the question of a systematic review; publication in English, Spanish, and Portuguese between 1960 and 2020; and the use of standard methodology. Forty-three articles were included, which were classified with respect to the year and country of publication, test-organisms and metals studied, temperatures tested, and the effects observed. In 80% of the studies analyzed, a temperature rise was responsible for increasing the toxicity of metals for the aquatic organisms. The temperatures studied contemplated the temperature rise predicted by the Intergovernmental Panel for Climate Change at the end of the 21st century. Brazil stood out among the countries for having the greatest number of research studies in this area, although there is still the need for an increase in studies in tropical climate regions. Based on the literature review, it was shown that the metals most studied were copper and cadmium and the test-organisms most used in the research projects were fish. The information obtained from ecotoxicological studies is essential to predict the effects and prevent the risks associated with the metal contamination of aquatic ecosystems due to climate changes.

Keywords: ecotoxicology; climate changes; microalgae; zooplankton; fish.

RESUMO

Ecosistemas estão sujeitos a diversos estressores, como o aumento da temperatura em razão das mudanças climáticas e do lançamento de metais. O estresse térmico pode amplificar ou mascarar os efeitos dos metais nos organismos aquáticos. Este estudo teve como objetivo realizar uma revisão sistemática dos efeitos do aumento da temperatura, associado às mudanças climáticas, na toxicidade dos metais para organismos de água doce. Foram realizadas buscas em diferentes bases de dados eletrônicas, e a seleção dos artigos teve como critérios de inclusão: concordância com a questão da revisão sistemática, publicação em inglês, espanhol e em português entre 1960 e 2020 e emprego de metodologias padronizadas. Incluíram-se 43 artigos, que foram classificados com relação ao ano e país de publicação, organismos-teste e metais estudados, temperaturas testadas e efeitos observados. Em 80% dos estudos analisados, o aumento da temperatura foi responsável por elevar a toxicidade dos metais para os organismos aquáticos. As temperaturas estudadas contemplam o aumento previsto pelo Painel Intergovernamental de Mudanças Climáticas no fim do século 21. O Brasil destaca-se entre os países com maior número de pesquisas nesta área, embora seja necessário o aumento dos estudos em regiões de clima tropical. Com base na revisão bibliográfica, constatou-se que os metais mais estudados foram o cobre e o cádmio, e os organismos-teste mais utilizados nas pesquisas foram os peixes. As informações obtidas com estudos ecotoxicológicos são essenciais para a previsão dos efeitos e a prevenção dos riscos associados à contaminação por metais dos ecossistemas aquáticos mediante as mudanças climáticas.

Palavras-chave: ecotoxicologia; mudanças climáticas; microalgas; zooplâncton; peixes.

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Introduction

One important variable to be considered in aquatic ecosystems is the temperature, due to its importance in maintaining the species and the metabolism of the aquatic systems (Esteves, 2011). Climate change, deforestation of the riparian forest, the construction of reservoirs, canalization of aquatic bodies, and the disposal of hot water used in the refrigeration processes of refineries, steel mills, and thermoelectric plants are related to the temperature rise of aquatic systems (Qiu, 2012; Raptis et al., 2016).

The aquatic ecosystem biota is especially vulnerable to temperature variations since most of the species are ectothermic, that is, their body temperatures change with alterations in the environmental temperature (Hochachka and Somero, 2002) and temperature rises are associated with alterations in the distribution and a decline in the diversity of phytoplankton (Lenard et al., 2019), zooplankton (Adamczuk, 2016), and fish (Herrera-R et al., 2020) in freshwater systems.

Temperature rises and the entrance of pollutants are considered stressors that affect the occurrence of species in the ecosystems (Noyes and Lema, 2015; Gill et al., 2020). According to the fifth report of the Intergovernmental Panel for Climate Change (IPCC, 2014), the temperature rise could remain below 2°C in 2100 in a scenario of low greenhouse gas release, with the highest predicted increase being above 2°C in 2037 and more than 4.8°C in 2100 in a scenario of elevated gas emission. Freshwater ecosystems are particularly more sensitive to climate change due to the temperature rise and changes in the precipitation patterns and water flow (Da Silva et al., 2020).

An understanding of the consequences of releasing and dispersing pollutants in aquatic ecosystems is one of the challenges of aquatic ecotoxicology. Aquatic ecotoxicology is the study of the effects of toxic chemical substances on representative organisms of aquatic ecosystems (Hoffman et al., 2003). Aquatic organisms belonging to different trophic levels are used to evaluate the potential toxicity of environmental samples, effluents, and chemical substances. Toxicity tests should be carried out with species belonging to different trophic levels to cover the natural variability in sensitivity among the species (Zagatto and Bertolotti, 2006).

The diverse contaminants released into aquatic ecosystems metals are of special concern due to their persistence, bioaccumulation, and toxicity, demanding particular attention from the human and environmental health points of view (Ali et al., 2019). In aquatic ecosystems, metallic ions come from natural sources such as the weathering of rocks and soils, volcanic eruptions, and anthropogenic sources such as untreated industrial and domestic effluents, mining residues, the application of agricultural pesticides to crops, and rainfall in places with atmospheric pollution (Esteves, 2011; Amoatey and Baawain, 2019).

The aquatic biota is subject to a combination of stress agents. In this context, some studies have revealed that a temperature rise can increase the toxicity of some metals in freshwater organisms. In a study concerning the effects of high temperatures and exposure to copper on the

microalgae *Scenedesmus quadricauda*, Yong et al. (2018) determined that the combination of these factors caused significant disturbances in the metabolism of the microalgae. Bae et al. (2016) also showed that a temperature rise of the water was responsible for increasing the toxicity of copper for the microcrustacean *Daphnia magna*. The same tendency was observed by Park et al. (2020) for the fish species *Danio rerio*, in a study aimed at determining any physiological damage in fish exposed to the metal lead and to high temperatures. According to Val et al. (2016), the interactions between metals, temperature, and organisms are too complex to predict the effects on the aquatic biota, since a temperature rise also stimulates detoxification processes and the excretion of certain metals by the individuals, reducing the toxicity of the metal ions.

Various reviews concerning different aspects of temperature rises in freshwater ecosystems due to climate change and thermal pollution (release of hot effluents from thermoelectric and hydroelectric factories) and their effects on hydrology, biogeochemistry (Xu et al., 2019; Copetti and Salerno, 2020), biological diversity (Madden et al., 2013; O'Briain, 2019), and the risks associated with human diseases (Ahmed et al., 2020) have been reported in the literature. Within this context, one of the important effects, as yet little studied, is the change in action of metals with a temperature rise, on aquatic organisms belonging to the different trophic levels. Metals are one of the stressors that affect aquatic ecosystems, and as the climate changes occur, it becomes necessary to understand the combined effect of the thermal and chemical stresses on the biota of these environments (Radinger et al., 2016). There are no studies that compare and discuss the combined effect of temperature rise and the presence of metals for representative species of freshwater ecosystems. From this perspective, systematic reviews make it possible to reunite and discuss the scientific evidence concerning the combined action of physical (temperature) and chemical (metal) stressors on the aquatic biota.

Based on the above, the goal of this study was to carry out a systematic review of the effects of a temperature rise on the toxicity of metals for freshwater organisms. The hypothesis presented was that a rise in temperature influences the toxicity of metals for aquatic organisms. In addition, some gaps in the literature were highlighted and recommendations made concerning new directions for future studies. Papers discussing studies concerning this theme are certainly important for students, professors, and researchers in environmental sciences.

Methodology

The steps of a systematic review contemplate the limits of the question (question formulated containing the description of the theme), search for evidence (identify the databases to be examined), review and selection of papers, and the checking of the methodological quality of the research and description of the results (Sampaio and Mancini, 2007). In this present survey, the guiding question was, What is the effect of a temperature rise on metal toxicity for the aquatic biota? Scientific articles available in the databases Scielo, Science Direct, Web of

Science, and the Google Academic search system were used, as well as a search among the references of the selected articles. Articles published in English, Spanish, and Portuguese between 1960 and 2020 were analyzed. This period was chosen because the standardization of ecotoxicological research methodologies dates from the sixties (Zagatto and Bertolotti, 2006).

The following descriptors were used: “systematic review AND toxicity AND temperature,” “toxicity AND algae AND temperature,” “toxicity AND zooplankton AND temperature,” “toxicity AND fish AND temperature,” and “toxicity AND climate change AND metal.” For the search according to the metals, the following descriptors were used: “toxicity AND metal AND temperature,” and this structure was used for the search for the remaining metals of the periodic table.

During the selection of the studies, the articles were evaluated independently by two researchers, one being an undergraduate student in environmental engineering and the other a researcher in the same area, following the inclusion and exclusion criteria. An analysis of the titles and abstracts identified in the initial search was carried out. When the title and abstract were not explicative, the entire articles were analyzed. Divergencies were discussed. The inclusion and exclusion criteria were according to Martins and Carmo Junior (2018) and include:

- The question guiding the review (in agreement with the review question) and studies considering the effect of the exposure of freshwater organisms to metals at different temperatures were included. Studies concerning saltwater and land organisms were excluded as well as those that did not analyze the metal toxicity and articles already reviewed that were reselected during the search;
- Search period defined (60 years);
- Use of standardized methods and methodological criteria (described in articles, books, protocols, and research norms in the ecotoxicol-

ogy area) according to standardization agencies such as American Society for Testing and Materials (ASTM), *Associação Brasileira de Normas Técnicas* (ABNT), Environment Canada, Organisation for Economic Co-operation and Development (OECD), International Organization for Standardization (ISO), Standard Methods (APHA), and the U.S. Environment Protection Agency (USEPA).

For the data analysis, the studies were separated in blocks distributed according to the publication year, country, and results encountered. Tables and graphs were also elaborated to analyze the number of publications per year, the articles published per country, and the effects observed on the test-species due to the combined exposure to high temperatures and metals.

Results

After carrying out the literature review in the databases, 218 articles were found as from the descriptors used. The abstracts were then read, and after applying the exclusion and inclusion criteria, 43 articles were selected.

Tables 1, 2 and 3 present the studies selected after the literature reviews for microalgae, zooplankton, and fish, respectively, and their descriptions per author, year, country, test-organism, metal, temperature tested, and effect were observed.

Based on the review carried out, 4 studies were published before 2000, 12 between 2000 and 2009, and 27 as from 2010 (Figure 1).

As shown in Figure 2, the articles were published in 19 different countries and most of the studies found in this review were published in Belgium (6), Brazil (6), the USA (4), and France (4).

With respect to the distribution of studies per continent, Europe published the largest number of articles (17) on the subject, followed

Table 1 – Studies with microalgae test-organisms and principal characteristics.

Authors	Year	Country	Species	Metal	T (°C) tested	Effect observed
Oukarroum et al.	2012	Canada	<i>Chlorella vulgaris</i>	Cu	24, 28, and 31	Decrease in emission of fluorescence by chlorophyll with 3°C rise in the presence of Cu
Lambert et al.	2016	France	Peripheral community	Cu	8, 13, 18, and 23	Decrease in metal toxicity with rise from 8°C to 23°C
Val et al.	2016	Spain	Peripheral community	Hg	17, 19, and 22	Increase in toxicity with 5°C temperature rise
Morin et al.	2017	France	Diatomaceous species	Cu	8, 13, 18, and 23	For some species, metal toxicity increased at 23°C
Lambert et al.	2017	France	Peripheral community	Cu	18 and 28	Cu inhibited photosynthesis with temperature rise
Yong et al.	2018	Malaysia	<i>Scenedesmus quadricauda</i>	Cu	25 and 35	Cell density increased with temperature rise
Silva et al.	2018	Portugal	<i>Raphidocelis subcapitata</i>	Cu	15, 20, and 25	Algal growth inhibited by metal at temperatures of 20°C and 25°C

Table 2 – Studies with zooplankton test-organisms and principal characteristics.

Authors	Year	Country	Species	Metal	T (°C) tested	Effect observed
Stuhlbacher et al.	1993	UK	<i>Daphnia magna</i>	Cd	3, 10, 20, 25, and 30	Increase in Cd toxicity with 10°C rise
Heugens et al.	2003	Holland	<i>D. magna</i>	Cd	10, 13, 16, 20, 26, 29, 32, and 35	Increase in metal toxicity with 3°C rise
Tsui and Wang	2004	China	<i>D. magna</i>	Hg	14, 19 and 24	Hg elimination by organism not influenced by temperature
Gama-Flores et al.	2005	Mexico	<i>Brachionus rotundiformis</i>	Cu	20 and 25	Species growth inhibited by temperature rise when exposed to Cu
Boeckman and Bidwell	2006	USA	<i>Daphnia pulex</i> , and <i>Diaptomus clavipes</i>	Cu	10, 20, and 30	<i>D. clavipes</i> : greatest toxicity at 30°C. <i>D. pulex</i> : least toxicity at 20°C
Heugens et al.	2006	Holland	<i>D. magna</i>	Cd	10, 20, and 26	Cd reduces reproduction of cladoceran at 20°C and 26°C
Nandini et al.	2007	Mexico	<i>Moina macrocopa</i>	Cu and Zn	22 and 27 °C	Adverse effects on organism due to metal exposure and temperature rise
Martínez-Jerónimo et al.	2008	Mexico	<i>Daphnia exilis</i>	Cr	20 and 25	Increase in toxic effect of metal with 5°C rise
Ferreira et al.	2010	Portugal	<i>D. magna</i>	Ni	4, 12, 20, 25, and 30	Greatest Ni toxicity for species at 25°C and 30°C
Messiaen et al.	2010	Belgium	<i>D. magna</i>	Cd	20 and 24	Reduction in birth rate with temperature rise and presence of Cd
Gama-Flores et al.	2014	Mexico	<i>Brachionus calyciflorus</i>	Cd	20, 25, and 30	Metal reduced mean survival time of organism with 5°C rise
Bae et al.	2016	South Korea	<i>D. magna</i>	Cu	20 and 25	Increase in toxicity with temperature rise
Pereira et al.	2017	Belgium	<i>D. magna</i>	Cu, Ni, and Zn	15, 20, and 25	Decrease in Ni toxicity with temperature rise from 15°C to 25°C. Decrease in Cu and Zn toxicity with temperature rise from 15 °C to 20 °C
Pereira et al.	2019	Belgium	<i>D. magna</i>	Ni	15, 19, and 25	Decreases in assimilation and elimination rates for Ni with rise from 19°C to 25°C. Both rates showed similar values at 15 °C and 19 °C
Van Ginneken et al.	2019	Belgium	<i>Asellus aquaticus</i>	Cd, Cu, and Pb	15 and 20	Increase in mortality rate for metal exposure with temperature rise. Greatest mortality for Cd and Pb exposure at 20 °C

by North America (8). No studies were found concerning this question in Oceania.

Of the test-species employed in the studies, fish were the most used (21), followed by zooplankton (15) and microalgae (7). Of the zooplankton species used, the microcrustacean *D. magna* was the most used, corresponding to 64% of the studies carried out with cladocerans. Of the 55 species studied, 33 were from temperate regions and 22 from tropical regions, a result compatible with the numbers of studies carried out in these regions, since 53.8% of the studies were carried out

in Europe and North America. Most of the species of tropical origin studied were fish, where 18 species of tropical origin were included. Nine metals were studied in the articles analyzed: aluminum, arsenic, cadmium, lead, copper, chromium, mercury, nickel, and zinc. Of these, the elements most frequently studied were copper (20 articles) and cadmium (15 articles).

Another aspect considered referred to acclimatation of the test-organisms to the temperatures tested before starting the toxicity. Of the 43 studies analyzed, 20 carried out acclimatation, corresponding to

Table 3 – Studies with fish test-organisms and principal characteristics.

Authors	Year	Country	Species	Metal	T (°C) tested	Effect observed
Rehwoldt et al.	1972	USA	<i>Cyprinus carpio</i> , <i>Fundulus diaphanus</i> and <i>Lepomis gibbosus</i>	Cd, Cu, Cr, Hg, Ni and Zn	15 and 28	Increase in Hg toxicity to species with temperature rise. Temperature did not influence on toxicity of Cd, Cu, Cr, Ni and Zn to fishes
Hilmy et al.	1987	Egypt	<i>Tilapia zilli</i> and <i>Clarias lazera</i>	Zn	9.3, 15.3, 18.5 and 25	Increase in Zn toxicity to species with temperature rise to 25 °C
Nussey et al.	1996	South Africa	<i>Oreochromis mossambicus</i>	Cu	19 and 29	Increase in Cu toxicity with temperature rise
Hallare et al.	2005	Germany	<i>Danio rerio</i>	Cd	21, 26 and 33	Cd toxicity increased with temperature rise from 21°C to 33°C
Perschbacher	2005	USA	<i>Ictalurus punctatus</i>	Cu	21, 23, 25 and 27	Decrease in mortality with temperature rise of 2°C
Kumar and Gupta	2006	India	<i>Catla catla</i> , <i>Cirrhinus mirigala</i> and <i>Labeo rohita</i>	Hg	16 and 35	Increase in Hg toxicity with temperature rise for the three species
Carvalho and Fernandes	2006	Brazil	<i>Prochilodus scrofa</i>	Cu	20 and 30	Rise in water temperature does not influence copper toxicity
Salazar-Lugo et al.	2009	Venezuela	<i>Colossoma macropomum</i>	Cd	25 and 30	Cd reduces blood cells at high temperature
Sassi et al.	2010	Tunisia	<i>Gambusia affinis</i>	Cd	24 and 32	Cd reduces body size of species with temperature rise
Vergauwen et al.	2013	Belgium	<i>D. rerio</i>	Cd	12, 18, 26 and 34	Increase in mortality rate at 18°C, 26 °C and 34°C
Abdel-Tawwab and Wafeek	2014	Egypt	<i>Oreochromis niloticus</i>	Cd	20, 24, 28 and 32	The survival rate was the same at temperatures of 20°C and 24°C, greater at 28°C and smaller at 32°C
Braz-Mota et al.	2017	Brazil	<i>Hoplosternum littorale</i>	Cu	28 and 34	Metal reduced species survival with temperature rise
Abdel-Tawwab and Wafeek	2017	Egypt	<i>O. niloticus</i>	Cd	20, 24, 28 and 32	Decrease in Cd toxicity from 20°C to 28°C & increase in toxicity from 28°C to 32°C
Philippe et al.	2018	Belgium	<i>Nothobranchiusfurzeri</i>	Cd	24 and 28	Reduction in body size & delay in female maturation with temperature rise
Kumar et al.	2019	India	<i>Pangasianodon hypophthalmus</i>	As	25 and 34	Increase in toxicity with temperature rise
Hani et al.	2019	France	<i>Gasterosteus aculeatus</i>	Cd	16 and 21	Decrease in survival & in the number of embryos with temperature rise
Merçon et al.	2019	Brazil	<i>Geophagus brasiliensis</i>	Pb	25 and 28	Decrease in Pb concentration in tissues with temperature rise
Zebral et al.	2019	Brazil	<i>Poecilia vivipara</i>	Cu	22 and 28	Increase in Cu concentration in liver & reduction in antioxidant capacity with temperature rise
Pinheiro et al.	2019	Brazil	<i>Astyanax altiparanae</i>	Al	20, 25 and 30	Increase in Al concentration in tissues with temperature rise from 25 to 30°C
Zebral et al.	2020	Brazil	<i>P. vivipara</i>	Cu	22 and 28	Inhibition of metabolism due to temperature rise and increase in Cu
Park et al.	2020	South Korea	<i>D. rerio</i>	Pb	26 and 34	Pb reduced species survival with temperature rise

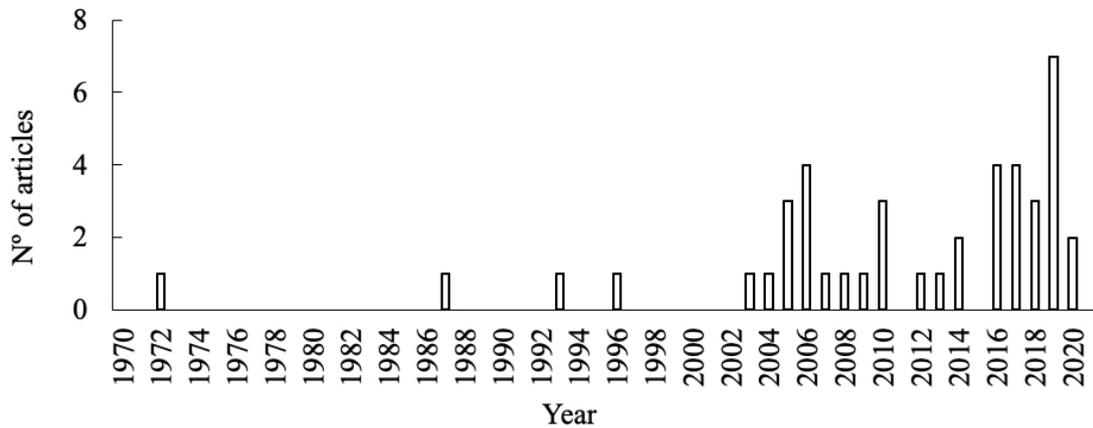


Figure 1 – Number of articles published per year.

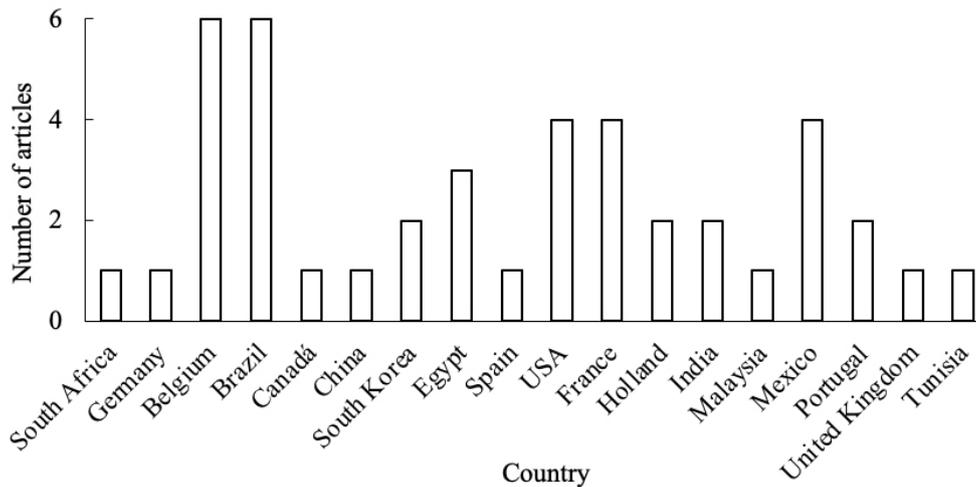


Figure 2 – Number of articles published per country.

45.45% of the articles. The proportion of studies which acclimatized the organisms decreased as the years went by, being 60% before 2000, 50% between 2000 and 2010, and 40.74% as from 2010.

Based on the literature review carried out, the influence of temperature on metal toxicity for the test-organisms was studied (Table 4). For all the groups of organisms, the main effect observed was an increase in toxicity of the metals analyzed with rise in temperature—71.4% of the articles used microalgae, 86.7% zooplankton, and 77.3% fish. Of the studies carried out with zooplankton and fish, 6.7 and 4.6%, respectively, showed no variation in the toxicity of the metal analyzed with rise in temperature. In addition, 4.5% of the studies with fish first observed a decrease followed by an increase in metal toxicity with temperature rise.

Table 4 – Effect observed (in percent articles) on the test-organisms with temperature rise.

Effect observed	Microalgae	Zooplankton	Fish
Increase in toxicity	71.4	86.7	77.3
Decrease in toxicity	28.6	6.6	13.6
Decrease followed by increase	–	–	4.5
No variation	–	6.7	4.6

For the groups of microalgae and zooplankton studied, effects on metal toxicity were observed as from a rise of 2°C. However, for most of the studies carried out with these organisms, a variation in metal

toxicity was only observed with a temperature rise of 5°C. With respect to the studies with fish, differences in metal toxicity occurred as from a temperature rise of 4°C, and the main variation in temperature studied was between 5 and 7°C.

Discussion

In this systematic review, a comparative analysis was carried out between the studies which analyzed the effects of temperature rises on metal toxicity for different groups of aquatic organisms. The present investigation provided evidence that in 80% of the studies analyzed, a temperature rise was responsible for increasing the toxicity of metals for the aquatic organisms studied. The data published in this review also indicated an increase over the past few decades in the number of research projects concerning the effects of temperature rises on metal toxicity for aquatic organisms. This increasing concern of the scientific community in understanding the combined effect of temperature rises of the water and aquatic contaminants occurred due to some studies and forecasts showing that thermal pollution and climate changes are threats to biodiversity (Cardoso-Mohedano et al., 2015; Gill et al., 2020). The current rise in the water temperature already exceeds the capacity of some species to adapt, causing changes in the structure and functions of aquatic ecosystems (Schiedek et al., 2007; Pound et al., 2021).

Despite the increase in number of articles published over the past few decades concerning the influence of temperature on the action of metals, there are still some questions that need to be approached concerning the countries where the studies were developed, the test-organisms employed, and the metals studied.

The present survey demonstrated that most of the scientific investigations were carried out by research institutions in countries with temperate climates, as compared to the amount produced in countries with tropical climates. Thus, research on the potential effects of contaminants on the biota have concentrated on species and test conditions representative of temperate regions (Daam et al., 2020). Of the South American countries, Brazil had the largest number of articles published on this theme. The absence of studies in Oceania and the scarcity of studies in Africa and South America revealed the need to amplify investment in the ecotoxicology area in regions with tropical climates, since species from regions with different climatic characteristics do not react in the same way to temperature rises or a combination of this factor with exposure to metals (Graham and Harrod, 2009). For this reason, the use of results obtained for temperate region species to predict risks for the tropical fish biota should be done with caution. The use of native species can provide more realistic results concerning the toxicity of chemical agents, since they reflect local environmental conditions (Harmon et al., 2003; Raymundo et al., 2019).

With respect to the groups of organisms tested, it is important to note the scarcity of studies on microalgae. These organisms are the base of the food chain in aquatic ecosystems, and toxic effects in their com-

munities can influence the upper trophic levels (Wetzel, 2001). On the other hand, fish were the test-organisms most studied in the theme of this review. There is adequate knowledge for some fish species and their cultivation presents a low level of difficulty, showing ecological and commercial importance (Zagatto and Bertoletti, 2006; Esteves, 2011). Nevertheless, the toxic effects of metals associated with thermal stress should be evaluated in species from different trophic levels, due to variation in sensitivity to the contaminants (Hoffman et al., 2003) and in the thermal tolerance limits (Silva et al., 2020) existent among the organisms, and also the accumulation of metals via the trophic chain (DeForest and Meyer, 2015). Hence, studies with microalgae must be amplified and the species used within each group of test-organism diversified.

The literature survey indicated a predominance of studies on the metals copper and cadmium and the absence of research on other metals. Copper, an essential micronutrient for the organisms in determined concentrations, was the metal most used in research with the three groups of test-organisms evaluated. Cadmium, differently from copper, has no known metabolic function and is toxic even in low concentrations. Both metals reached the water bodies via the discharge of industrial effluents and by way of mining residues (Vardhan et al., 2019). The fact that these metals were the most used in the research projects found in this review can be explained by the great number of studies concerning these elements already existent, making data collection, comparative analysis, and a discussion based on already published articles much easier. Based on the finding of the present survey, the authors consider it necessary to amplify investigations concerning the effect of temperature rises on the action of other metals, for example, aluminum, chromium, lead, iron, manganese, and nickel. These metals come from mining, electroplating, civil construction, tanneries, and the production of pigments, batteries, metal alloys, and agrochemicals and can enter aquatic systems via direct or indirect ways (Azevedo and Chasin, 2003).

The research projects analyzed reported the effects on metal toxicity as from 3°C temperature rises for microalgae and zooplankton, and as from 4°C rises for fish, in experiments carried out in laboratories. Therefore, the temperature ranges studied contemplated the temperature rises predicted by the IPCC (2014) at the end of the 21st century. In ecotoxicological studies carried out under laboratory conditions, the test-species are exposed to the chemical agents at the standard temperature, within the temperature range considered adequate for the organisms (Zagatto and Bertoletti, 2006). The evident impact of temperature rises on the toxicity of chemicals, as revealed by the present systematic review, emphasizes the need for the standard protocols in the area to consider standard temperatures and those to be registered under natural conditions.

With respect to acclimatation of the species to the temperatures, in recent years, the number of research projects with acclimatized organisms for toxicity studies has decreased. Acclimatation is necessary to guarantee that the toxic effects observed in the experiments are a consequence of the metal toxicity at high temperature, without the occurrence

of thermal shock by the individual. The acclimation potential of organisms is an aspect of global climate changes that should be considered in the studies (Delorenzo, 2015). According to Silva et al. (2020), acclimation can collaborate to a better understanding of the strategies used by organisms to deal with environmental changes, considering their capacity to adapt to unfavorable environmental conditions. It is, therefore, fundamental that future research considers the acclimation of the organisms, guaranteeing that the results obtained are more representative.

The present review also indicated adverse effects on the test-species due to temperature rises in the medium and their association with an intensification of the toxicity of the metals. For microalgae, the increase in metal toxicity with temperature rise was due to a decrease in photosynthetic efficiency (Oukarroum et al., 2012) and to growth inhibition due to metabolic changes and in the levels of amino acids, fatty acids, and sugars (Yong et al., 2018). For zooplankton, it was observed that the increase in toxicity due to a temperature rise was due to a greater accumulation of metal, protein denaturation, and a destabilization of homeostasis, with a reduction in reproduction and survival (Lannig et al., 2006). For fish, the increase in metal toxicity due to the temperature rise was due to an accumulation of metal in different body tissues and a reduction in the metabolism and antioxidant capacity of the organisms to deal with the metal toxicity (Pinheiro et al., 2019; Zebal et al., 2019). In consequence, the heartbeat was reduced, bad body formation and reproductive damage occurred, and the fish mortality rates were high (Park et al., 2020). Thus, considering the toxic effects registered in important representatives of the biota of aquatic systems, the loss of the ecosystem services they offer is likely to occur under possible climate change scenarios in metal-containing environments.

Considering that the duration and intensity of heat waves will probably increase in coming decades as a function of climate change, this increases the concern with the potential effects of a simultaneous temperature rise and pollution of aquatic environments and emphasizes the need for wider environmental monitoring to better forecast the

impacts on the biota (Jacquin et al., 2019). Thus, an adequate protection of the biodiversity depends on the advance of research concerning the sensitivity of aquatic organisms to different pollutants (metals, agrochemicals, nanoparticles, for example) under current climatic conditions and under those projected for the future, and of the population's ability to understand the possible effects of changes to the ecosystems when faced with this scenario.

Conclusions

There is evidence that temperature rises can increase or decrease the effects of metals on aquatic organisms and can also show no influence on these contaminants. This systematic review showed that according to most of the studies concerning the effects of metals with temperature rises, there was an increase in toxicity for microalgae, zooplankton, and fish species. In addition, an increase in interest concerning this theme within the scientific community was found, possibly due to the increase in importance given to questions of climate change and to the increase in research institutions and the training of human resources. Despite the increase in publications in recent decades, there is a need to amplify the number of metals and organisms analyzed. Attention should be given to the diversification of the test-organisms studied, principally among the bacterioplankton, phytoplankton, and zooplankton species.

It is important to acclimatize the individuals, such that the laboratory conditions represent the stress factors found in the natural environment in the most realistic manner. There is also a need for research that improves the understanding of the effects of temperature on the toxicity of other aquatic contaminants. Considering the temperature rise predicted for future decades due to climate change, an advance in research concerning the effects of temperature rises associated with chemical stressors on aquatic biodiversity is primordial, especially in tropical regions. Ecotoxicological analyses are of great importance in forecasting and preventing threats associated with the contamination of water bodies by toxic agents within the scenario of climate change.

Contribution of authors:

Nin, C.J: Conceptualization, Methodology, Formal analysis, Writing – original draft. Rodgher, S: Conceptualization, Supervision, Writing – original draft, Writing – review & editing.

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