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Toxic Effects of Disinfectants on Aquatic Organisms

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ABSTRACT

Depending on increasing chaotic climatic and microbial changes in recent years, various approaches have emerged to ensure environmental welfare and stabilization of public health. Although disinfection processes are one of them, the presence of disinfection products in the environment has also become a concern, and their toxicological effects on organisms have been questioned. This study was conducted to comparatively investigate and evaluate the effects of various disinfectants on organisms in aquatic ecosystems. For this purpose, toxicity significance levels based on life cycle studies with certain species in the aquatic environment were investigated, and a significant number of studies including the effects of different disinfectant types on target species were grouped. According to the studies examined, it has been observed that organisms are most affected by chlorine exposure due to its economical and easy use. The results showed that disinfectants pose a risk to the ecosystem and may even cause more genotoxic, mutagenic and teratogenic consequences for organisms in long-term exposures.

Dezenfektanların Sucul Organizmalar Üzerindeki Toksik Etkileri

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ÖZ

Son yıllarda artan kaotik iklimsel ve mikrobiyal değişimlere bağlı olarak çevre refahı ve halk sağlığının stabilizasyonunu sağlamaya yönelik çeşitli yaklaşımlar ortaya çıkmıştır. Dezenfeksiyon işlemleri bunlardan biri olmasına karşın, çevrede dezenfeksiyon ürünlerinin mevcudutiyeti düşündürücü bir duruma gelmiş ve organizmalar üzerindeki toksikolojik etkileri sorgulanmaya başlanmıştır. Bu çalışma, çeşitli dezenfektanların sucul ekosistemlerdeki organizmalara etkilerini karşılaştırmalı olarak araştırmak ve değerlendirmek amacıyla yapılmıştır. Bu amaçla, su ortamındaki belirli türlerle yapılan yaşam döngüsü çalışmalarına dayalı toksisite önem seviyeleri araştırılmış, farklı dezenfektan türlerinin hedef türler üzerindeki etkilerini içeren önemli sayıda çalışma gruplandırılmıştır. İncelenen araştırmalara göre organizmaların, ekonomik oluşu ve kullanım kolaylığı nedeniyle en çok klor maruziyetinden etkilendikleri görülmüştür. Sonuçlar dezenfektanların ekosistem için bir risk oluşturduğunu ve hatta uzun süreli maruziyetlerde organizmalar için daha fazla genotoksik, mutajenik ve teratojenik sonuçlara neden olabileceğini göstermiştir.

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Introduction

Water is an essential chemical compound for every organism and vital for the sustainability of life (Ghernaout, 2017). Aquatic ecosystems are contaminated not only by the mineral deposits, technological changes, agricultural production and the process of food becoming a suitable shelf product, but also by hospital wastes, veterinary services and disinfection processes, concurrently with a growing global population (Zhou et al., 1997; IARC, 2000). Disinfectants have numerous applications, and the main disinfectant sources are categorized in accordance with the European Union directive (Smith, 2015) (Figure 1). Additionally, it has been reported in a number of studies that various disinfectants are preferred to destroy harmful viruses and bacteria in water treatment facilities, aquaculture, agricultural uses, domestic and health institutions (Gümüş et al., 2013; Holm et al., 2019; Yun et al., 2020; Choi et al., 2021; Huang et al., 2021).

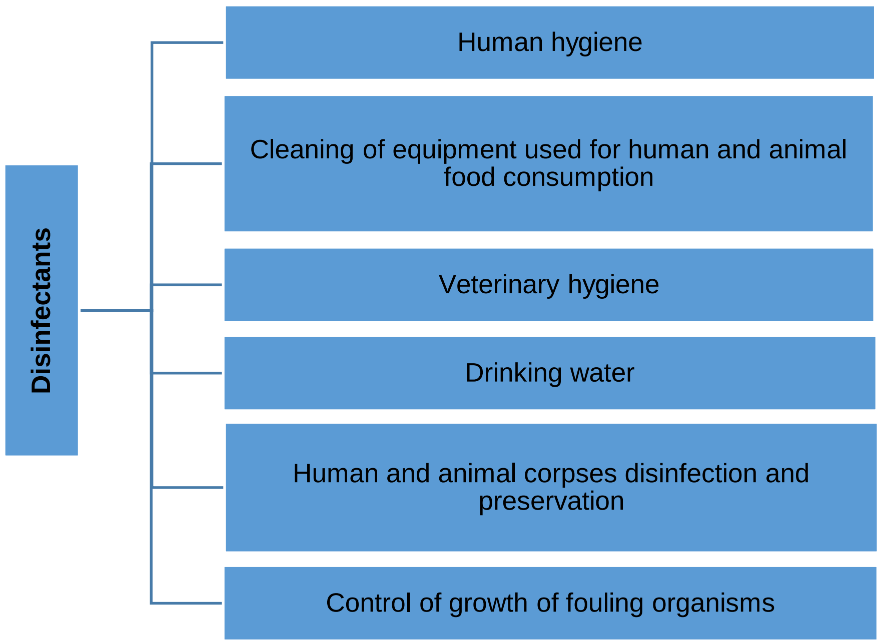

Figure 1. Diagram of usage areas of disinfectants used according to EU legislation (Smith, 2015)

The final destination that disinfectants reach as a result of excessive and irregular use is again the aquatic ecosystems as depicted in Figure 2. Disinfectants reaching the aquatic ecosystem from different sources react with natural organic substances such as humic and fulvic acids in the environment, causing occurrence of numerous disinfection byproducts with mutagenic, carcinogenic and teratogenic effects (Zhou et al., 1997; IARC, 2000). An essential component of the antioxidant defense system in organisms is formed by glutathione and antioxidant enzymes (Livingstone, 2001). As is common knowledge, chlorine compounds are pro-oxidants so strong that they can damage the antioxidant defense system and antioxidant components of exposed vertebrate and invertebrate organisms (Ueno et al., 2000; Pozzetti et al., 2003). In a study, although correlation results were determined between public health and disinfected drinking water, the level of this correlation wasfound to be relatively low (Barceló, 2012). However, a number of epidemiological studies have revealed that drinking water cleaned using disinfectants may increase the risk of contracting a number of diseases, including cancer of the bladder, kidneys, colon and rectum (Richardson et al., 2007; Yang and Zhang, 2016).

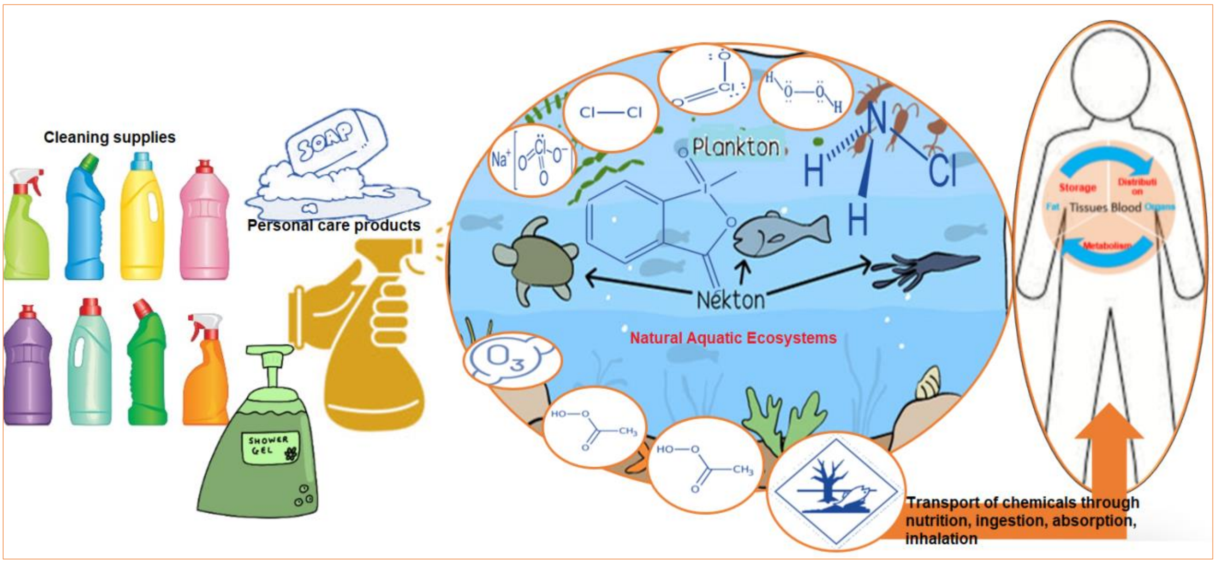

Figure 2. Illustration of disinfectants affecting organisms in the aquatic ecosystem and indirectly human health

The fact that the different disinfectants used cause changes in the structure of drinking water, surface water and underground water have led scientists to develop eco-friendly alternative materials both commercially and ecologically (Rai et al., 2018; Ghernaout et al., 2019). This review focused on the most commonly utilized disinfectants in various literatures such as chlorine, bromine chloride, monochloramine, hypochlorous acid, hypochlorite ion, dichloramine, sodium hypochlorite, malachite green, chloramine-T, ozone, potassium permanganate (VII), chlorine dioxide, peracetic acid, hydrogen peroxide. Furthermore, the toxic effects of these substances on aquatic organisms have been accordingly evaluated. For this, a literature review on disinfectants from various databases was made, and the effects of different types of disinfectants were categorized in Table 1 according to the years.

Chlorine

Chlorine is a highly reactive chemical oxidizing reagent. Once mixed with water, it easily reacts with inorganic substances such as oxidizable hydrogen sulfide, ferrous, and organic impurities such as microorganisms and nitrogen compounds, which decompose in the water due to animal residues (Shamrukh and Hassan, 2005).

Because of its powerful antibacterial properties and affordable price, chlorine has been the most popular of the commercial disinfectants available for usage (Reddy and Elias, 2021). Chlorination has generally been the most used method to prevent contamination of both wastewater and drinking water, but several studies have reported that chlorination leads to the formation of by-products that are potentially harmful to public health and aquatic organisms (Zhou et al., 1997; IARC, 2000; Lee et al., 2001). It has been determined that the increased chlorine level in water as a result of chlorination combines with organic substances to form carcinogenic trihalomethanes (THM) and other halogenated hydrocarbons, and it has been emphasized that disinfection techniques should be revised withal (Cotruvo, 1981).

Hypochlorous Acid and Hypochlorite Ion

Chlorine in the gaseous state becomes a strong oxidizing agent in aqueous solutions. Chlorine interacts in aqueous solution and produces hypochlorous acid and hypochlorite ions, as shown in the equation; [Cl_2 (g) + H_2O ⇔ HOCl + H^+ + Cl^- ; HOCl ⇔ H^+ + OCl^-] (USEPA, 1999). Hypochlorous acid ionizes depending on pH, temperature, and organic matter in the water. The level of hydrogen ions in the water ensures the formation of 100% hypochlorite acid at pH=5, and 100% hypochlorite ions at pH=10. This circumstance could be used to explain the key distinction between hypochlorous acid and hypochlorite ion (USEPA, 1999). Hypochlorous acid is identified as non-hazardous by regulations of the Environmental Protection Agency (EPA, 1999).

Bromine Chloride

Bromine was first applied to water as liquefied bromine as a disinfectant. Bromine chloride can be applied as gaseous or solid brominates. According to numerous researches, bromine chloride is less hazardous to fish than chlorine and is a more effective disinfectant. In addition, it has been stated that bromine chloride is as cost-effective as chlorine and its use is widespread enough to compete with chlorine (Mills, 1973; Mills, 1975). It has been determined that bromine chloride has a number of advantages over chlorine, including the capacity to disinfect the polio virus, convenience of usage, and safety. Toxicological information on organisms in aquatic ecosystems is relatively scarce, nevertheless (Keswick et al., 1978).

Monochloramine and Dichloramine

Monochloramine and dichloramine have been reported to have significant disinfecting power. However, it was also stated that high concentrations or contact times of chloramine derivatives should be high (Shull, 1981). However, some disadvantages have been reported in the use of chloramines as a primary disinfectant. It has been stated that a series of chromosome aberrations are observed with a radiomimetic reaction in a short-term exposure of monochloramine to plant and animal cells, but the incidence is low (Shull, 1981). Chlorine can be found in different forms in aqueous solutions, these are; free chlorine, hypochlorous acid, hypochlorite ion, monochloramine and dichloramine. However, the presence of ammonia in water affects the concentration of monochloramine and dichloramine. One can determine the type of chlorine by observing changes in the ammonia content of the water. The concentration of chloramine derivatives rises as a result of organic pollution in the water (Seegert et al., 1979).

Sodium Hypochlorite

Sodium hypochlorite, produced by adding elemental chlorine to sodium hydroxide contains 5-15% chlorine and is less dangerous than elemental chlorine, but has a short shelf life. It can form inorganic byproducts such as chlorate, chloride and bromate in their reaction with water. On the other hand, the high level of corrosion effect can damage the application sites (Oğur et al., 2004). It is thought that sodium hypochlorite alone does not contaminate the environment, since the hypochlorite ion is chemically degraded immediately before being accumulated by organisms (ASC-PT Asahimas Chemical, 2009). However, in a study in which physical and chemical parameters were kept constant, it was reported that adding sodium hypochlorite to wastewater increases toxicity in organisms (Chen et al., 2001). This can be explained by the fact that other inorganic and organic substances carried by the wastewater activate the toxicity of the hypochlorite ion.

Malachite Green

Malachite green is an important biocide that is highly effective against protozoal and fungal infections in aquatic organisms and is widely used in the aquaculture industry (Schnick, 1988). In addition, it is preferably used as a colorant, food additive, medical disinfectant and anthelmintic in the textile, paper and food industries (Culp and Beland, 1996). It has observed to have ecotoxic effects on various metabolic functional systems such as immunity and reproduction in aquatic organisms. As a consequence, it has become a highly controversial compound in terms of public health due to the risks it poses to processed seafood products (Alderman and Clifton-Hadley, 1993; Gouranchat, 2000).

Chloramine-T

Although chloramine-T is not licensed for use in fish as a therapeutic agent, it is used in freshwater fish aquaculture as an effective treatment of bacterial gill diseases at varying concentrations as a prophylactic and disinfectant for which there are unfortunately no alternatives (Bullock et al., 1991; Smith et al., 1993; Thorburn and Moccia, 1993). However, despite its unconscious use, literature on the mechanism of action of chloramine T, its physiology in fish or its toxicity to fish is still lacking (Powell and Perry, 1996).

Ozone

Ozone is preferably used for the disinfection of water, as well as for the removal of taste, odor, color, turbidity, cyanide, nitrite, ammonia and metals in drinking, surface waters and contaminated ground waters (Gray, 2014). In addition, they are used in cleaning the residues of agricultural pesticides, in cold storage where food is stored, in the disinfection of infection in livestock, in the removal of alphatoxin, in the ventilation systems of medical and research laboratories, in swimming pools and in many other daily areas. Ozone is a very common and powerful disinfectant (Guzel-Seydim et al., 2004). However, its production in situ makes it more costly than other disinfectants such as chlorination or UV. Although ozone is an effective disinfectant against harmful microorganisms in water, a lower level of chlorination is used to ensure that residual pests are destroyed in the public distribution of disinfected water in treatment facilities after ozone is applied (Guzel-Seydim et al., 2004; Gray, 2014). Undesirable aldehydes and ketones may be formed as a result of the reaction of ozone with various organic substances. This may cause toxic effects in aquatic organisms (Uzun, 2011).

Potassium Permanganate (VII)

Potassium permanganate is an oxidizing agent used in aquaculture, removal of harmful pathogens, and medical therapy for humans. However, in water treatment, organic residues are precipitated by oxidation and removed from the water by filtration. In addition, it is used as a chemical oxidant in the stabilization of odor, taste, color, plankton, iron and manganese chemicals in water (EPA, 1999). Along with such beneficial applications of potassium permanganate, several alarming situations have been observed in environmental toxicology. For instance, based on ecotoxicological studies, it has been pointed out that potassium permanganate concentrations above 0.12 mg/L may have chronic toxic effects on aquatic organisms and that other ecosystem elements may accumulate these toxicants by transport in the food chain (França et al., 2011).

Chlorine Dioxide

Used as a primary disinfectant and pre-oxidant in the treatment of drinking water, groundwater and surface water, chlorine dioxide has been used as an alternative to chlorine because it has a long-lasting effect and appears to be safe for public health (Berg et al., 1980; Elia et al., 2006). Because chlorine dioxide does not react with organic compounds in aqueous solutions to form serious carcinogenic trihalomethanes such as chloroform (Opresko, 1980). Chlorine dioxide, one of the chlorine compounds, is a powerful oxidant and biocide (Berg et al., 1980; Elia et al., 2006). Persistence of chlorite residues in aquatic ecosystems suggests that this compound may cause toxic effects against aquatic organisms. Various studies have been conducted on the eco-physiological effects of these disinfectants on viruses, bacteria, phytoplankton, zooplankton and fish, but negative effects have been determined (Huang et al., 1997, Svecevičius et al., 2005). In a study, it was observed that chlorine dioxide was 2-4 times more toxic than total residual elor (TRC) in *Pimephales promelas* and *Lepomis macrochirus* under the influence of chlorine dioxide (Wilde et al., 1983).

Peracetic Acid

Peracetic acid is known to be a useful disinfectant and has applications in medical establishments, research laboratories, clinics, factories and wastewater facilities (Baldry et al., 1995). It has been reported that the use of peracetic acid may cause the production of free radicals and halogenated organic by-chemicals as well as chlorine compounds (Booth and Lester, 1995). However, disinfection of river or lake water for potabilization with peracetic acid has been reported to produce several by-products that are not recognized as mutagenic (Monarca et al., 2002). Peracetic acid actually accelerates the proliferation of microorganisms by increasing the decay of organic matter in the process due to acetic acid (Kitis, 2004; Pedersen et al., 2013). Depending on time, low levels of peracetic acid support biofilm and microbial zone formation, which essentially creates a disadvantage for aquatic ecosystems (Liu et al., 2017).

Hydrogen Peroxide

Hydrogen peroxide is used in many areas and is an oxidizer as strong as other disinfectants. The unstable nature of Hydrogen peroxide and the difficulty of preparing its concentrated solution limit its usage areas. In addition to its use in disinfection of contaminated water, it can also be used safely in medical, agriculture, pharmaceutical, textile, mining, wastewater treatment facilities, paper production sectors and food industry with its disinfectant effect (Campbell, 2003). This compound destroys harmful pathogenic cells oxidatively, and essential structural components such as nucleic acids, proteins and lipids are broken down (Demirci and Ngadi, 2012).

Table 1. Toxic effects of some common disinfectants on aquatic species

Disinfectants IUPAC name (Chemical formula)	**Test animal**	**Exposure results**	**References**
Chlorine (Cl^-)	*Pimephales promelas*	Oxidation of hemoglobin to methemoglobin and mortality due to anoxia	Grothe and Eaton, 1975
Bromine chloride (BrCl)	*Pimephales promelas*	No fish survived to maturity. A 50% decrease was observed in the second generations.	Ward and DeGraeve, 1978
Monochloramine (ClH_2N)	*Notropis atherinoides*	LC50 value was 0.51 mg/L	Seegert et al., 1979
Monochloramine (ClH_2N)	*Catostomus commersonii*	LC50 value was 0.73mg/L	Seegert et al., 1979
Monochloramine (ClH_2N)	*Notropis spilopterus*	LC50 value was 0.59 mg/L	Seegert et al., 1979
Monochloramine (ClH_2N)	*Notropis cornutus*	LC50 value was 0.59 mg/L	Seegert et al., 1979
Monochloramine (ClH_2N)	*Ictalurus punctatus*	LC50 value was 0.65 mg/L	Seegert et al., 1979
Monochloramine (ClH_2N)	*Stizostedion canadense*	LC50 value was 0.68 mg/L	Seegert et al., 1979
Monochloramine (ClH_2N)	*Aplodinotus grunniens*	LC50 value was 1.75 mg/L	Seegert et al., 1979
Monochloramine (ClH_2N)	*Morone chrysops*	LC50 value was 1.80 mg/L	Seegert et al., 1979
Monochloramine (ClH_2N)	*Lepomis macrochirus*	LC50 value was 1.72 mg/L	Seegert et al., 1979
Monochloramine (ClH_2N)	*Cyprinus carpio*	LC50 value was 1.82 mg/L	Seegert et al., 1979
Hypochlorous acid (HOCl)	*Gambusia affinis*	The HOCl alone causing 50% mortality of *G. affinis* at a concentration of 0.38 ppm.	Mattice et al., 1981
Hypochlorite ion (ClO^-)	*Gambusia affinis*	The ClO^- is approximately one-quarter as toxic to *G. affinis* as HOCl	Mattice et al., 1981
Dichloramine ($NHCl_2$)	*Salmo gairdneri*	LC50 value was 0.57 mg/L	Brooks and Bartos, 1984
Dichloramine ($NHCl_2$)	*Ictalurus punctatus*	LC50 value was 0.20 mg/L	Brooks and Bartos, 1984
Dichloramine ($NHCl_2$)	*Notropis atherinoides*	LC50 value was 0.15 mg/L	Brooks and Bartos, 1984
Sodium hypochlorite (NaClO)	*Salmo gairdneri*	Depletion of liver glycogen and inhibition of liver UDP-glucuronosyltransferase and swelling and vacuolization of the gill epithelium observed	Soivio et al., 1988
Malachite green [4-{[4-(Dimethylamino) phenyl](phenyl)methylidene}-N,N-dimethylcyclohexa-2,5-dien-1-iminium chloride] ($C_{23}H_{25}ClN_2$)	*Heteropneustes fossilis*	LC50 value was 1.0 mg/L for 96h	Srivastava et al., 1995
Hypochlorite ion (ClO^-)	*Oncorhynchus mykiss*	Respiratory acidosis	Powell and Perry, 1996
Sodium hypochlorite (NaClO)	*Oncorhynchus mykiss*	Increase in haematocrit level	Powell and Perry, 1996

Chloramine-T [Sodium chloro(4-methylbenzene-1-sulfonyl)azanide] ($CH_3C_6H_4SO_2NClNa$)	*Oncorhynchus mykiss*	Hyperventilation	Powell and Perry, 1996
Ozone (O_3)	*Oncorhynchus mykiss*	Only ozone which can cross the membrane increased reactive oxygen	Fukunaga et al., 1999
Potassium permanganate (VII) ($KMnO_4$)	*Ictalurus punctatus*	Toxicant effect significantly reduced fish survival	Darwish et al., 2002
Chlorine dioxide (ClO_2)	*Oncorhynchus mykiss*	LC50 value was 8.3 mg/L for 96h	Svecevičius et al., 2005
Sodium hypochlorite ($NaClO$)	*Cyprinus carpio*	Significant increase in total glutathione and glutathione reductase levels	Elia et al., 2006
Chlorine dioxide (ClO_2)	*Cyprinus carpio*	Irregularity in total glutathione level	Elia et al., 2006
Peracetic acid (CH_3CO_3H)	*Cyprinus carpio*	Changes in total glutathione level	Elia et al., 2006
Potassium permanganate (VII) ($KMnO_4$)	*Clarias gariepinus*	A decrease in blood values was observed	Kori-Siakpere et al., 2009
Hydrogen peroxide (H_2O_2)	*Salmo salar* (diploid)	Significantly elevated the expression of catalase and superoxide dismutase and glutathione reductase, interleukin 1 beta and crp/sap1b in gills, while significantly decreased the expression of serum amyloid A-5 and C-reactive protein (CRP)/serum amyloid	Chalmers et al., 2018
Hydrogen peroxide (H_2O_2)	*Salmo salar* (triploid)	The levels of catalase, heat shock protein 70, superoxide dismutase, serum amyloid A-5, C-reactive protein (CRP)/serum amyloid P 1a and C-reactive protein (CRP)/serum amyloid P 1 b in liver and glutathione reductase, superoxide dismutase and interleukin 1 beta in gills was elevated	Chalmers et al., 2018
Peracetic acid (CH_3CO_3H)	*Oncorhynchus mykiss*	Post-treatment fish growth was not affected, but high mortality was observed.	Suurnäkki et al., 2020

Conclusion

Understanding the importance of public health is possible only with considering the welfare of organisms and the formation of environmental quality from a holistic perspective. The reason for increasing concern about the sustainability of environmental quality is actually that the chemicals used in wastewater treatment do not function as effective disinfectants in terms of quality. However, this concern might be diminished by having disinfectants that are biotechnological, inexpensive, degradable, and have minimal toxic effects on organisms in aquatic biomes. Based on the literature data that we have investigated so far, it has been observed that disinfectants have as many disadvantages as their advantages. For this reason, the correct use and use of disinfectants should be kept under control and monitored regularly. The results obtained in this study have a high potential to be very informative for the researchers working in the field of major species in aquatic ecosystems in order to address the toxicological effects of disinfectants on a regular basis.

Contribution Rate Statement Summary of the Researcher

The author declares that she has contributed to the article 100%.

Conflict of Interest Statement

The author declares no conflicts of interest.

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