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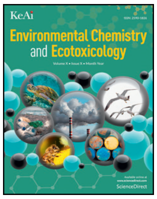

Occurrence, effects, and ecological risks of chemicals in sanitizers and disinfectants: A review

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ABSTRACT

In response to the novel coronavirus referred to as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) – a virus that causes COVID-19 disease has led to wide use of sanitizers and disinfectants. This, in turn, triggered concerns on their potential deleterious effects to human health and the environment due to numerous chemicals incorporated in both product categories. Here, the current state of science regarding the occurrence and ecological effects of different classes of chemicals in these products (e.g., ultraviolent filters, fragrances, etc.) are summarized in different natural (e.g., rivers) and engineered (e.g., wastewater treatment plants) systems. Data collected in the literature suggests chemicals incorporated in sanitizers and disinfectants are present in the environment, and a large portion are toxic to fish, algae, and daphnia. Using the risk quotient approach based on occurrence data, we found eight chemicals that posed the highest risk to aquatic organisms in freshwater systems were benzalkonium chloride, 4-chloro-m-cresol, sodium ortho phenyl phenate, hydrogen peroxide, 1, 2-propanediol, 4-Methyl-benzilidine-camphor, ethylhexyl methoxy cinnamate, and octocrylene. Considering limited occurrence and effects information for most chemicals, further studies on environmental monitoring and potential consequences of long-term exposure in aquatic ecosystems are recommended.

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1. Introduction

The emergence of the novel severe acute respiratory syndrome-coronavirus-2 (SARS-CoV-2) which causes coronavirus disease (COVID-19) outbreak triggered collective efforts by local authorities, governments, and public health institutions across the globe to implement effective preventive measures [1,2]. Among these measures were the non-pharmaceutical interventions (NPIs) (e.g., washing of hands, wearing masks, and social distancing) [2]. Washing of hands and regular decontamination of surfaces led to increased disinfection campaigns on public facilities, community-shared spaces, and homes. Concomitantly, this has led to sharp increase and unprecedented [3] use of sanitizers, and disinfectants across the globe [4–6]. For example, Choi and colleagues have found a rise in handwashing patterns and usage of hygiene product (e.g., hand sanitizers and soaps) during pre- and post-COVID-19 era in South Korea [6]. In addition, another work documented an exponential increase in use of sanitizers and disinfectants to the extent producers and/or manufacturers could not meet the extremely high market demand for both product categories especially at the beginning of the pandemic [7]. Therefore, the increase in use of these product categories has resulted to their constituent chemicals release into natural (rivers, lakes, and groundwater), and technical (e.g., wastewater treatment plants (WWTPs) and tap water) systems. For example, Nason and colleagues qualitatively identified upward trends of disinfectant concentrations (e.g., three ultraviolent filters) in sludge, reflecting increased use during the initial wave of the COVID-19 pandemic [8].

The NPIs have proven to be effective remedy to prevent the spread of COVID-19. However, they have been a source of chemicals incorporated in sanitizers and disinfectants into the aquatic environment, but largely with unknown risks to aquatic biota. Therefore, to investigate and quantify risks associated with sanitizers and disinfectants, systematic identification of their constituent chemicals under variant product categories is required. Remarkably, although there are distinctive differences between sanitizers and disinfectants [9,10], but certain ingredients and classes of chemicals are used in both product categories (Fig. 1). In brief, disinfection refers to the destruction or irreversible inactivation of infectious viruses, germs and bacteria on surfaces or objects using variant chemicals [2,9,10]. Conversely, sanitization entails use of chemicals to reduce microorganisms on inanimate surfaces, for example, in this case prone to the transmission of COVID-19 infection [1,2,10,11].

The chemicals widely incorporated in sanitizers and disinfectants, for example, found in the South African commerce (Fig. 1) are broadly solvents, oxidants and antioxidants, moisturizers, UV-filter, antimicrobials, emulsifiers, and fragrances. Each chemical used is aimed to achieve single or multiple functions in a given product. For instance, due to their strong activities against microbes and pathogens, antimicrobial agents and antiseptics are incorporated in sanitizers and disinfectants. Furthermore, to achieve effective or improved potency of sanitization and disinfection, two or more active ingredients are combined generally in a given product.

To elucidate the implications of chemicals widely incorporated in sanitizers and disinfectants, first, we systematically reviewed the occurrence, hazard, and risks of the constituent chemicals in the natural and technical systems. Second, we outline a summary of key findings including knowledge gaps related to the sources, occurrence, toxicity, and risks of sanitizers and disinfectants to the environment, and recommendations for plausible future research.

2. Materials and methods

To identify the occurrence and effects of chemicals incorporated in sanitizers and disinfectants in different environmental compartments, a literature review was conducted using sources including Google Scholar, Science Direct (published papers, book chapters, and reviews), a dataset of European Chemical Agency (ECHA), and technical documents e.g., material safety database sheet (MSDS) for a given product. Only articles in English were included in this study. The literature search was performed using a suite of keywords (Table 1) following a framework proposed by Hartmann et al. [12]. Keywords either singularly, or as combinations were used in the search. An example of combined keywords is “UV-Filters review surface water”, among many others used in this study. Each chemical was given a symbol for ease of updating the information and a list of the chemicals are in Table S1 in the supporting information (SI).

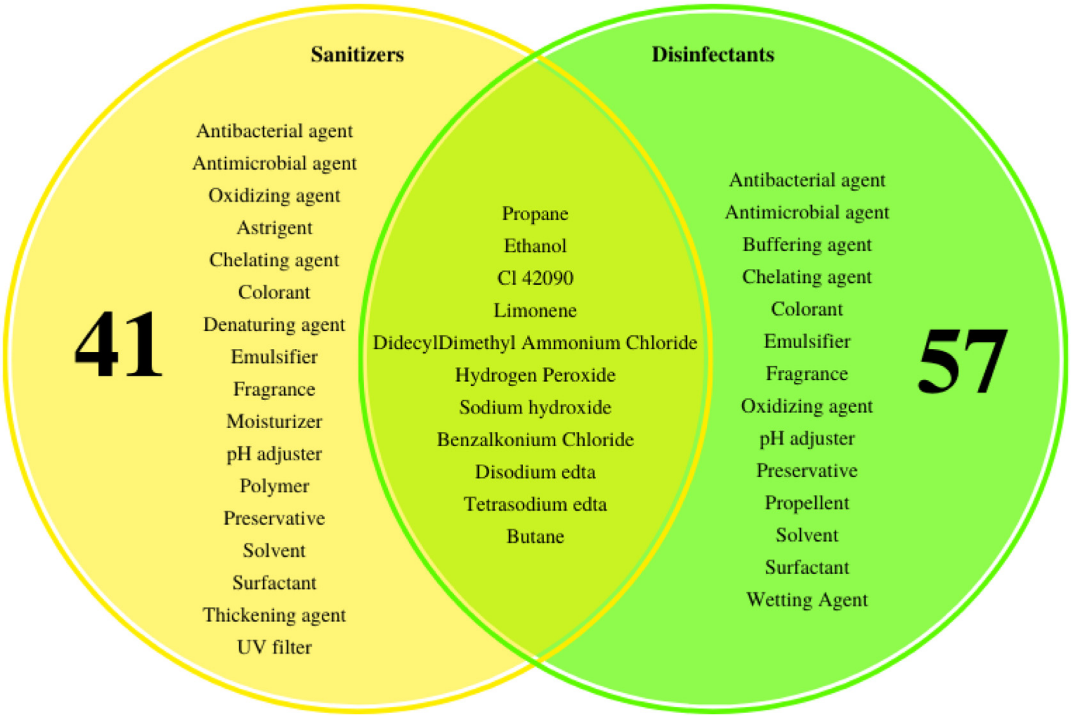

Fig. 1. Constituent chemical classes, and those commonly incorporated in sanitizers and disinfectants identified in South Africa commerce from October 2020 to January 2021 [Source: data collected by researchers in South African market].

Table 1

Search words and or their combinations used to retrieve occurrence and effects data of chemicals investigated in the study. These were used with, without spaces, and the AND search function.

Concept 1: Class of chemicals OR specific chemicals in the given class[a] OR product category[a]	Concept 2: Occurrence	Concept 3: Toxicity	Concept 4: Aquatic environment
"Antimicrobials" OR "Fragrances" OR "UV filters" OR "Solvents" OR "Oxidants/antioxidants" OR "Emulsifiers" OR "Moisturizers" OR "disinfectants" OR "sanitizers" OR "chemical name[a]"	"occurrence" OR "detection" OR "analysis" OR "fate" OR "concentration" OR "measured"	"effects" OR "toxicity" OR "NOEC" OR "EC50" OR "LC50" OR "ecotoxicity" OR "MSDS", OR "fish" OR "algae" OR "daphnia"	"ecosystem" OR "fresh water" OR "freshwater" OR "surface water" OR "wastewater" OR "wastewater" OR "effluent" OR "river" OR "influent" OR "sludge" OR "aquatic environment" OR "treated water" OR "soil" OR "sediment" OR "lake" OR "groundwater"

[a] Chemical names and product categories in place of classes.

Following the described procedure, a summary of sources per class of chemicals found relevant for the effects and occurrence data used is set out in Table S2. Sources that reported the effects and occurrence for all chemicals were in total 331 (with 150 and 181 for occurrence and effects, respectively). To gain insights on the occurrence data distribution, analysis was done based on continent and environmental compartment (Table S3). Most occurrence data were in Europe ($n = 56$) and North America ($n = 29$), but only three in Africa (Table S3). These findings are in good agreement with those previously reported for chemicals incorporated in personal care products where their occurrence data were severely lacking in Africa and South America [13].

3. Occurrence and toxicity of sanitizers and disinfectants

Chemicals used in sanitizers and disinfectants are widely detected in aquatic, terrestrial and engineered environmental systems ranging from very low to high concentrations (ng/L–μg/L). The distribution in the environment were observed to be dependent on use patterns, access, or lack thereof to services (e.g., sanitation), standards of living, and geographical loci across the globe. For example, geographical distribution may be dependent on: (i) regulatory regime of a given country or region, (ii) categories of sanitizers and disinfectants in commerce in a specific region or country over a certain period, and (iii) the extent to which certain chemicals have been banned or recommended for use under strict conditions. Here, chemicals incorporated in sanitizers and disinfectants were critically reviewed for their occurrence, sources, ecotoxicity, and plausible impacts on the environmental systems.

3.1. Solvents

Solvents are carbon-based organics that include alcohols, ketones, amines, ethers, esters and aliphatic, cyclic, and halogenated hydrocarbons [14]. These chemicals have homogeneous physicochemical properties, and are further grouped linked to their polarity, and ability to donate a hydrogen bond during interactions with solutes. Solvents play a key role in the manufacturing industry due to limitations set by physicochemical properties of substances, for safety, and control of selectivity during chemical reactions [15].

An estimated 20 million tonnes of solvents are produced yearly [16], and commonly used in sanitizers and disinfectants, and these includes 1,2-propanediol, benzyl alcohol, isopropanol, ethanol, isobutane, Polyethylene glycol (PEG)-40 hydrogenated castororbate-60. This has led to the presence of certain chemicals in soils, surface water, groundwater, and wastewater [17–20]. For example, concentrations of isopropanol were high in Greece of up to 40.6 μg/L in wastewater [21]. The high concentrations were due to use of isopropanol as a solvent for photo-resistant stripping and cleaning following the etching of silicon wafers in the semiconductor industry by companies located in the industrial science park near the sampling area. In addition, Lee and colleagues detected isopropanol in WWTP effluents (292 ng/L) and lake water (3.10 μg/L) [22].

Benzyl alcohol is used as a solvent in different product categories including paints, adhesives, perfumes, and sanitizers [23]. Benzyl alcohol was detected in wastewater treatment plants (WWTPs) in China at concentrations of 500–11,000 and 150–400 ng/L, respectively, in the influents and effluents [20]. Data suggest ethanol is the most commonly detected solvent (Fig. 2a). For example, Avery et al. [24] reported concentrations of 2.73 and 23.59 μg/L for ethanol in surface waters and lakes, respectively, in USA (Fig. 2a). Studies suggest that frequent and continued use of sanitizers may pose severe human health risks including cardiac dysrhythmias, respiratory arrest hypothermia, cancer, among others [25,26], especially due their extended period of use as was the case during peak COVID-19 pandemic.

In the USA, 1,2-propanediol was detected at very high concentrations in the surface water (19 μg/L), but very low in the groundwater (4 ng/L) [27] (Fig. 2a). It is likely the elevated quantities of 1,2-propanediol were from de-icing agents as these values were detected in storm water runoff at an airport in Utah, USA [27]. Further, propane and butane were detected in soil samples in India at concentrations of 1–34 μg/L and 1–9 μg/L, respectively [28]. Conversely, solvents were detected in the air due to their high volatility. For example, in Canada 199, 80.23, and 62.03 ng/L of butane, isopropane, and isobutane, respectively, were detected in air; and as a result increased the likelihood for direct exposure to humans.

Effects of solvents to different taxa (fish, algae, *Daphnia magna*, and bacteria) under different test durations of 24 to 96 h for acute studies have been reported for a number of solvents [29–31]. For example, 96-h lethal concentration 50 (96-h LC_{50}) values of benzyl alcohol on three different fish species: *Leuciscus idus*, *Pimephales promelas* (fathead minnow), and *Lepomis macrochirus* (Bluegill) were established at 646, 460, and 10 mg/L, respectively. A study by Mattson [32] reported 96-h LC_{50} acute toxicity test on *Pimephales promelas juveniles* of 460 mg/L nominal concentration. Twenty-four- and forty-eight-h effective concentration 50 (EC_{50}) values on immobilization of *D. magna* were, respectively, 55 mg/L [33], and 230 mg/L [34]. Moreover, studies using *Scenedesmus quadricauda* as exposure organism yielded 96-h EC_{50} value on growth inhibition at 640 mg/L. These results indicate benzyl alcohol can potentially exert harmful to non-harmful effects to fish.

Toxicity data reviewed herein show alkyl dimethylamine oxide (dodecyldimethylamine oxide or lauryldimethylamine oxide) as most toxic solvent to different taxa e.g., fish, algae, etc. [35] dependent on exposure duration and organism type. For example, documented 96-h LC_{50} and no observed effect concentration (NOEC) values for *Pimephales promelas* (fathead minnow) fish were 3.46 mg/L and 0.420 mg/L, respectively. In addition, a low NOEC of 1.30 mg/L was recorded for *Oryzias latipes* [36]. In another work, *Danio rerio* were found to be the most tolerant species assessed with LC_{50} of 31.8 mg/L [37].

Similarly, results of *D. magna* [38] demonstrated very low NOECs (0.700 mg/L) on epical endpoints (production and survival). In addition, algae *P. subcapitata* species effects data for the production and survival endpoints yielded 72-h ErC_{50} values of 0.153 [30], and 0.250 mg/L [35] respectively. However, certain solvents (e.g., 1,2-propanediol and isopropanol) were observed to be non-harmful to different taxa with $E(L)C_{50}s > 1000$ mg/L (Fig. 2b). For example, Bridie et al. [39] reported $LC_{50} > 5000$ mg/L on *Carassius auratus* species (goldfish); whereas West and colleagues [40] reported 48-h LC_{50} of 10,000 mg/L following exposure of *Lebistes reticulatus* (guppy) to 1,2-propanediol. These authors also conducted 24-h studies on the immobilization of *D. magna* which yielded

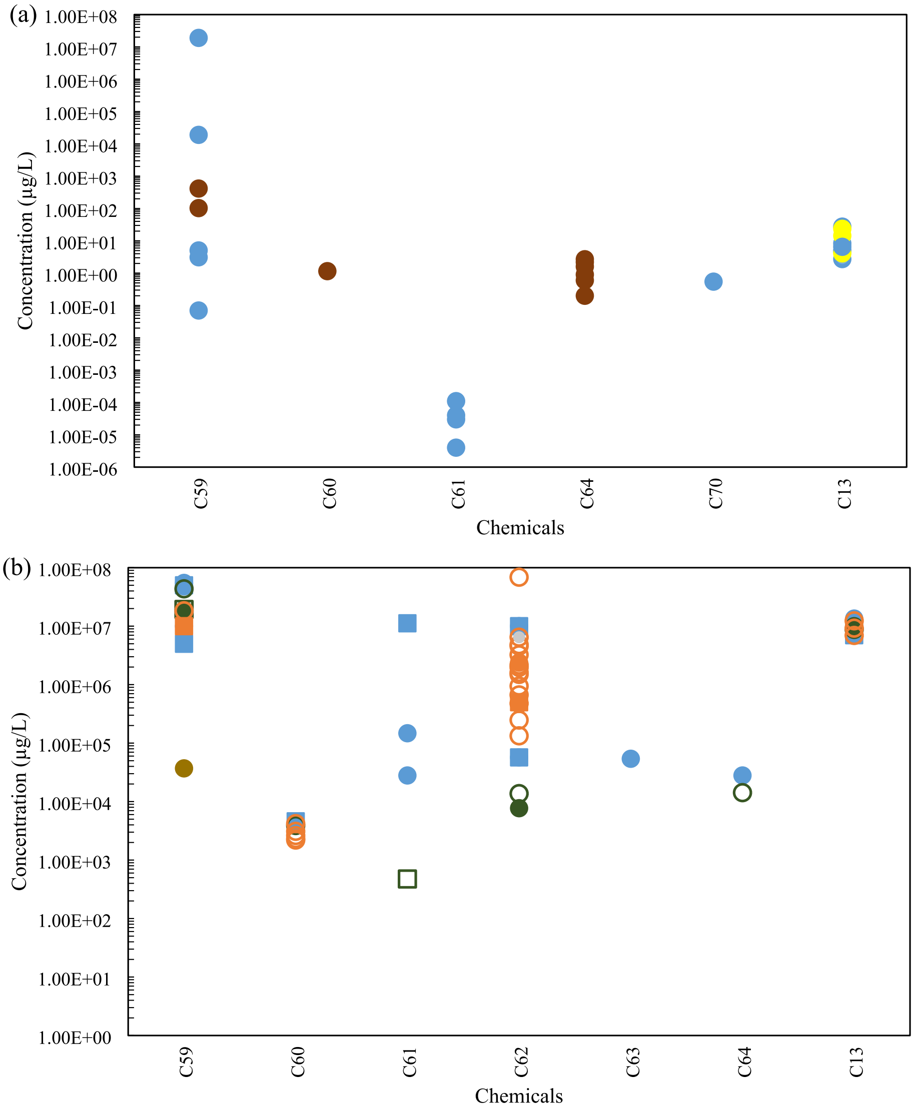

Fig. 2. (a) Occurrence of chemicals classified as solvents in sanitizers and disinfectants in variant environmental matrices (surface water (blue), lake water (yellow), and groundwater (brown). And (b) their E(*L*)C$_{50}$s tested on fish (blue), algae (green) and daphnia (orange) at different exposures (24 h (full squares), 48 h (open circles), 72 h (open squares) and 96 h (full circles). In the entire paper, the following colors are used for consistency to represent variant exposure durations in this report in toxicity graphs. There are: black (0.083 h), brown (0.25 h), purple (0.5 h), pink (3 h), red (17 h); green (24 h); navy blue (48 h); orange (72 h), and sky blue (96 h).

EC$_{50}$ > 10,000 mg/L [40]. The low toxicity of 1,2-propanediol can be attributed to its rapid degradation in different environmental media with half-lives of 1–4, and 0.8 d in water and air, respectively [41].

The glycerol and glycerin are among widely used solvents. Herein, results of both chemicals were grouped together owing no specificity on toxicity reported as in certain cases it included their derivatives [42]. For example, Perales and colleagues documented effects of different glycerol derivatives with EC$_{50}$ values >100 mg/L for different species, and therefore were broadly non-toxic except for the solvent code 444 on *D. magma* which yielded a EC$_{50}$ of 13.7 mg/L [42]. For sanitizers and disinfectants containing polyalkylene glycols, it was not possible to classify their toxicity and occurrence data based on a specific chemical as the term includes a broad number of compounds e.g., polyethylene glycol, polypropylene glycol, among others.

For alcohol-based solvents, data indicates that they are non-harmful to the aquatic taxa (Fig. 2b). For example, isopropanol (isopropyl alcohol) exerted no toxicity on fish *Carassius auratus* mortality as 24-h EC$_{50}$ values were > 5000 mg/L, and 7060 mg/L over 7-d chronic studies on *Poecilia reticulata* (guppy) [37]. Results on exposure of *D. magna* to isopropanol showed similar trends with very low EC$_{50}$ of 3010 mg/L as well as NOECs of 2100 mg/L and 757 mg/L for the reproduction and growth endpoints, respectively. These results and other data summarized in Fig. 2b on effects of solvents point to highly varied effects from non-harmful (e.g., 1,2-propanediol or isopropyl alcohol) (irrespective of organisms' trophic level) to high toxic (e.g., dodecydimethylamine oxide to algae).

3.2. Oxidants and antioxidants

Antioxidants are used to preserve lipid components from quality deterioration through the prevention of oxidation with an estimated global production of 1.25 million tons by 2016 [43]. These chemicals are classified broadly into three categories based on their antioxidant mechanisms, namely; primary, secondary, and tertiary antioxidants [44,45]. Their mechanisms of action include neutralizing or scavenging reactive nitrogen (RNS) or oxygen species (ROS); or inhibition on the formation of RNS or ROS; or removing O$_2$ and binding the metal ions required for the generation of ROS. Antioxidants are widely used in product categories including personal care products (PCPs), foods, sanitizers, plasticizers, textiles, and other household goods [46]. Conversely, oxidizing agents are used in fabric bleaches, water purification, fuel combustion, and rubber vulcanization.

Data demonstrates the widespread occurrence of oxidants and antioxidants in surface waters, wastewater, soils, and sludge [47–50], but this is only for limited chemicals different environmental matrixes (Fig. 3a). Results herein indicate oxidants and antioxidants commonly detected are tocopheryl acetate and hydrogen peroxide (Fig. 3a). For example, tocopheryl acetate was detected in sludge with maximal concentrations reaching 1.10 mg/g [51]; whereas in surface water measured hydrogen peroxide was 3.67 μg/L [52]. Further, in Germany elevated concentrations of tocopheryl acetate were detected in WWTPs effluent in the range of 6–25 μg/L [51]. Blum and colleagues detected 660 μg/kg and 110 ng/L of tocopheryl acetate, respectively, in soils and WWTP effluents in Sweden [53]. Therefore, the release of effluent with high concentrations in the μg/L range of tocopheryl acetate may end up into surface waters unless it undergoes several hundred-fold dilution factors, or are effectively removed in the WWTPs. This, in turn may pose reasonably high risks to aquatic organisms at different biological levels of organization.

Methylisothiazolinone a heterocyclic compound [54,55] was detected at concentrations (mean and standard deviation with $n = 4$ independent experiments) of 1.21 ± 0.46 in untreated sewage as well as in the beach (at two different locations i.e., Leba and chlapowo) at levels of 2.19 ± 0.47 and 4.48 ± 1.04 μg/L, and soil at levels of 1.04 ± 0.06–10.8 ± 1.07 μg/kg, respectively, [48]. However, in the seawater and river samples the concentrations of methylisothiazolinone were below the limit of quantification (LOQ) [48] likely due to high dilution in both environmental matrixes. In addition, the presence of oxidants in tap water samples have been documented (Fig. 3a). This implies ineffective portable water treatment technologies and concomitant increasing use of sanitizers and disinfectants may lead to human exposure to their constituent chemicals through drinking water. However, most chemicals permissible exposure threshold values especially to vulnerable populations (e.g., elderly, children, etc.) remain yet to be established.

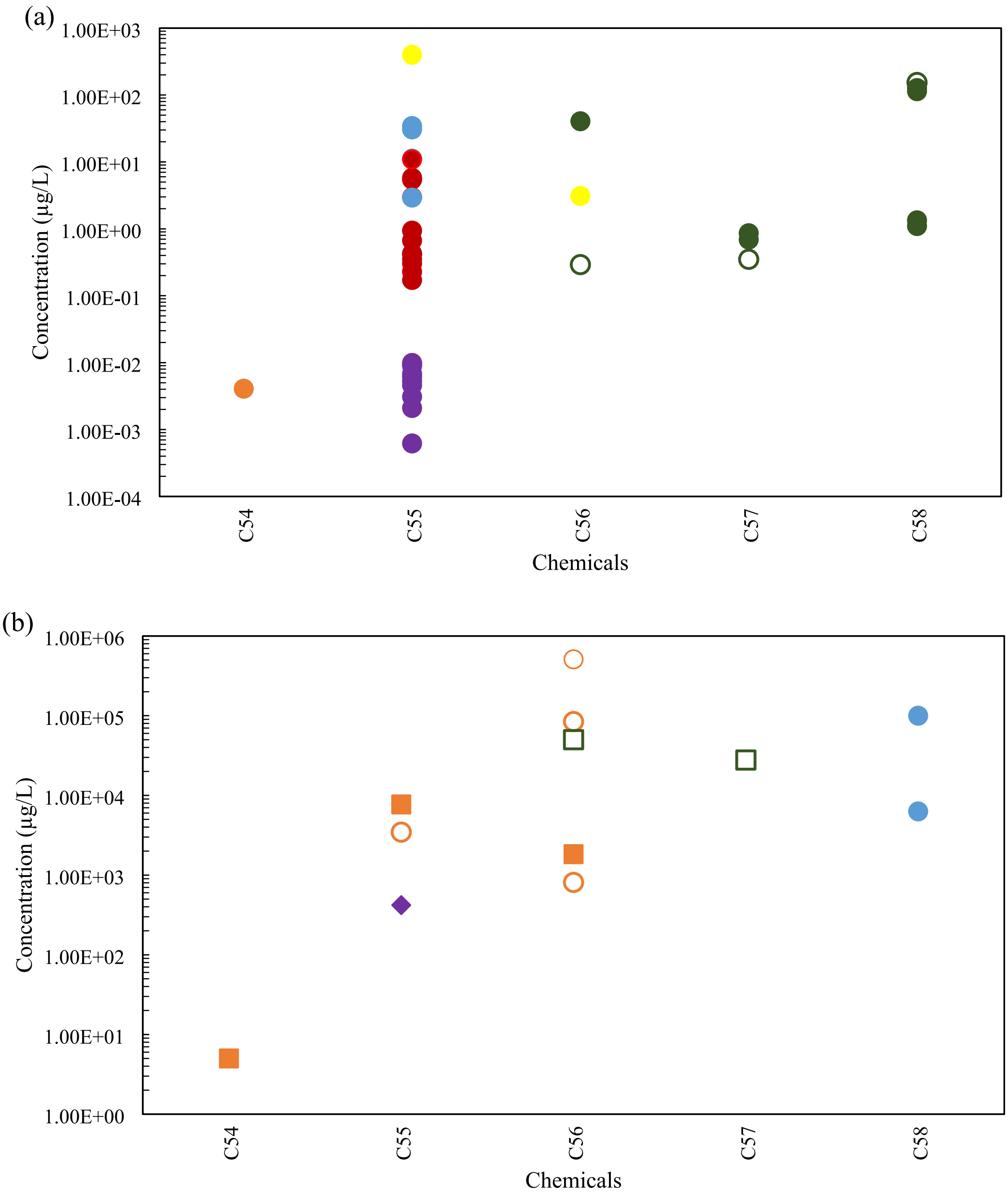

Fig. 3. (a) Occurrence of chemicals classified as oxidants and antioxidants in sanitizers and disinfectants in variant environmental matrices (WWTP influent (full green circles) and effluent (open green circles), surface water (blue), river water (red), tap water (orange), lake water (yellow) and marine water (purple). And (b) their E(*L*)C_{50}s tested on fish (blue), algae (green) daphnia (orange) and bacteria (purple) at different exposures (0.5 (full diamonds), 24 h (full squares), 48 h (open circles), 72 h (open squares) and 96 h (full circles).

Effects data of oxidants and antioxidants on aquatic organisms at different levels of biological organization are summarized in Fig. 3b. Similar to their occurrence data (Fig. 3a), the ecotoxicity studies of these compounds are limited (Fig. 3b). In this review, the assessed data indicate hypochlorous acid as the most toxic oxidant (Fig. 3b) with 48-h EC_{50} values for crustaceans and for fish as 5 [56], and 40 μg/L [57], respectively.

Recent increasing interest in peracetic acid (PAA) as a sustainable disinfectant for use in aquaculture due to its low concentrations (as low as 1 mg/L) required, and knowledge deficits on its toxicity to fish has made it to be the most investigated chemical in this class [58,59]. PAA releases into the environment and various waste streams are due to wide usage as a disinfectant, and from the production facilities. There are propositions that PAA may not pose toxicity effects when diluted in water to its effective concentration [60,61]. However, Straus et al. [62] exposure study on Channel catfish (*Ictalurus punctatus*) found that 24-h LC_{50} values of 2.60 and 1.60 mg/L for yolk-sac fry and swim-up fry, respectively. Furthermore, NOECs of 2.20 and 1.30 mg/L for yolk-sac fry and swim-up fry, respectively, were observed. Similarly, Straus et al., (2012) [63] observed 48- and 72-hEC_{50} values in the ranges of 0.152–1.10 mg/L, and 35.0–350 μg/L on *D. magna* and *Scenedesmus subspicatus,* respectively. Elsewhere, several researchers [64,65] reported the EC_{50} values of 1.38 and 0.18 over 72 and 120 h, respectively, on *Selenastrum capricornutum*. In addition, Hicks and colleagues [64] observed very low NOEC of 130 μg/L for the same species. Taken together, reviewed data point to high toxicity of PAA to fish, crustaceans, and unicellular organisms, and therefore, contradicts the proposition that PAA is non-toxic to aquatic organisms.

Other works have reported high toxic effects of solvents on aquatic organisms [66,67]. For example, sodium dichloroisocyanurate dihydrate was found to be very toxic to daphnia with 48 h EC_{50} of 0.19 mg/L [66]. Further, terpineol has also been found to induce toxic effects to salmonid fish species with observed 96-h LC_{50} values of 6.30 and 6.60 mg/L for *coho salmon* and rainbow trout, respectively [67]. Conversely, hydrogen peroxide and L-Lactic acid were non-harmful to aquatic organisms with most EC_{50} values >100 mg/L [68,69]. Overall, data suggest PAA and hypochlorous acid to be toxic or very toxic irrespective of the taxonomical class as results summarized in Fig. 3b as both chemicals has mostly $E(L)C_{50}$ values <10 mg/L. Data suggest fish and daphnia as most sensitive species with several $E(L)C_{50}$ values <1 mg/L [62,65,66]. Due to data deficit on the occurrence and/or effects of oxidants and antioxidants compounds impede establishing their risks to aquatic organisms. This, in turn raises the need for occurrence and effects studies of oxidants and antioxidants to aid their risk assessment in the aquatic environments.

3.3. Antimicrobials

Antimicrobials are chemicals or their mixtures thereof employed to destroy, deter, render harmless, prevent the action of, or otherwise exert a controlling effect on any harmful organism by any means other than mere physical or mechanical action [49]. Different classes of chemicals are used as antimicrobials, and these include alcohols, [70], aldehydes [71], biguanides [72], and halogen-releasing agents [73] with N-halamines as most dominant [74]. Recent advances have led to the replacement of iodine by more effective antimicrobials [75] including peroxygens and other forms of oxygen (e.g., hydrogen peroxide, ozone), peracetic acid, and chlorine dioxide [76], and phenols [77].

Thirty-two antimicrobials were reviewed in this study, and their concentrations varied widely from low 0.60 ng/L(South Korea) [78] to 3.87 mg/L (Ghana) [79] in the influent and effluent. Notably, the exceptionally high concentrations of benzalkonium chloride (BAC) detected in Ghana were attributed to its wide use in household cleaning products [80,81]. BAC is the widely detected antimicrobial in wastewaters across the globe in countries including Austria, Germany, Sweden, USA [82], France [49], and Ghana [79]. For example, BAC was detected in river water at concentrations of 0.67–1.60 ng/L in China [83], and 1220 ng/L in USA [84]. Further, BAC was detected in digested sludge at very high concentration of 210–89,000 ng/g [85]. These results demonstrate the release of BAC to water resources and soil compartments through effluents, and sludge application in agricultural fields, respectively.

Following the incomplete removal of antimicrobials in wastewater, have led to their eventual presence in surface water. Seven antimicrobials were detected in surface water in five different countries. For example, BAC was detected in urban runoff in France [86], chloroxylenol in the UK [87,88], sodium ortho phenyl phenate in China [22], and isopropanol (isopropyl alcohol) in Korea [22]. Compounds with the maximum concentrations recorded in surface water were chloroxylenol at 21.9 μg/L (UK) [87] and isopropanol (isopropyl alcohol) (Korea) at 3.10 μg/L [22]. This is possibly because both chemicals are widely used as antiseptics and disinfectants in cosmetics and personal care products, leading to their consequent high concentrations in surface waters linked to incomplete removal in WWTPs.

Although antimicrobials are widely used, but their toxicological effects on non-target environmental microorganisms [89], and other aquatic organisms are severely lacking. Susceptibility to antimicrobial agents is due on their ability to kill microorganisms and/or inhibit growth. This poses challenges to comparing toxicity results between those conducted in laboratory settings versus in actual environment matrixes as testing conditions significantly influence the observed outcome effects [90–92]. Results in Fig. 4a summarize the toxicity of antimicrobials on different aquatic taxonomical groups. Of the 17 antimicrobials documented in this review, four were found to induce very high acute toxicity (4-chloro-m-cresol, methylisothiazolinone, peracetic acid, benzalkonium chloride, and sodium ortho phenyl phenate) relative to the rest.

In addition, a large portion of chemicals were found to exert effects ranging from very toxic to harmful on different taxa except in certain cases e.g., glutaraldehyde (on fish), and methylisothiazolinone (on daphnia), with algae and daphnia as the most sensitive species. For example, EC_{50} values of 4-chloro-m-cresol and sodium ortho phenyl phenate on fish *Acartia tonsa* (planktonic copepod) indicates they are very toxic at 130 and 116 μg/L, respectively, on the same species [88]. Elsewhere, results of Leung [93] demonstrated that glutaraldehyde was toxic to different fish species including *Oncorhynchus mykiss*, *Pimephales promelas*, *Lepomis macrochirus*, and *Salmo salar* with EC_{50} values of 11, 5–6, 9–11, and 3 mg/L, respectively. Other works by Pereira and colleagues [94] observed glutaraldehyde to be toxic to *Danio rerio* with EC_{50} of 5.80 mg/L.

Other organisms including *D. magna* [95], *Ceriodaphnia dubia* [96], and *Neocaridina denticulata* [97] were found to be sensitive to antimicrobials, nine were identified to be highly toxic with toxicity values ranging from 0.04 to 1.80 mg/L. These chemicals included 4-chloro-m-cresol, BAC [98], benzisothiazolinone [99], chlorine [65], chlorophenols [100], chloroxylenol [88], hypochlorous acid [56], methylisothiazolinone [83], PAA [65,101], and sodium ortho phenyl phenate [88]. The CCR report [102] documented the chronic toxicity of glutaraldehyde exposed to *D. magna* for 21 d with NOEC and LOEC values of 2.13 and 4.25 mg/L, respectively. For BAC, Lavorgna et al. [103] reported the chronic toxicity tested over 21 d on *D. magna,* and 7 d on *C. dubia* with high EC_{50s} of 1 μg/L and 44 μg/L, respectively. In addition, BAC induced DNA damage on *D. magna*, and *C. dubia* at an EC_{50} at low concentrations of 38.2 and 403.7 μg/L [103], respectively. Results of BAC demonstrate that both chronic and acute observed effects fall within the same range and highlight its high toxicity to the crustacean daphnia.

Studies on algae showed these organisms are sensitive to antimicrobials, with reported EC_{50}s in the range of 0.01–10 mg/L (Fig. 4b). As an example, BAC tested on *P. subcapitata* had EC_{50} of 41 μg/L [98], whilst benzisothiazolinone tested on green algae had an EC_{50} of 150 μg/L [104]; therefore, both chemicals are very toxic to algae. Both BAC and octyldecyl dimethyl ammonium chlorides had a higher growth inhibition effect on *Chlorella vulgaris* with an EC_{50} of 203 μg/L and 110 mg/L [105], respectively. Utsunomiya and colleagues [106] also found BAC to be highly toxic on *Chlorella pyrenidosa*. Notably, most individual antibacterial compounds are predominantly toxic. This, in turn raises the likelihood of resultant chemical mixtures with common

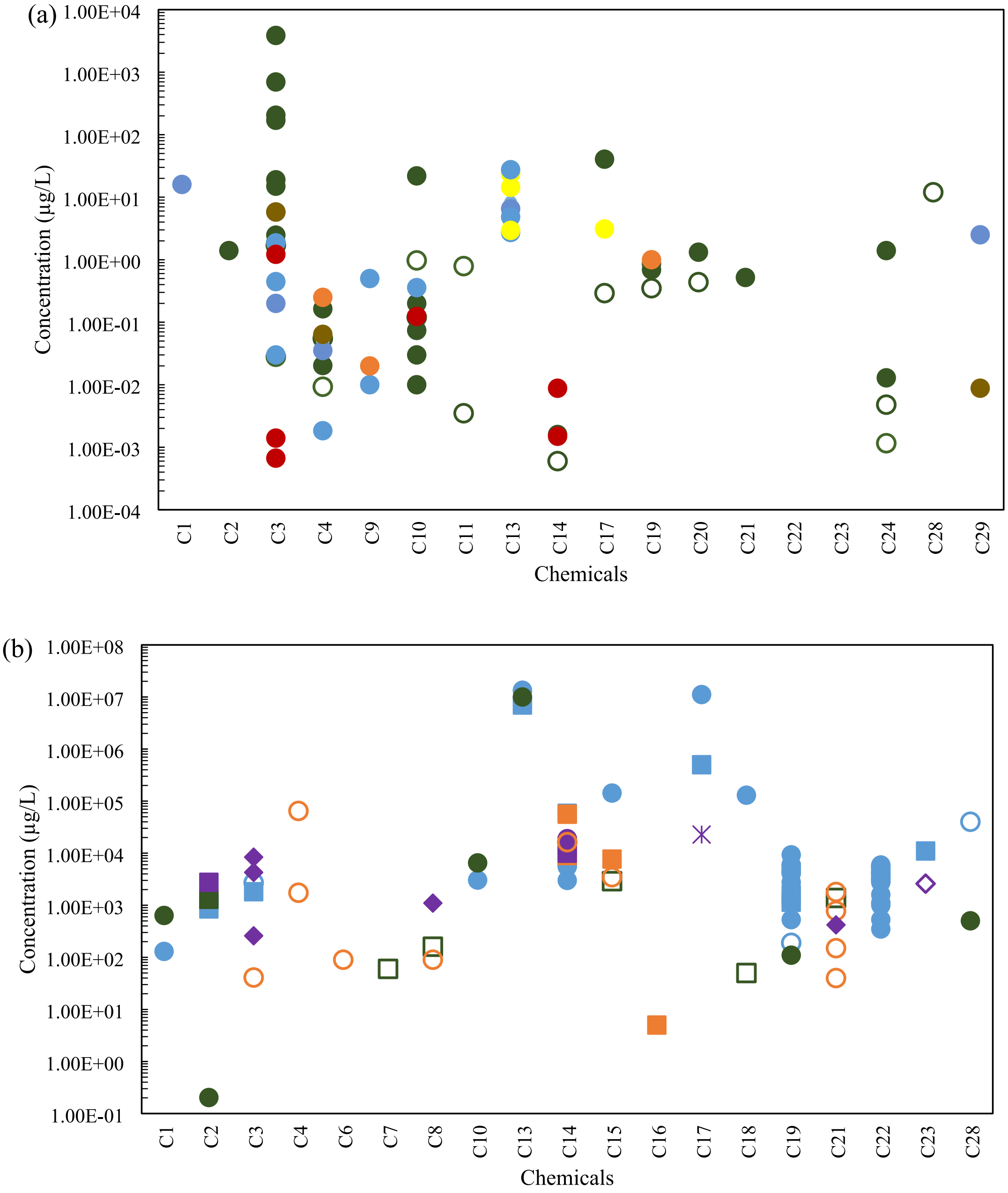

Fig. 4. (a) Occurrence of antimicrobial chemicals in sanitizers and disinfectants in variant environmental matrices (WWTP influent (full green circles) and effluent (open green circles), surface water (blue), river water (red), tap water (orange), lake water (yellow), and groundwater (brown). And (b) their E(*L*)C_{50}s tested on fish (blue), algae (green) daphnia (orange) and bacteria (purple) at different exposures (0.083 h (asterisk),0.25 h (open diamond), 0.5 h (full diamond), 24 h (full squares), 48 h (open circles), 72 h (open squares) and 96 h (full circles).

mechanisms of action with higher combined deleterious effects to the aquatic organisms [107].

Reviewed data also showed high bactericidal effects of antimicrobials (Fig. 4b). For example, Chhetri and co-workers [65] observed very high EC_{50} values following 30 min bioluminescence exposures of PAA, hydrogen peroxide, chlorine dioxide, and chlorine on *Vibrio fischeri* at 0.42, 5.67, 1.10, and 1.10 mg/L, respectively. These results indicate PAA as most toxic to bacteria. In another study, 24 h chronic studies following exposure of chlorhexidine gluconate on different bacterial species *Bacillus subtilis*, *Staphylococcus aureus,* and *Escherichia coli* induced inhibition at concentrations of 3.46 mg/L, 4.42 mg/L and 2.33 mg/L, respectively, thus indicative of *Escherichia coli* being the most sensitive bacterial species.

3.4. UV filters

Organic ultraviolent (UV) filters are used in numerous consumer products chiefly to provide protection against damage from UV irradiation [108] with eventual increasing release into the environment from different sources. These sources include human recreational activities (e.g., swimming and bathing), industrial wastewater discharges, construction (e.g., in paints), and laundry activities. There are two classes of UV filters, viz.: organic and inorganic filters, and account for approximately 20% of the sunscreen products in commerce [109]. Here, the focus is on the organic category as they are incorporated in sanitizers and disinfectants found in the South African commerce. Examples of UV filters identified were benzophenone-3 (BP-3), benzophenone-4 (BP-4), 4-Methyl-benzilidine-camphor (4MBC), ethylhexyl methoxy cinnamate (EHMC), and octocrylene (OC), and are widely used globally [110].

Until now, UV filters have been detected in natural aquatic, terrestrial environments, and engineered systems (e.g., WWTPs) across the globe. Data demonstrates wide variability of UV filters concentrations (0.505–2196 μg/L) in wastewater [87,111–115]. This may be due to a combination of factors including low water solubility, high lipophilicity, low degradability, and high organic content [116,117]. Thus, UV filters are likely to accumulate in the aquatic environment [116].

BP-3 is the most widely measured UV filters in environmental systems including rivers, surface waters, and wastewater, but few detections in lakes, groundwater, and seawater (Fig. 5a). Owing to the high use of BP-3 elevated concentrations have been detected e.g., in sludge (Norway; 0.824–2.12 μg/g [113], wastewater effluent (Italy; 46.9 μg/L) [118], and sea water (Central Pacific Ocean; 34.3 μg/L) [119]. Additionally, maximum concentrations of 5.72, 3.35, and 44 μg/L have been measured in river waters in Spain [120], China [121], and the UK [87], respectively. In another study, BP-3 was detected in Spain in surface water and tap water at concentrations of 5429 as well as 10 to 295 ng/L, respectively, [111].

Other chemicals incorporated in UV filters have also been detected in the aquatic environment including EHMC (3.0–27.1 μg/L) [119,122], and OC (4.4 μg/L) in lake water (Fig. 5a). The occurrences for the BP-4 were very high measuring in certain cases over 1000 mg/L both in the influent and effluent (Fig. 5a), and river water samples in the UK [87]. The higher BP-4 concentrations in the effluent were attributed to the inefficacy of WWTPs; thus, pointing to the treatment systems' inability to completely remove the UV filter [87]. At present, only few studies have documented the occurrence of UV filters in tap- and ground-waters with most concentrations <100 ng/L [111,122]. Other works have documented UV filters presence in sediments and sludge at elevated concentrations in the μg/g range for BP-3 (2.1), EHMC (4.7), and OC (41.6) [113], and BP-4 (5.0) [114]. Differences in concentrations of UV filters in river water, and their presence in sludge were dependent on variability of removal efficiencies based on technologies adopted in a given WWTP. For example, activated sludge

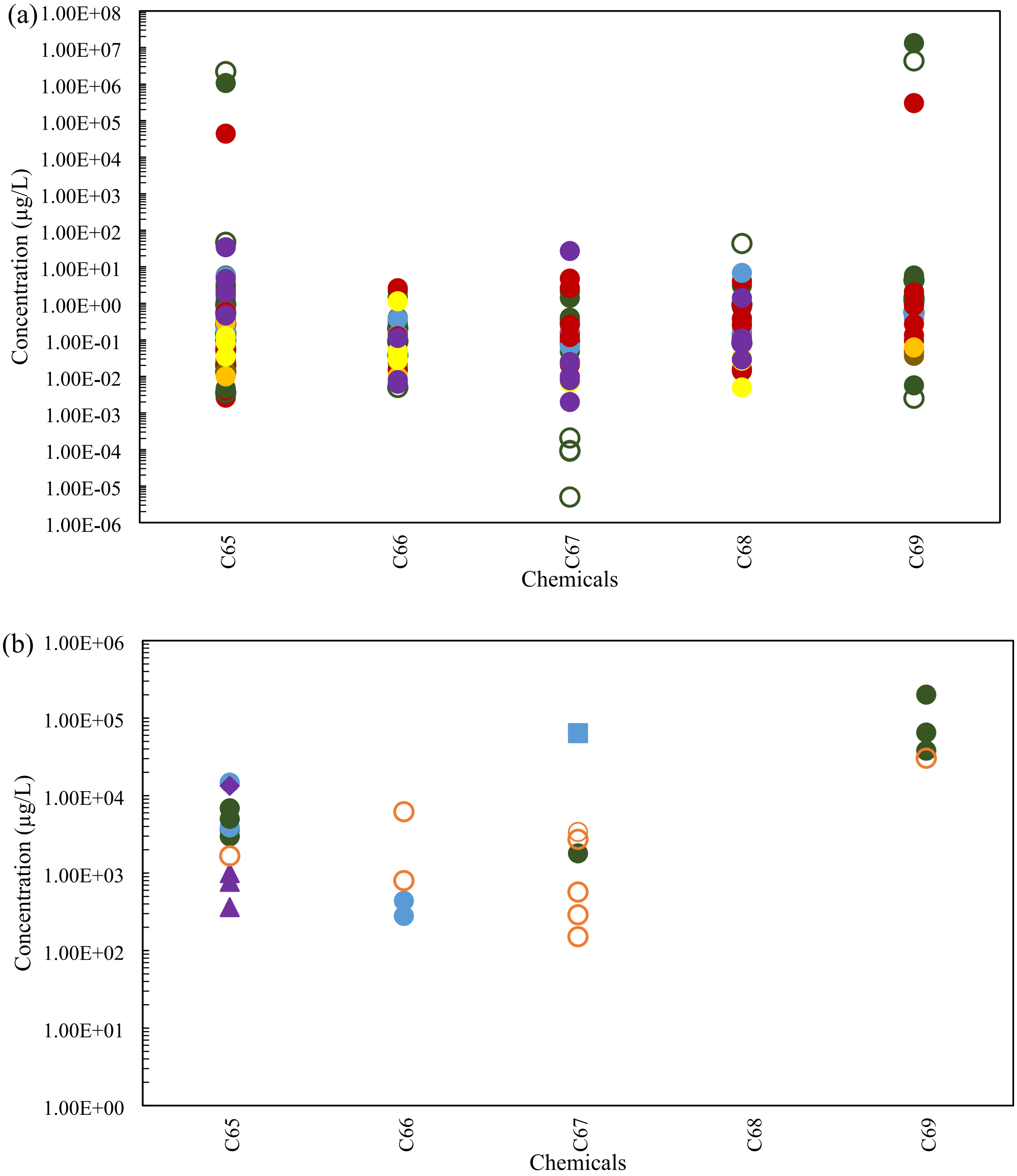

Fig. 5. (a) Occurrence of chemicals incorporated in UV filters in sanitizers and disinfectants in variant environmental matrices (WWTP influent (full green circles) and effluent (open green circles), surface water (blue), river water (red), lake water (yellow), marine water (purple) and groundwater (brown). And (b) their $E(L)C_{50}$s tested on fish (blue), algae (green) and daphnia (orange) at different exposures (0.5 (full diamonds), 24 h (full squares), 48 h (open circles), 72 h (open squares) and 96 h (full circles).

treatment was inefficient to remove UV filters compared to other treatment processes e.g., filter beds [87]. Therefore, owing to increasing and high concentrations of UV-filters detected in the aquatic environments, they have been identified as among chemicals of emerging environmental concern [123].

Data indicates UV filters can induce different levels of effects on the aquatic life (Fig. 5b). Due to deleterious effects on coral reefs, some chemicals used as in UV filters have been banned in several countries. For instance, 4MBC has been banned as a sunscreen component in the USA [124]. Other countries like Hawaii, Key West, and the United States Virgin Islands (USVI) have recently banned the use of sunscreens containing BP-3 and EHMC owing to associated correlation between adverse effects and the coral reef bleaching [117,125]. Several studies have demonstrated the degradation of UV filters through the photolysis processes; however, the effects of the formed transformation products (TPs) remain unquantified [124]. For example, 4-HB (4-hydroxybutyrate) a TP of benzophenones was observed to induce adverse effects on reproduction, and interference with aquatic and terrestrial organisms' growth [126].

Toxicity studies for UV filters are largely for the crustacean species with observed effects ranging from moderate to high (<10 mg/L) except for BP-4 and OC. In addition, BP-4 and OC data showed they had harmful effects with 48 h LC_{50s} (Fig. 5b) (30.4–50 mg/L) [126–128] and very high toxicity (48-h EC_{50} 0.03 mg/L) [129], respectively. The mechanism of toxicity mostly entailed hormone interference as well as bioaccumulation effects [130]. For instance, exposure of *D. magna* to OC induced behavioral impairment on their photo-tactic response, and delayed mortality up to seven days post-exposure at environmentally relevant concentrations (0.20–200 μg/L) [129]. Similarly, BP-3 and EHMC were observed to induce moderate toxicity to algae (96 h EC_{50} of 2.98 mg/Land 72 h EC50 of 1.80 mg/L) [126,127]. In addition, BP-4 can cause slight to non-toxicity (96 h EC_{50} for growth of 38.0 mg/L) [131,132]. However, no toxic effects on algae were observed following exposure to 4MBC and OC. Additionally, OC and BP-4 were non-toxic on fish, but BP-3 and 4MBC induced moderate to high toxicity with results for EHMC indicative of low toxicity.

In another study, results indicated BP-3 can reduce egg production, and with subsequent fewer hatchings and feminization of male fish. As a result, this has deleterious implications on reproduction and ultimate fish population [133]. EHMC was observed to induce increased malformation, heart rate, and hatching delay in fish embryos [134] whereas BP-4 interfered with expression of genes involved in hormonal pathways and steroidogenesis following exposure to zebra fish [135]. In other works, 4MBC was observed to impair motility, and also the induction of morphological abnormalities during embryonic development of fish [136,137]. In addition, 4MBC was found to increase the production of vitellogin and chorigenin in male fish (*Oryzias latipes*) [138], increases in hatching time, reduction on hatching rate, and retarded growth [139]. Overall, the toxicity of UV filters on aquatic organisms especially on bacteria is limited with data accessible only for BP-3. Results indicate BP-3 is highly toxic to bacteria (*Bacteroidetes* and *Proteobacteria*) (48 h EC_{50} 0.36–1.00 mg/L) [140]), and toxic to *V. fisheri* (15 min EC_{50} 13.4 mg/L) [141]. Therefore, high release of UV filters from sanitizers and disinfectants may have serious implications to microbes e.g., bacteria.

3.5. Fragrances

Fragrances are organic compounds with pleasant odours, and widely incorporated in numerous daily products including perfumes, hair care products, baby care products, lotions, essential oils, air fresheners, detergents, and as a flavor in bakery items [142,143]. As they are PCPs subclass [144,145]; and are classified according to their source, chemical structure, and their provided note. Natural fragrances consist of two classes, namely; aroma and musk compounds differentiated by their plant and animal sources, respectively [146]. The largest class of fragrances are synthetics but are not included in this work as none were identified in sanitizers and disinfectant product categories. In early 2010s, with increasing demand globally, fragrances production volumes were projected above 1000 t annually in the EU [147], and are on the rise.

To date, however, there are limited studies on measured environmental concentrations of different fragrances especially the organic forms in comparison to synthetic ones including polycyclic musks such as galaxolide (HHCB) and tonalide (AHTN), and bicyclic hydrocarbon [148]. Occurrence data for most fragrances ranged from low (4.95 ng/L) to high (238 μg/L) concentrations, but none >100 mg/L in different matrixes except for two chemicals: benzyl salicylate and methylpropional (Fig. 6a). Benzyl Salicylate to date has been widely reported in different environmental matrixes as demonstrated by data retrieved from the published literature (Fig. 6a).

Concentrations of Benzyl salicylate ranged from < LQL (lowest quantifiable limit) to 127 μg/L in wastewater effluent [149], and potentially high levels were released into the surface waters. Further, this compound has been detected in WWTP effluent leading into seawater in Terra Nova Bay, Antarctica at low concentrations of 2.20–4.50 ng/L [150]. In other works, for example, D-Limonene and Alpha-isomethyl ionone were qualitatively detected, but unquantified in WWTPs effluents in Henares River located in the Tajo River Basin, Spain [151]. Similarly, other fragrances have been detected at low concentrations in the aquatic environments including lakes, rivers, and coastal systems [150,152–154]. For example, Alvarez et al. [152] reported limonene concentrations ranging from undetectable limits to 46 ng/L in the coastal waters of San Francisco Bay and the Southern California Bight, USA.

Although certain fragrances are pseudo-persistent in the aquatic environments through continuous release from technical systems (e.g., WWTPs), however, evidence point to their effective removal through wastewater treatment processes. For example, Lilial was detected at low concentrations of 10.0 to 57.0 ng/L in German WWTPs, and the subsequent receiving waters [147]. In addition, hexylcinnamaldehyde was measured at high concentration of 10.0 μg/L in the influent; but was reduced to <10.0 ng/L (>99.99% removal efficiency) in the effluent [147]. Hence, WWTPs can achieve high removal efficacies (≥90%) for certain fragrances in efficient and effective functioning treatment systems.

Alpha-isomethyl ionone (AIM) is widely used in product cosmetics, toiletry products, household cleaners, and detergents in excess of 100 t annually [155]. At present, AIM was identified as active ingredient in sanitizer brands commercialized in South African although they have been banned in certain jurisdictions. Alpha-ionone was also identified as an active ingredient in sanitizers; but no detected concentrations have been reported in the literature. Measured concentration of ionones (only for beta-ionone was detected in two WTPs (XWTP and SWTP) in S City (subtropical maritime climate), Guangdong Province, China in the ranges of 7. 90 to 28.5 ng/L in raw water; but none was detected in the effluent [156]. The removal of ionones is associated to its hydrophobic character, and ease of degradation through oxidation, heating, and irradiation processes [157].

Limited studies have documented the effects of organic fragrances as demonstrated by results depicted in Fig. 6b for different taxa in the aquatic environment. Benzyl salicylate has EC_{50} of 2.80 μg/L, and NOEC and lowest observed effects concentration (LOEC) of 0.1 and 1 μg/L (48 h) on copepod *Acartia tonsa*, respectively [158]. These concentrations are within the range detected in surface water systems such as river water (Fig. 6a). Therefore, high use of sanitizers and disinfectants may exacerbate the adverse effects of Benzyl salicylate in the environment. Effects studies of citral on fish, daphnia, and algae yielded were 6.78, 6.8, and 103.8 mg/L, respectively (Fig. 6b), thus being toxic to fish and daphnia. Notably, these values are above the reported EC_{50}s for fragrances (Fig. 6b). However, according to the classification of chemicals, herein most fragrances had their effects in the order of harmful to toxic. As such, more studies are required to ascertain their effects on aquatic species, particularly at sub-lethal effects where apical effects would not be observable but may induce deleterious effects particularly at molecular level with long-term impact to ecological integrity.

The 72 h EC_{50} toxicity of AIM were 2.89 (under growth phase), 3.23 (number of cells) and 7.47 mg/L (growth rate) for algae, whilst the NOEC for algae was 0.404 mg/L. Similarly, fish 96 h EC_{50} of 10.9 mg/L and 1.9 mg/L for *Orocorhynchus mykiss* and zebrafish, respectively [159] have

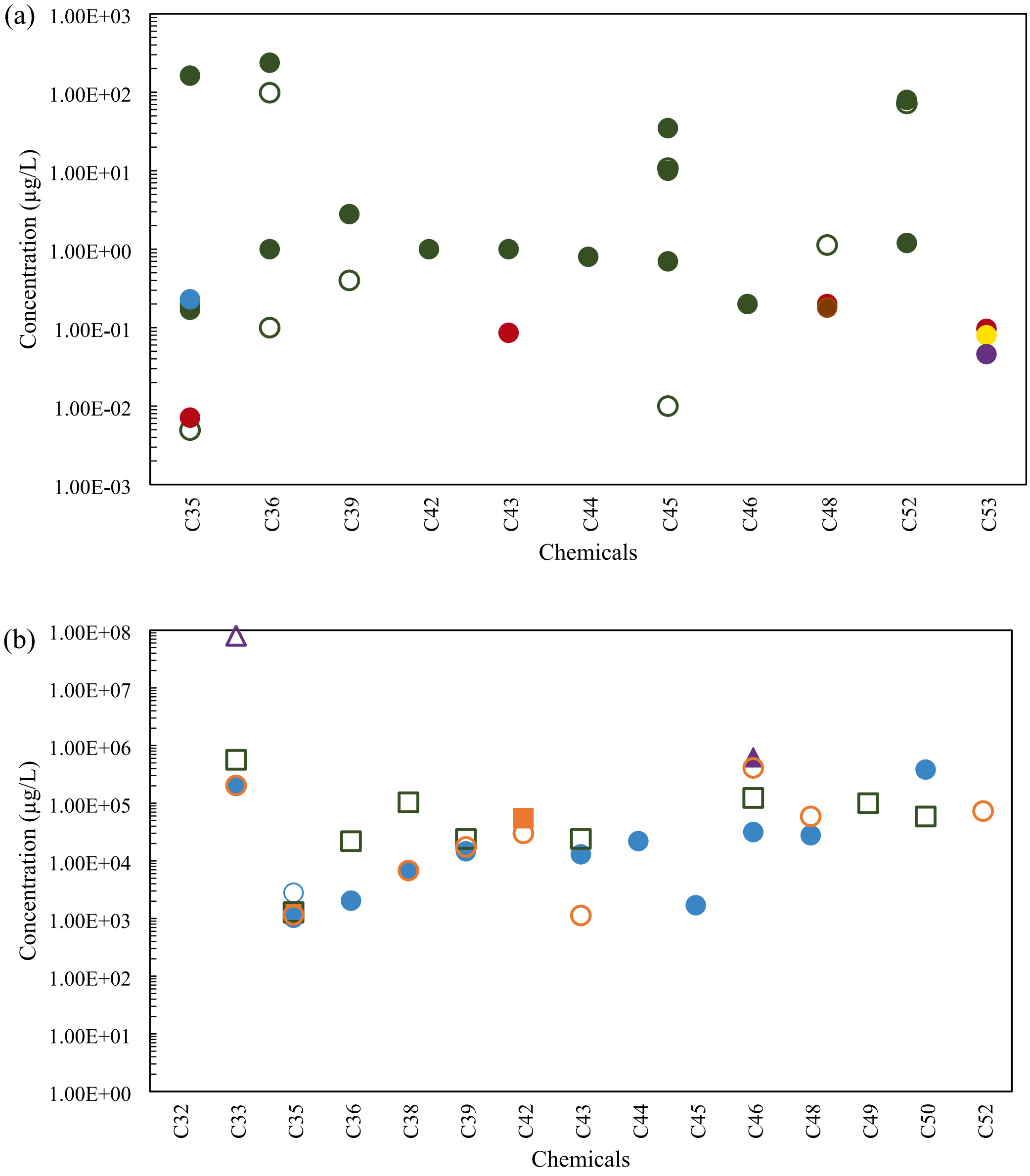

Fig. 6. (a) Occurrence of chemicals classified as fragrances in sanitizers and disinfectants in variant environmental matrices (WWTP influent (full green circles) and effluent (open green circles), surface water (blue), river water (red), tap water (orange), lake water (yellow), marine water (purple) and groundwater (brown). And (b) their E(*L*)C_{50}s tested on fish (blue), algae (green) daphnia (orange) and bacteria (purple) at different exposures (3 h (open triangles), 17 h (full triangles), 24 h (full squares), 48 h (open circles), 72 h (open squares) and 96 h (full circles).

been observed. Other fragrances such as Limonene showed concentration-dependent effects on the growth inhibition and photosynthetic abilities of the algae *Chlorella vulgaris*, but no ECs were provided [160].

3.6. Emulsifiers

Emulsifiers consist of polymers and proteins among other chemical classes, and are essential stabilizers utilized in formulations that require emulsion, and exhibits both hydrophobic and hydrophilic properties [161,162]. According to Tcholakova and colleagues [163] the physiochemical properties of emulsifiers are dependent on the genesis of the emulsifier in question. As such, emulsions are predominantly formulated using an amalgamation of emulsifiers to improve their functionality [164].

Numerous studies have demonstrated that use of an amalgamation of emulsifiers to form emulsion-based antimicrobials has the potential to enhance antimicrobial activity and physical stability [165,166]. At present, however, data on the environmental occurrence and toxicity of emulsifiers are largely lacking, and/or defined by numerous data deficits, but also highly contradictory [167]. This, in turn, limits our collective ability to estimate the ecological risk of emulsifiers in different environmental matrices.

The data retrieved from the literature indicates triethanolamine as the most investigated emulsifier with over 20 E(*L*)C_{50}s (41%) across the three taxa (Fig. 7). Further, data showed triethanolamine to be toxic with E(*L*)C_{50}s of 7.10 mg/L to *Scenedesmus subspicatus* following 48 h exposure [168]. However, other works have ranked the chemical as non-toxic to all taxa [167,169,170]. Results in Fig. 7 also show that cetrimonium bromide and polymeric biguanide hydrochloride are highly toxic to algae with E(*L*)C_{50}s of 4.00 mg/L and 19.0 µg/L, respectively [171].

About two decades ago, Tišler and colleagues highlighted lack of documentation on the ecological toxicity data for emulsifiers (e.g., cetrimonium bromide), and our review results indicate these knowledge gaps have remained largely undressed although emulsifiers are widely used in numerous product categories. Yet, other studies have categorized cetrimonium bromide as extremely toxic to aquatic organisms [172]. Toxicity data for the emulsifiers are characterized by contradictions. An example of data

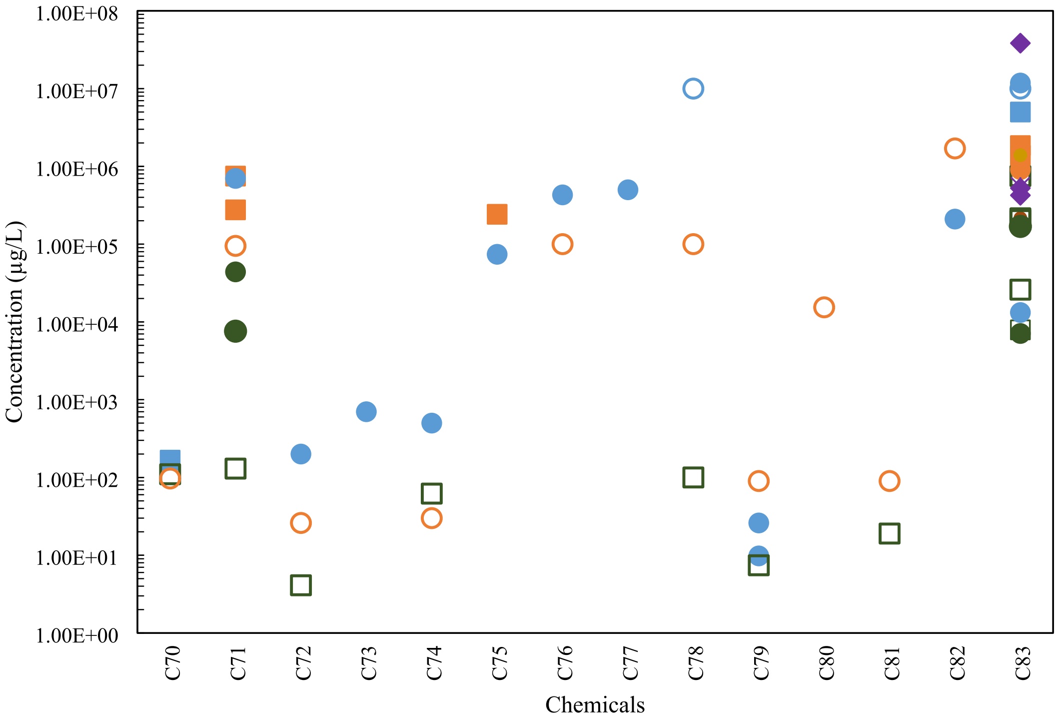

Fig. 7. E(L)C$_{50}$ of chemicals classified as emulsifiers in sanitizers and disinfectants values tested on fish (blue), algae (green) daphnia (orange) and bacteria (purple) at different exposures (0.083 h (asterisk),0.25 h (open diamond), 0.5 (full diamonds) 24 h (full squares), 48 h (open circles), 72 h (open squares) and 96 h (full circles).

contradiction is that the United States Environmental Protection Agency [173] classified polymeric biguanide hydrochloride among chemicals of low environmental risks. However, recent findings have demonstrated biguanide hydrochloride to be toxic to *Biomphalaria glabrata* (freshwater snails) at all different growth stages [174].

4. Environmental risk characterization

To gain an understanding on the likely implications of chemicals incorporated in sanitizers and disinfectants on different environmental systems. Here, a chemical risk was deterministically calculated in surface waters, lakes, and rivers. For each chemical, its ecological risk was determined for three taxa: fish, algae, and daphnia by calculating the risk quotient (RQ). RQ is a ratio of measured environmental concentration (MEC) to the predicted no effect concentration (PNEC). PNEC was determined by dividing E(L)C$_{50}$ values with an assessment factor (AF). The AF aids to account for inter- and intra-species effects variability. For each chemical, the PNEC was calculated using the least toxicity among the three taxa (fish, algae, or daphnia) [175]. To identify the hot spots (i.e., waters with increased risk), the retrieved occurrence data for each chemical was used (as MEC), and the results are summarized in Fig. 8.

Owing to lack of ecotoxicity chronic effects datasets for a large portion of chemicals reviewed herein, acute toxicity was used to determine the PNECs. Since PNEC was determined using acute toxicity an AF = 1000 [175] was used. For chemicals with published E(L)C$_{50}$ values, calculated PNEC ranges for the fish, daphnia, and algae taxonomical groups were 0.03–5000, 0.001–10,000, and 0.11–19,000 µg/L, respectively. Low PNECs suggest that even at low MECs, the MEC in question may exceed the threshold toxicity, and in turn, pose risk to the aquatic organisms. Conversely, very high PNECs signify a chemical does not pose risk to aquatic organisms unless released at very high concentration(s) into the aquatic environments.

According to Technical Guideline Document on risk assessment [176], if RQ ≥ 1, risk is considered unacceptable for the aquatic habitat; whereas if RQ < 1 no risk is posed to aquatic organisms. Here, framework by Lemly [177] for risk classification was employed, and consists of four classes, thus: RQ < 0.1, 0.1 ≤ RQ < 1, 1 ≤ RQ <10, and RQ ≥ 10 signifying none, low, moderate, and high risks, respectively. Results summarized in Fig. 8 indicate risks of chemicals (having both toxicity and occurrence data) ranked from none to very high. As the occurrence data used in the model were MECs for specific locations, RQ values >1 indicate moderate to high risks of chemicals in question to the aquatic environment. These results are important as can aid to prioritize chemicals of concern using the derived risk scores, and secondly, identify hot spots/hot events.

Using the safety threshold of RQ ≥ 10 for a chemical risk to be ranked as high – priority of chemicals of concern were identified per category (e.g., fragrances, UV filters, etc.). These spanned in various classes including antimicrobials (4-chloro-m-cresol, benzalkonium chloride, and sodium ortho phenyl phenate in surface water), solvents (1,2-propanediol in surface water), oxidants and antioxidants (hydrogen peroxide in lakes and rivers), and UV filters (4-Methylbenzilidine-camphor, ethylhexyl methoxy cinnamate, and octocrylene) across all three compartments. This assumption is justifiable because most published ecotoxicity data are highly variable, and broadly, reported observed effects are at individual level for the taxonomical group on focus.

This is because individual effects are not necessarily reflective of population-level effects as the later are more important as they offer insights into realistic risks of a given chemical to the environment. The toxicity numerous endpoints (e.g., growth, reproduction, hatching rate, etc.) in which E(L)C$_{50}$ values were determined and used here; however, in most cases we could not ascertain how the actual experiments were conducted – as this information was not documented in many reviewed articles. For example, it was not possible to establish if the toxicity retrieved from the literature reflected population-level effects; therefore, the threshold RQ for high risk was set at ≥10. This approach, however, should be used with caution. The reason is because it reflects only the current state-of-knowledge on exposure and effects of the chemicals with available data, and therefore, likely to be refined in future as more occurrence and toxicological data become accessible.

Results listed in Fig. 8 demonstrate daphnia as the most sensitive species as evidenced by high RQ values across different chemical classes. This does not imply that under all circumstances, the daphnia will be the most

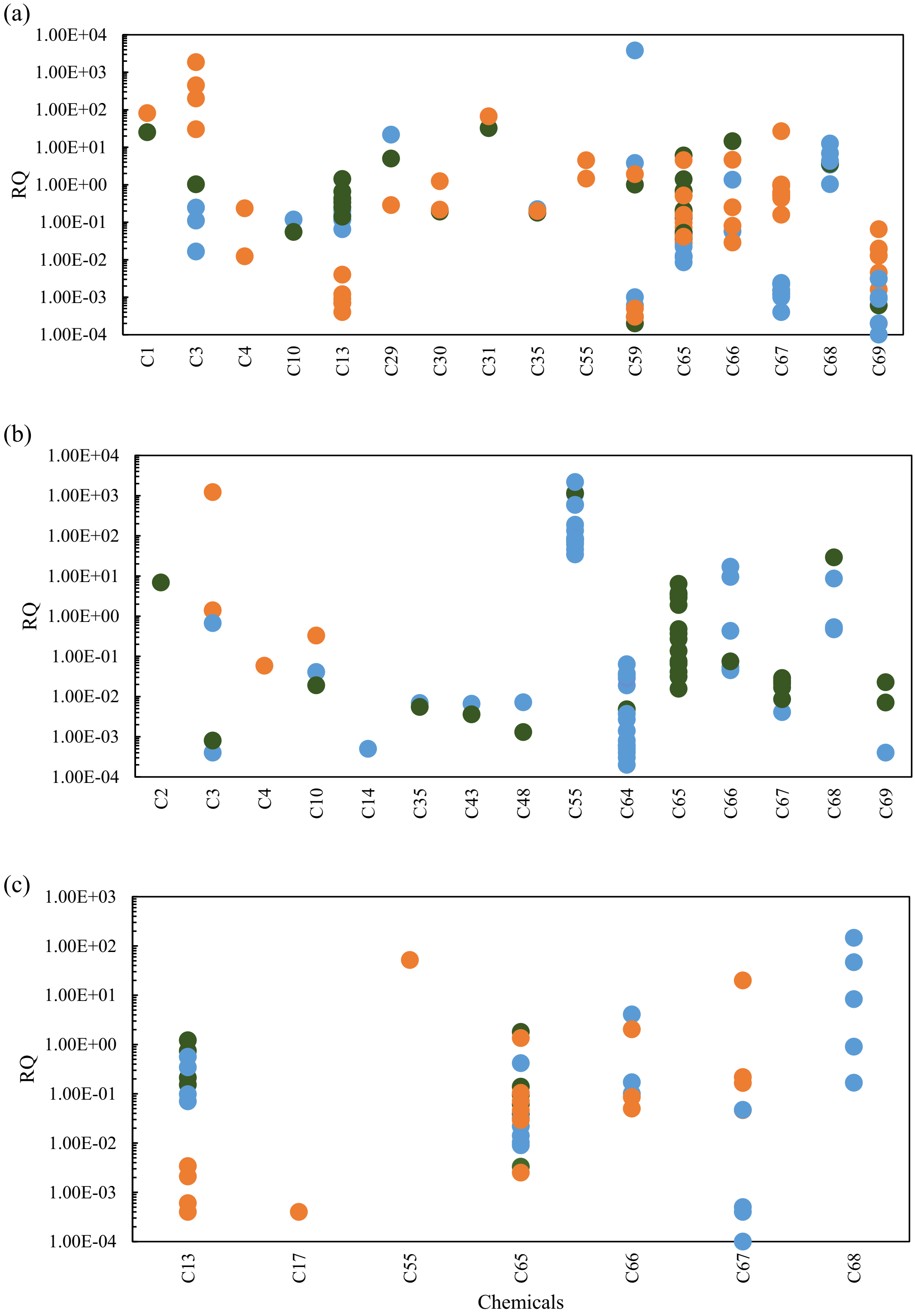

Fig. 8. Summary of risk characterization of sanitizers and disinfectants using measure concentrations in the aquatic environments: (a) surface water, (b) river water, and (c) lake water across the globe relative to no-effect concentrations for fish (blue), algae (green) and daphnia (orange) taxonomical groups.

affected organism. Rather, use of PNECs for specific taxonomical groups offer a practical approach owing to its high variability driven by chemical composition (both spatial and temporal) in a given aquatic environment, exposure variability based on changes in concentration as well as underlying drivers of the observed toxicity for specific taxa (e.g., age, trophic level, mode of action, experimental setup, etc.).

Of the 22 chemicals with data where RQs were calculated, nine had their risks ranked as *none* and/or *low* (RQ < 1) across three aquatic environments, and taxonomical groups. These chemicals were antimicrobials (benzothiazoline, chloroxylenol, ethanol, glutaraldehyde, and isopropanol), oxidants and antioxidants (hydrogen peroxide), fragrances (benzyl salicylate, eugenol, and linalool), and UV-filters (B-4). Notably, all fragrances with occurrence and effects data exhibited no risks to the aquatic organisms. In addition, nine chemicals in different classes, namely: antimicrobials (4-chloro-m-cresol benzalkonium chloride, and sodium ortho phenyl phenate), oxidants and antioxidants (hydrogen peroxide), solvents (1,2-propanediol), emulsifiers (didecylammonium chloride), and UV-filters (4-Methyl-benzilidine-camphor, ethylhexyl methoxy cinnamate, and octocrylene) posed high risks to different taxonomical groups as RQ values were >10 (Fig. 8).

Therefore, these nine chemicals were identified as of high priority based on their risk scores. Authors acknowledge that due to limited occurrence and toxicity data, environmental risks of most chemicals (78.8%) identified in the five classes (78.8% of total 99 chemicals) were indeterminable. This means the top list of chemicals of concern are likely to be higher as data become accessible. Furthermore, to fill these information deficits for these chemicals and generate data to aid their risk assessment and management in freshwater systems; we propose use of modelling approaches. For example, occurrence data can be derived using material flow analysis approaches to derive the predicted environmental concentrations, whereas in silico techniques (e.g., quantitative structure-activity relationships (QSARs), etc. can be used to generate environmental toxicity effects to diverse taxa across variant compartments and taxonomy. This is because modelling approaches at present are well established and their derived data are accepted for legislative functions e.g., jurisdictions in the USA and European Union. These models have been applied successfully for risk assessment of chemicals incorporated in pharmaceuticals and personal care products. The modelling approaches can thus be used to carry out rapid first tier risk assessment of chemicals incorporated in sanitizers and disinfectants. The proposed approaches are neither tedious, costly, nor time consuming as well as eliminates use and sacrificing of numerous organisms unlike the experimental-based approaches.

In South Africa, only a single study has reported UV filters occurrence in the aquatic environment [178]. Their calculated aquatic risks for benzophenones (with MEC based on combined concentrations of BP-1, BP-3, and BP-4 in river water) had RQ of 0.07, and effects data were determined using the ECOSAR model. This RQ value for South Africa is very low relative to most values obtained for individual benzophenones of BP-3 and BP-4 results listed in Fig. 8. This is likely due to differences in UV filters consumption patterns per country or region, standards of living, wastewater treatment efficacies, and geographical loci across the globe especially based on likely dilution of the pollutants in the environment.

5. Concluding remarks

Published literature indicates most chemicals widely incorporated in sanitizers and disinfectants, are used in other product categories. As a result, they are highly ambiguous in different aquatic environments both in the natural (lakes, rivers, seas/oceans), and engineered matrixes (wastewater, tap water) with largely potential consequences to humans and the environment. Many of these chemicals are of environmental concern as their concentrations vary greatly from low (<1 ng/L) to very high (>100 μg/L), and therefore, are pseudo-persistent owing to their continuous release into the environment – although their long-term consequences remain largely unquantified.

This review has also dealt with the ecotoxicity of these chemicals to taxonomical groups in natural and engineered systems. Results demonstrate the effects are dependent on factors including taxa under consideration, their habitant (freshwater, marine, etc.), experimental setup, chemical in question, life-cycle phase of exposure organism (eggs, juveniles, etc.), among others. Moreover, most chemicals lacked chronic data, and even a large portion had neither acute nor chronic data. Further, it is unclear whether chemicals in sanitizers and disinfectants may be transferred from the aquatic environments to humans because of biomagnification through water and food chain pathways. This is urgent owing to their wide use in sanitizers and disinfectants especially in response to COVID-19, but also since many were already at elevated environmental concentrations above toxicity threshold(s) to variant aquatic taxonomical groups even during pre-pandemic period. Yearly, large tonnages of these chemicals are discharged into the environment; therefore, both parent and/or their TPs can induce deleterious effects especially at sub-lethal level, though at present remain unquantified.

Of the chemicals assessed benzalkonium chloride, 4-chloro-m-cresol, sodium ortho phenyl phenate, hydrogen peroxide, 1,2-propanediol, 4-Methyl-benzilidine-camphor, didecylammonium chloride, ethylhexyl methoxy cinnamate, and octocrylene posed high risks to different taxa in the aquatic environment. Several of these chemicals are persistent in the environment even when removed via WWTPs to very low concentrations at ng/L levels. This point to the importance of controlling their flows, e.g., through improved treatment efficacies, and consideration of use of substitutes developed using green chemistry-based alternatives among other approaches to mitigate subtle environmental consequences.

From the reviewed literature, most occurrence studies were in the Organization for Economic Co-operation Development (OECD) countries and China, and least in South America and Africa. This raises the need to monitor and detect constituent chemicals incorporated in sanitizers and disinfectants in the environment with emphasis in the later countries. Second, there is need to achieve a fine balance between the benefits of incorporating certain chemicals in products against their risks. Such data should be used as a guiding principle in regulatory framework, but also to consider banning certain chemicals. Thirdly, there is research gap that need redress especially to develop greener chemicals for use in sanitizers d disinfectants. For example, increasing release of antimicrobial agents e.g., chlorhexidine and quaternary ammonium compounds may induce emergence of tolerant, resistant, and cross-resistant microbial strains even at sub-inhibitory concentrations.

Finally, a national database of chemicals used in domestic and industrial applications is existentially beneficial if a holistic and robust risk assessment valuable to achieve effective chemicals management in the environment. For instance, due diligence was done to identify chemicals reviewed herein incorporated in sanitizers and disinfectants in South Africa commerce. However, due to lack of chemicals national database it was improbable to ascertain whether all major chemicals were included in this review. This drawback can be remedied by the development and maintaining of widely accessible national databases of variant categories of products, and their constituent chemicals.

Declaration of Competing Interest

The authors declare that they have no known competing financial or personal interests that plausibly appeared to influence the work on this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enceco.2023.01.003.

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