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Increased use of sanitizers and disinfectants during the COVID-19 pandemic: identification of antimicrobial chemicals and considerations for aquatic environmental contamination

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Abstract

In response to the coronavirus (COVID-19) pandemic, there has been an increased need for personal and environmental decontamination to aid in curbing transmission of the SARS-CoV-2 virus. Products used for this purpose include sanitizers for hands and disinfectants for surfaces. The active chemical ingredients used in these products, termed antimicrobials, can enter waste streams after application and may be emerging as more prominent environmental contaminants. Even prior to COVID-19, there was recognized need to examine their implications for aquatic biota, which is now made more pressing due to their exaggerated use in response to the pandemic. Our objectives were to identify current antimicrobial active ingredients, quantify their increased use, and determine which may be candidates for further consideration as possible aquatic contaminants. By consulting multiple sources of publicly available information in Canada, we identified current-use antimicrobials from the lists of sanitizers and surface disinfectants approved for use against SARS-CoV-2 by Health Canada and the drug registration database. To estimate the use of sanitizers and disinfectants, we evaluated import quantities and grocery store retail sales of related compounds and products (Statistics Canada) and both lines of evidence supported increased use trends. The list of identified antimicrobials was refined to include only candidates with potential to reach aquatic ecosystems, and information on their environmental concentrations and toxicity to aquatic biota was reviewed. Candidate antimicrobials ($n = 32$) fell into four main categories: quaternary ammonium compounds (QACs), phenols, acids, and salts. Benzalkonium chloride, a QAC, was the most prominent active ingredient used in both nonalcohol-based hand sanitizers and surface disinfectants. Four QACs followed in prevalence and the next most used antimicrobial was triclosan (hand sanitizers only), an established and regulated environmental contaminant. Little information was found on environmental concentrations of other candidates, suggesting that the majority would fall into the category of emerging contaminants if they enter aquatic systems. Several were classified as acutely or chronically toxic to aquatic biota (Globally Harmonized System), and thus we recommend empirical research begin focusing on environmental monitoring of all candidate antimicrobials as a critical next step, with detection method development first where needed.

Key words: biocide, pharmaceutical and personal care products, PPCP, pandemic, SARS-CoV-2, Canada, COVID-19, antimicrobial

Résumé

En réponse à la pandémie de coronavirus (COVID-19), un besoin accru de décontamination personnelle et environnementale s'est manifesté pour aider à freiner la transmission du virus SRAS-CoV-2. Les produits utilisés à cette fin comprennent des assainisseurs pour les mains et des désinfectants pour les surfaces. Les ingrédients chimiques actifs utilisés dans ces produits, appelés antimicrobiens, peuvent entrer dans les systèmes des eaux usées après leur application et peuvent devenir des contaminants environnementaux plus importants. Avant même l'avènement de la COVID-19, on reconnaissait qu'il était nécessaire d'examiner leurs implications pour le biote aquatique, ce qui est aujourd'hui rendu plus urgent en raison de leur utilisation exagérée en réponse à la pandémie. Nos objectifs consistaient à identifier les ingrédients actifs antimicrobiens actuels, à quantifier leur utilisation accrue et à déterminer ceux qui pourraient être considérés comme des contaminants aquatiques potentiels. En consultant de multiples sources d'information publiquement accessibles au Canada, nous avons pu identifiéer les antimicrobiens utilisés actuellement à partir des listes d'assainisseurs et de désinfectants de surface dont l'utilisation contre le SRAS-CoV-2 a été approuvée par Santé Canada, et de la base de données sur les produits pharmaceutiques. Pour estimer l'utilisation des assainisseurs et des désinfectants, nous avons évalué les quantités importées et les ventes au détail dans les épiceries de composés et de produits connexes (Statistique Canada) et les deux sources de données ont confirmé les tendances à l'augmentation de l'utilisation. La liste des antimicrobiens identifiés a été affinée pour n'inclure que les candidats susceptibles d'atteindre les écosystèmes aquatiques, et les informations sur leurs concentrations environnementales et leur toxicité pour le biote aquatique ont été examinées. Les antimicrobiens candidats ($n = 32$) se répartissent en quatre grandes catégories: les composés d'ammonium quaternaire (CAQ), les phénols, les acides et les sels. Le chlorure de benzalkonium, un CAQ, était l'ingrédient actif le plus utilisé dans les désinfectants non alcoolisés pour les mains et les désinfectants de surface. Quatre CAQ suivaient en prévalence et l'antimicrobien le plus utilisé ensuite était le triclosan (uniquement dans les désinfectants pour les mains), un contaminant environnemental avéré et réglementé. Peu d'informations sur les concentrations environnementales des autres candidats étaient accessibles, ce qui suggère que la majorité d'entre eux entreraient dans la catégorie des contaminants émergents s'ils pénètrent dans les systèmes aquatiques. Plusieurs d'entre eux ont été classés comme présentant une toxicité aiguë ou chronique pour le biote aquatique (Système général harmonisé de classification et d'étiquetage des produits chimiques, SGH). Les auteurs recommandent donc que la recherche empirique commence à se concentrer sur la surveillance environnementale de tous les candidats antimicrobiens comme prochaine étape critique, en commençant par le développement de méthodes de détection si nécessaire. Le texte intégral de l'article en français est disponible parmi les documents supplémentaires.

Mots-clés : biocide, produits pharmaceutiques et de soins personnels, PPSP, pandémie, SRAS-CoV-2, Canada, COVID-19, antimicrobien

1. Introduction

The use of sanitizing and disinfecting products dramatically increased during the COVID-19 pandemic (da Silva et al. 2021; Dhama et al. 2021), and more information on the impacts of this rapid global change on aquatic communities is needed. The active chemical ingredients in these products, termed antimicrobials, are compounds designed to kill or deactivate numerous pathogens, including bacteria, fungi, algae, and viruses. Many antimicrobials, categorized under pharmaceuticals and personal care products (PPCPs) (Ebele et al. 2017, and references therein) or pesticides (e.g., PMRA 2005, 2017), have been increasing in use for some time and several have been considered as established or emerging environmental contaminants (Ebele et al. 2017; Abbott et al. 2020).

The SARS-CoV-2 virus, which causes COVID-19, can remain active on surfaces for several hours (Pastorino et al. 2020; Van Doremalen et al. 2020) to days (Chin et al. 2022), and the World Health Organization (WHO 2020) and governments around the world, including in Canada, made early recommendations for the use of hand sanitizers and disinfection of high-touch surfaces (Government of Canada, GoC 2020*a*), which currently remain in place (WHO 2020; GoG 2020*a*: last reviewed September 2022). Like other PPCPs, following consumer use, many of these sanitizers and disinfectants are washed down the drain, may reach stormwater systems following outdoor application, or may be released during product manufacturing. With respect to the former pathways, because wastewater treatment technologies in Canada, and elsewhere, are not designed to remove these chemicals (Senta et al. 2013), antimicrobials may be released from effluent outfalls into aquatic ecosystems, or leach from biosolids applied to agricultural fields, and exert toxicity on nontarget biota (Lapen et al. 2008; Luo et al. 2014; Krogh et al. 2017; Srain et al. 2021). These releases, which have the potential to be continuous, may render contaminants that might otherwise breakdown quickly to have pseudopersistence, resulting in chronic exposure to aquatic biota (Ebele et al. 2017). Due to their bioactivity, low levels of many PPCPs (e.g., as micropollutants) may be enough to elicit effects in nontarget organisms (e.g., Chalew and Halden 2009) and communities, including microbiomes (Evariste et al. 2019). The potential for an increased input of antimicrobials into the aquatic environment is likely under elevated pandemic use, and may be predicted to continue based on projected market expansion (CMI 2020; GVR 2021); thus, the risk they may pose to aquatic biota is of global concern (Wilkinson et al. 2022).

For many sanitizers, the antimicrobial ingredient is an alcohol (usually ethanol or propanol-2), which evaporates quickly following application (<1 min; Macinga et al. 2014) and thus is not likely to enter aquatic environments through waste- or stormwater (and these alcohols are not considered environmental concerns by Canada's Pesticide Management Regulatory Agency; PMRA 2018*a*, 2018*b*). However, there are numerous other active antimicrobial ingredients that are used in non-alcohol-based sanitizers and disinfectants and these may have potential to enter the environment. A number of antimicrobial compounds are currently considered as established (e.g., triclosan, reviewed in Ebele et al. 2017), or emerging environmental contaminants (e.g., 2-phenylphenol, chlorophene: Salimi et al. 2017; quaternary ammonium compounds, QACs; Zang et al. 2015) and there remains the need to determine which antimicrobials are in current use to support hazard review and to direct environmental monitoring efforts.

In response to the increased need for decontamination during the COVID-19 pandemic, and using Canada as an example, our first two objectives were to identify the most prominent current-use antimicrobial active ingredients in sanitizers and disinfectants and to quantify the recent increased use of these products. Three lines of evidence were reviewed based on continuously available drug registration and economic data: (*i*) active antimicrobial ingredients listed in registered sanitizers and disinfectants in Canada, (*ii*) import quantities of antimicrobials or products containing them, and (*iii*) domestic grocery store retail sales of hand sanitizers and surface disinfectants. We predicted that a wide variety of antimicrobials would be identified, which is typical for other types of PPCPs, and that imports and sales of products containing antimicrobials would reflect the common assumption that they were in increased use during the COVID-19 pandemic. The success of examining these types of economic and health-product registration data in the context of environmental contamination was discussed. Our third objective was to refine the long list of identified antimicrobials in current use to a list of candidates with potential to reach aquatic environments based on chemical properties (likelihood of evaporation or stability in water). To support this goal, we additionally reviewed existing information on environmental concentrations, toxicity indicators, and Canadian regulation of candidate antimicrobials, to separate established from potentially novel candidate compounds. We predicted that the majority of candidates would fall into the latter group, similar again to many PPCPs. Although the focus here is on the Canadian context, we submit that our findings are broadly relevant to regulators, scientists, and other parties in various countries where there is concern for this emerging source of aquatic pollutants, and we conclude with recommendations for future research and policy.

2. Approach

2.1. Identification of current-use antimicrobial compounds and estimation of domestic demand

2.1.1. Hand sanitizers and disinfectants approved for use against SARS-CoV-2

In Canada, hand sanitizers and products labelled as disinfectants are considered as drugs, and they undergo review for human safety and registration by Health Canada (GoC 2014). During the pandemic, surface disinfectants that were industry-tested for effectiveness against the SARS-CoV-2 virus (directly or indirectly on similar viruses) were approved for this use by Health Canada and compiled into a publicly available list by the Natural and Non-Prescription Health Products Directorate of Health Canada (GoC 2020*b*). While there are no hand sanitizers proven to deactivate SARS-CoV-2, a list of product registrations with likely effectiveness was also published (GoC 2020*b*). These lists were updated weekly with new registrations and all of the active antimicrobial ingredients are conveniently included. These lists were assessed in October 2020 and again in May 2021 to determine what antimicrobial chemicals were being used for hand sanitization and surface disinfection purposes in Canada (and remain available in October 2022 with monthly updates). Because many products have multiple active ingredients, we treated the data to generate one entry for each active ingredient in each product. The number of these "entries" per active ingredient was determined and the proportion of entries was calculated for each antimicrobial. Though numerous registrations were added to these lists between the two assessment points, the active ingredients and their proportional presence in products changed little between the two assessment time points, thus only those from May 2021 are presented.

2.1.2. Other registered disinfectants

There are numerous surface disinfectants that are registered and marketed in Canada but not approved for use against SARS-CoV-2 because they were not industry-tested for effectiveness against this virus. While those that are approved have likely been favoured generally, Health Canada states that most registered disinfectants are beneficial for use against SARS-CoV-2 (GoC 2020*b*). Hence, other registered disinfectants are also likely receiving some increased current use, particularly if there were any shortages in approved products or any lack of awareness of the distinction. To identify active ingredients used in disinfectants not captured by the detailed analysis of the lists of approved products, the Health Canada Drug Product Database (updated daily) was searched (GoC 2021*a*; September 2021) using the following criteria status: "marketed", class: "disinfectant" (which also includes those approved for use against SARS-CoV-2 which cannot be eliminated from the search). Because only the top active ingredient is listed in the search results, each product was reviewed and new active ingredients recorded along with the number of products containing them. Those found in the largest number of products were included in our list of identified antimicrobials.

2.1.3. Import quantities

To examine quantities of products containing antimicrobial ingredients entering the country, import data were obtained from the Canadian International Merchandise Trade Program at Statistics Canada (available for public purchase; https://www.statcan.gc.ca/en/reference/custom). The aim was to use this data both to identify antimicrobials in increased use and as a coarse estimate of national demand. Globally, traded products are categorized by the International Harmonized Item Description Coding System (HS code) which, for sanitizing and disinfecting goods, is based on their format, purpose, and (or) main chemical constituents. Data on all HS codes relevant to cleaning or disinfection were obtained as were single chemicals that may have antimicrobial uses.

Table 1. International Harmonized Item Description Coding System (HS) codes for products or single chemicals related to sanitization and disinfection imported into Canada between 2018 and 2020 and annual total imports by mass.

HS code	Name	Total annual import mass (million kg) 2018	2019	2020
2828.90.00.00	Hypochlorites of metals or chlorites and hypobromites of metals	40.5	41.5	39.8
2905.12.00.20	Propanol-2	11.9	7.4	29.1
(*a*) 2207.10.10.00; (*b*) 2208.90.29.00	Ethyl alcohol [(*a*) 80% or (*b*) <80%]	48.3	53.5	72.0
(*a*) 2847.00.00.10; (*b*) 2847.00.00.20	Hydrogen peroxide [(*a*) not solidified with urea; (*b*) solidified with urea]	31.4	28.9	15.9
3808.94.10.90; 3808.94.20.90	General disinfectants (coded based on package weight)	39.6	42.6	138.4
3808.94.10.10; 3808.94.20.10	Disinfectants with bromoethane/bromochloromethane (coded based on package weight)	0.4	0.3	0.8
8419.20.00.20	Medical and surgical sterilizers	0.01	0.02	0.01
3402.12.00.00	Laboratory sterilizers	0.006	0.009	0.03
8419.20.00.10	Quaternary ammonium salts and hydroxides	4.7	5.8	2.8
2923.90.00.00	Cationic surface-active agents (surfactants)	9.3	6.2	7.1

Note: Data were obtained from Statistics Canada, Canadian International Merchandise Trade Program.

Data were available in monthly import quantities by total product mass (kilograms) and were examined from January 2018 until March 2021; due to the similarity between 2018 and 2019, we statistically assessed only 2019 to include 1-year prior (baseline) and 1 year after the pandemic began in Canada. For HS codes with a clear common purpose or active ingredient (Table 1), data were pooled. For standardization with available retail data (see the next section), an index of monthly import quantities was calculated (monthly imports in kilograms of product × 100/average monthly imports in 2019). The reference year of 2019 was used in the denominator to provide the percentage increase relative to recent prepandemic baseline values. Data were graphed chronologically and monotonic trends assessed using Mann−Kendall tests (using the Mann−Kendall function from the {Kendall} package in R; McLeod 2011). Any product categories with increasing importation following the onset of the pandemic in Canada (March 2020) were considered products likely to have increased in use. We aimed to use products that identified chemical constituents to further identify current use antimicrobial compounds from the active ingredients, alongside the analysis of product registrations (see above). There are a number of limitations to these import data that we discuss (see Section S1 of Supplementary Material), and they are thus used here as a proxy to identify potential candidate antimicrobial chemicals and their use in Canada in conjunction with retail sales (next section).

2.1.4. Retail sales

To broadly determine whether household use of antimicrobials has increased since the beginning of the COVID-19 pandemic in Canada (March 2020), grocery store retail sale indices of products categorized as either “hand sanitizers” or “disinfectants” in Canada were obtained from the Consumer Prices Division of Statistics Canada (publicly available for purchase; see link above). These were the only sales data available for these product categories; they contained no chemical specificity (brands are not identified nor active ingredients) and thus could only be used to estimate demand. Data spanned from January 2019 to June 2021 (representing all available data for 2021 at the time of the request and to capture baseline and pandemic trends and roughly match import data timeframe). These data were only available in the form of a sales index (%) (weekly product sales in Canadian dollars × 100/average weekly sales in 2019); raw sales numbers were not available due to privacy reasons. The sales indices were graphed chronologically and monotonic trends were examined using the Mann−Kendall test. Similar to imports, there are a number of limitations to these data (discussed in Section S1 of the Supplementary Material); sales indices are used herein as a proxy to highlight potential demand, or increased use, during the pandemic and to support import numbers that are not fully synonymous with domestic sales or use.

2.2. Aquatic environmental considerations

2.2.1. Candidate antimicrobial contaminants

To fulfil our objective of determining which identified antimicrobials should be further considered in the context of aquatic environmental contamination, we eliminated all obvious unlikely candidates. First, any that would have little potential to reach aquatic environments were not considered further. These include any alcohols that evaporate quickly from the surfaces they are applied to (e.g., Macinga et al. 2014) and any with similar volatility based on indicative chemical properties: low boiling point (<25 °C) and (or) high vapour pressure (>10^{-4} mm Hg at 20–25 °C; US EPA 2015). These also included any identified antimicrobials that break down rapidly into harmless transformation products in water which would likely occur prior to wastewater release into the environment (low stability in water). The related chemical properties were collected for all non-alcohol-based identified antimicrobials from the US National Library of Medicine’s National Centre for Biotechnology Information’s (NCBI) PubChem database (www.pubchem.ncbi.nlm.nih.gov). We also eliminated any established antimicrobials related to available chlorine (e.g., hypochlorites, used in pools and water treatment), or which are also used as road salt (sodium chloride, NaCl; Szklarek et al. 2022), as their contribution to the environment from disinfectants is likely to play a minor role compared to these other wider uses. Additionally, environmental review of hypochlorites is conducted regularly by the PMRA, with no concerns noted in 2005 (PMRA 2005; a re-review was scheduled to begin in 2021, hypochlorite cluster: PMRA 2021*b*). All other identified antimicrobials were included in our list of candidates to be considered for their potential to enter aquatic systems in future work, and they were ranked for prominence based on the number of products containing them.

2.2.2. Environmental concentrations

To determine if any candidate antimicrobials are already known environmental contaminants or have been detected in aquatic systems, we searched for reports on environmental concentrations in Canada. Due to the timing, we expected only prepandemic levels to be available. We consulted national water contaminants monitoring programs (CMP Wastewater Monitoring Program, National Long-term Water Quality Monitoring) and the literature using the following search string: environment∗ AND concentration AND (water OR aquatic) AND Canada AND "*antimicrobial*". The search was conducted for each identified antimicrobial to replace the last term, as well as the following general terms: antimicrobial, disinfect∗, PPCP, quaternary ammonium compound (or salt), or phenol. All results were scanned for relevance to our objective, that is, they reported Canadian environmental concentrations of identified sanitizing or disinfecting antimicrobials. Antibiotic pharmaceuticals, also termed antimicrobials, were excluded and considered out of scope as they were not predicted to increase in use during a viral pandemic.

2.2.3. Toxicity indicators

As an overall measure of aquatic toxicity, hazard warnings by the Globally Harmonized System (GHS) of Classification and Labelling of Chemicals of the United Nations Economic Commission of Europe (UNECE) were recorded (obtained from the PubChem database). These classifications are based on the results of standard toxicity tests on aquatic biota (algae/aquatic plants, invertebrates, and fish) at three levels for either acute (e.g., for fish: very toxic, H400: LC_{50} < 1 mg/L; toxic, H401: LC_{50} = 1–10 mg/L; or harmful, H402: LC_{50} = 10–100 mg/L) or chronic toxicity (very toxic, H410: no observable effect concentration, NOEC < 0.01 mg/L; toxic, H411: NOEC < 0.1 mg/L; or harmful, H412: NOEC < 1 mg/L) (UNECE 2019). These thresholds (LC_{50} or NOEC) are used for rapidly degradable compounds, a category we expect most antimicrobials to fall under; however, it should be noted that thresholds for nonrapidly degrading compounds are 10× higher (UNECE 2019). We searched for any aquatic environmental toxicity thresholds or benchmarks that have been developed for candidate antimicrobials from multiple sources including: (*i*) the Canadian Council of Ministers of the Environment's water quality Guidelines for the Protection of Aquatic Life (CCME 2021), (*ii*) Canadian Government chemicals fact sheets (GoC 2021*b*), and (*iii*) US Environmental Protection Agency's water quality criteria (US EPA 2021). Finally, we determined whether any identified antimicrobials are restricted in use in Canada and present on Schedule 1 List of Toxic Substances in the *Canadian Environmental Protection Act* (CEPA; S.C. 1999, c. 33); i.e., determined to be "toxic" under CEPA and with an accompanying risk management plan in place in Canada that outlines preventive and control actions.

3. Findings

3.1. Identification of antimicrobial compounds

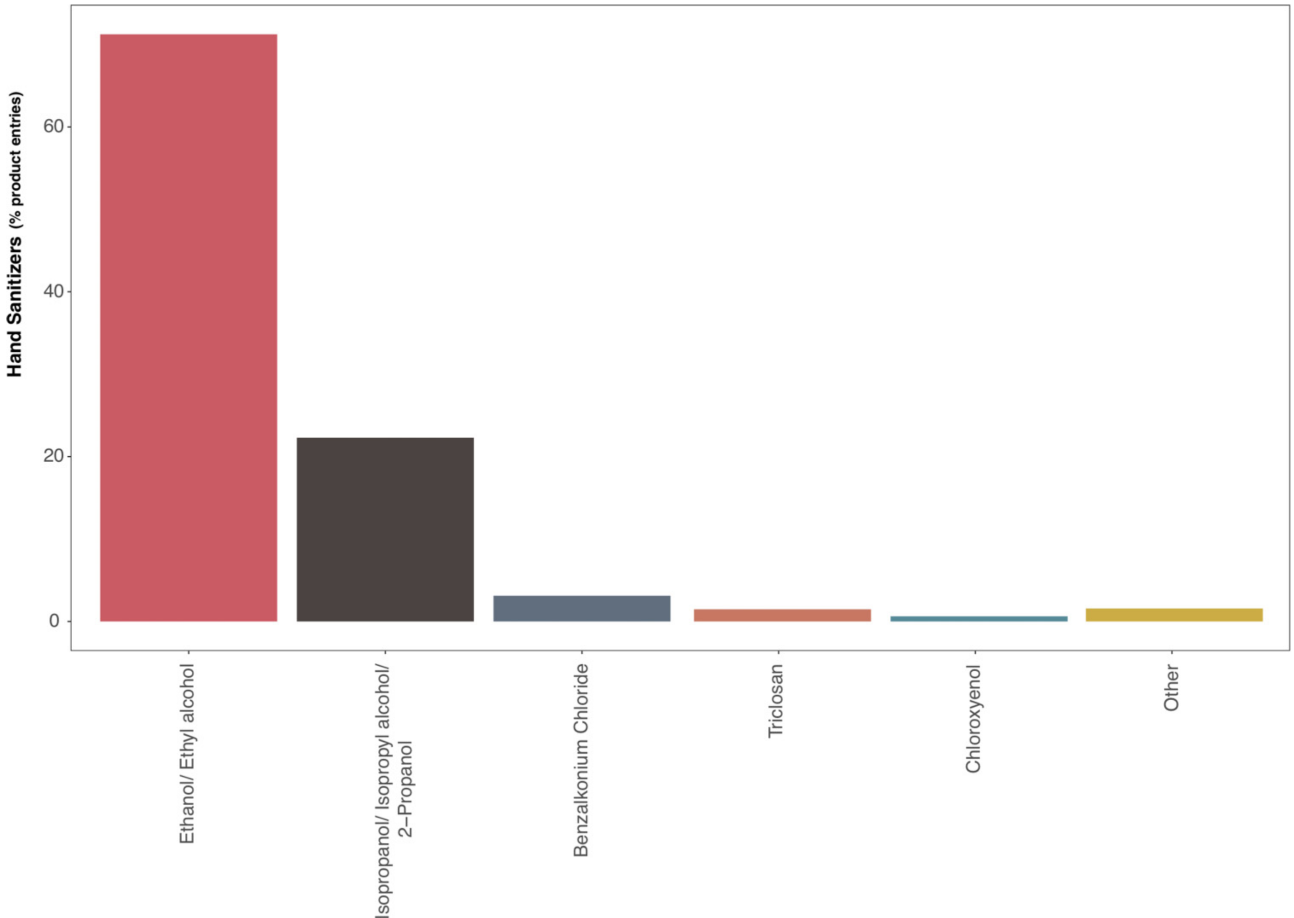
3.1.1. Hand sanitizers approved for use against SARS-CoV-2 in Canada

A total of 5094 hand sanitizers were included on the list of products approved for use against SARS-CoV-2 by Health Canada up until May 2021. There was a wide diversity in the types of products included; however, the majority appeared to be leave-on products, described as sanitizer, wipes/swabs, sanitizing gel, spray, cleanser, and others. Several antimicrobial (or "antiseptic" or "antibiotic") soaps were also listed among these hand sanitizing products. As these are applied while washing hands directly under water, they may differ from leave-on products in how they transform and (or) reach aquatic environments. The products in the list of hand sanitizers typically contained only one active ingredient (only 12 of these products contained a mixture of them) and entries extracted from this list of hand sanitizers totalled 5111 from which 13 antimicrobials were identified. The antimicrobial active ingredients in hand sanitizers were dominated by alcohols (ethyl alcohol: 71% of entries; propanol-2: 22%; and anhydrous alcohol: 0.3%; Fig. 1). Of the remaining 6% of entries, the nonalcohol active ingredients in these 335 product entries were dominated by benzalkonium chloride (alkyl dimethyl benzyl ammonium chloride; 56% of nonalcohol-based hand sanitizers) followed by triclosan (21%), chloroxylenol (10%), chlorhexidine gluconate (7%), benzethonium chloride (benzyl dimethyl trimethylpentan phenoxy ethodyetan ammonium chloride, 5%), and five others found in very few approved products (Supplementary data, Table S1). It was not always possible to know which products were soaps (terminology such as hand wash, foam, lotion, skin cleanser, and company names were used); however, 74 clearly included "soap" in the product name, and they contained strictly nonalcohol-based antimicrobials: benzalkonium chloride (n = 30), triclosan (n = 29), chlorhexidine gluconate (n = 9), chloroxylenol (n = 4), benzethonium chloride (n = 1), and bronopol (n = 1).

3.1.2. Surface disinfectants approved for use against SARS-CoV-2 in Canada

A wider variety of antimicrobial chemicals (n = 35) were identified from approved surface disinfecting products,

Fig. 1. Per cent of hand sanitizers approved for use against SARS-CoV-2 by Health Canada grouped according to active antimicrobial ingredients in product entries. The lists of products approved for use against SARS-CoV-2 by Health Canada were consulted (GoC 2020*a*). Each product was entered separately, once for each active ingredient per row (entries $n = 5111$, May 2021).

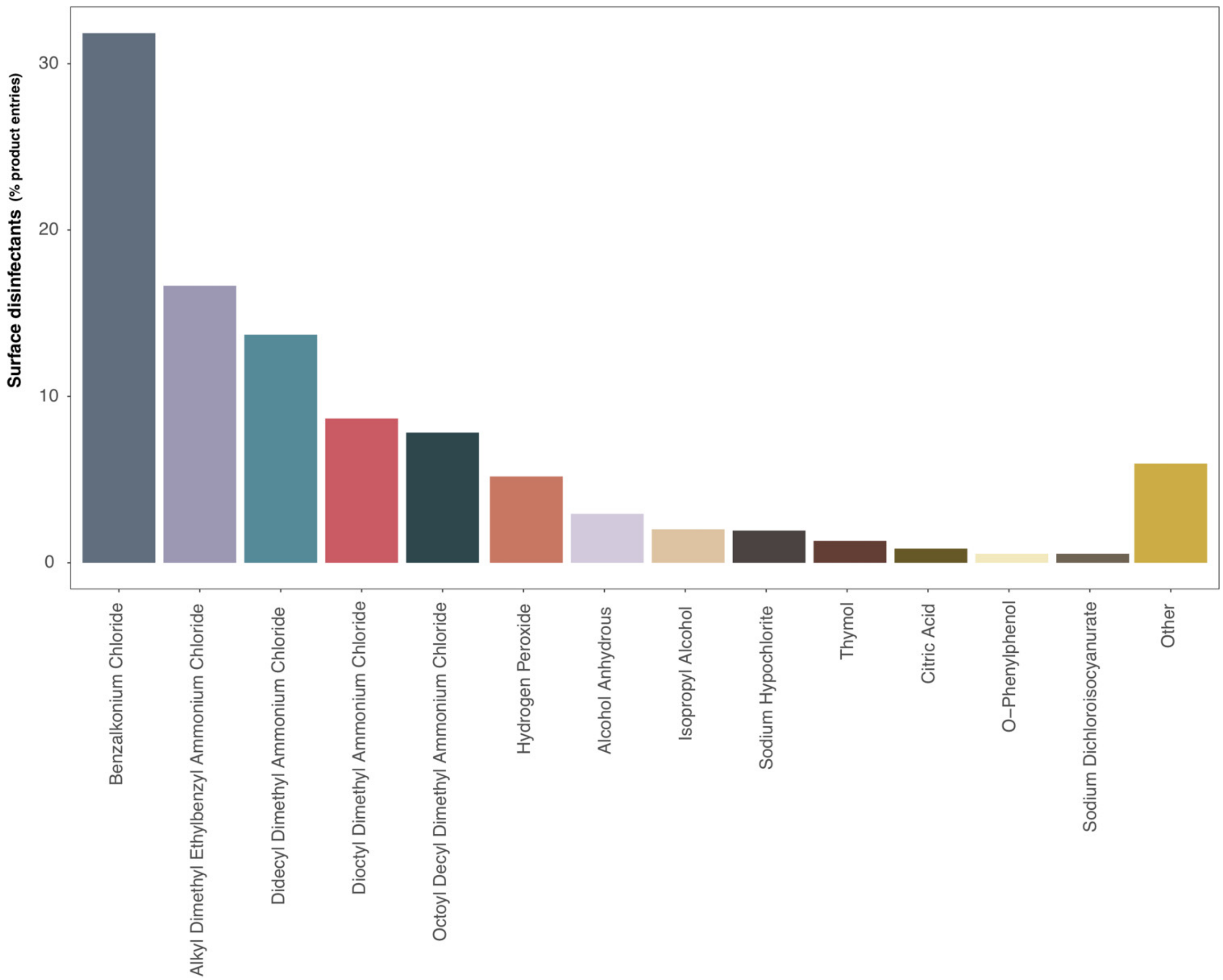


which is likely consistent with the fact that they are not restricted by the safety of use on skin (Fig. 2). A total of 621 surface disinfecting products were registered with proven effectiveness against SARS-CoV-2 by May 2021, each containing up to four active antimicrobial ingredients for a total of 1353 entries. In contrast to hand sanitizers, alcohol active ingredients were in the minority (propanol-2 at 2% of entries and anhydrous alcohol at 3%) as were hypochlorites (sodium hypochlorite at 2%; Fig. 2). Nonalcohol-based compounds were the favoured antimicrobials found in approved surface disinfectants and these were highly dominated by QACs (82% or 1104 entries), most commonly again, benzalkonium chloride (32%), followed by alkyl dimethyl ethybenzyl ammonium chloride (17%) and didecyl dimethyl ammonium chloride (8%) (Fig. 2). The remaining 18% of entries included thymol (1%), citric acid (1%), acetic acid (1%), and 17 other compounds found in a small number of approved products (including five other QACs; Fig 2 and Table S1).

Close to one-third (27%) of the approved disinfecting products contained only one active ingredient which may suggest that they are particularly effective as antimicrobials, and these included sodium hypochlorite, hydrogen peroxide and anhydrous alcohol, as well as several QACs (benzalkonium chloride, alkyl dimethyl ethylbenzyl ammonium chloride, and saccharinate and dodecyl dimethyl ammonium chloride) and others (citric acid, glycolic acid, hydrochloric acid, hypochlorous acid, lactic acid, potassium peroxymonosulfate, sodium dichlorocyanurate, and thymol). The majority of disinfectants, however, included a mixture of 2–4 antimicrobials ($n = 451$); almost all of these products contained at least one QAC (95% or 429 products) and the majority were mixtures of only QACs (89% or 400 products).

The surface disinfectants in the assessed list were approved for use in various settings (domestic, hospital, industrial, food premises, and barns) which could impact how, and where, they enter the aquatic environment (e.g., wastewater effluents vs. runoff). Most of the approved products can be used in multiple settings. The majority are approved for use in hospitals (88%) followed by industrial areas and food premises (75% and 73%, respectively), and fewer are approved for use in

Fig. 2. Percent of surface disinfectants approved for use against SARS-CoV-2 by Health Canada, grouped according to active antimicrobial ingredients in product entries. The lists of products approved for use against SARS-CoV-2 by Health Canada were consulted (GoC 2020*a*). Each product was entered separately, once for each active ingredient per row (entries $n = 1353$, May 2021).



homes or barns (38% and 36%, respectively). Those approved for use in domestic settings, which were captured in the grocery store retail sales, contained mainly QACs (72%), followed by thymol and sodium hypochlorite (7% each), and a number of the other antimicrobials, each in a small number of products.

3.1.3. Other marketed disinfectants in Canada

At the time of query (September 2021), there were 1140 registered and marketed disinfectants in the drug product database which included those approved for use against SARS-CoV-2. A total of 25 single chemical active ingredients were found that were not listed in products approved for use against SARS-CoV-2 (Supplementary data, Table S2) and each was found in only a small number of products (1–10). Otherwise, the vast majority of active ingredients in marketed disinfectants were the same as those found in formulations approved for use against SARS-CoV-2. The top two additional antimicrobial active ingredients identified were P-*tert*-pentyphenol (used in 10 products) and clorophene (used in nine products) and these were thus included in our list of identified antimicrobials (Supplementary data, Tables S1 and S2).

3.1.4. Imports into Canada

In our exploration of HS codes related to cleaning and decontamination, products categorized under 13 codes imported by Canada from 2019 to March 2021 showed some relevance to our objectives (Table 1; Figs. 3 and 4). Imported products under these codes came from several countries, including Canada originally for some, indicating that a certain amount of domestic production was also captured in these data. Several product categories identified the active ingredients which could be used to both identify antimicrobials in increased use as well as to estimate domestic demand. The only antimicrobials identified from import codes

Fig. 3. Index of monthly import quantities (kg) for disinfecting products with chemical specificity, 1 year before and 1 year after the pandemic began in Canada (March 2020, dashed line), captured under international Harmonized Item Description Coding System (HS code, see also Fig. 2). Data were obtained from the Canadian International Merchandise Trade Program at Statistics Canada. Import index = monthly imports in kilograms × 100/average monthly imports in 2019. Cationic surface-active agents and quaternary ammonium salts and hydroxides include QACs (see Table 1 for HS import codes). For a monochromatic version of this figure, see the Supplementary Material.

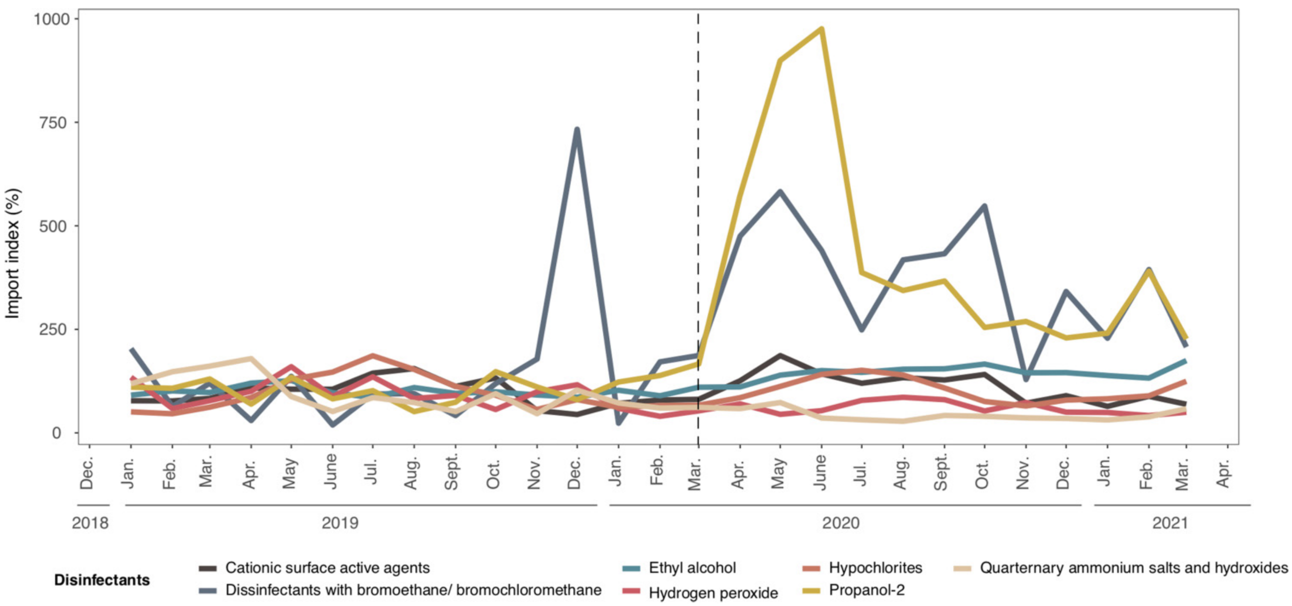
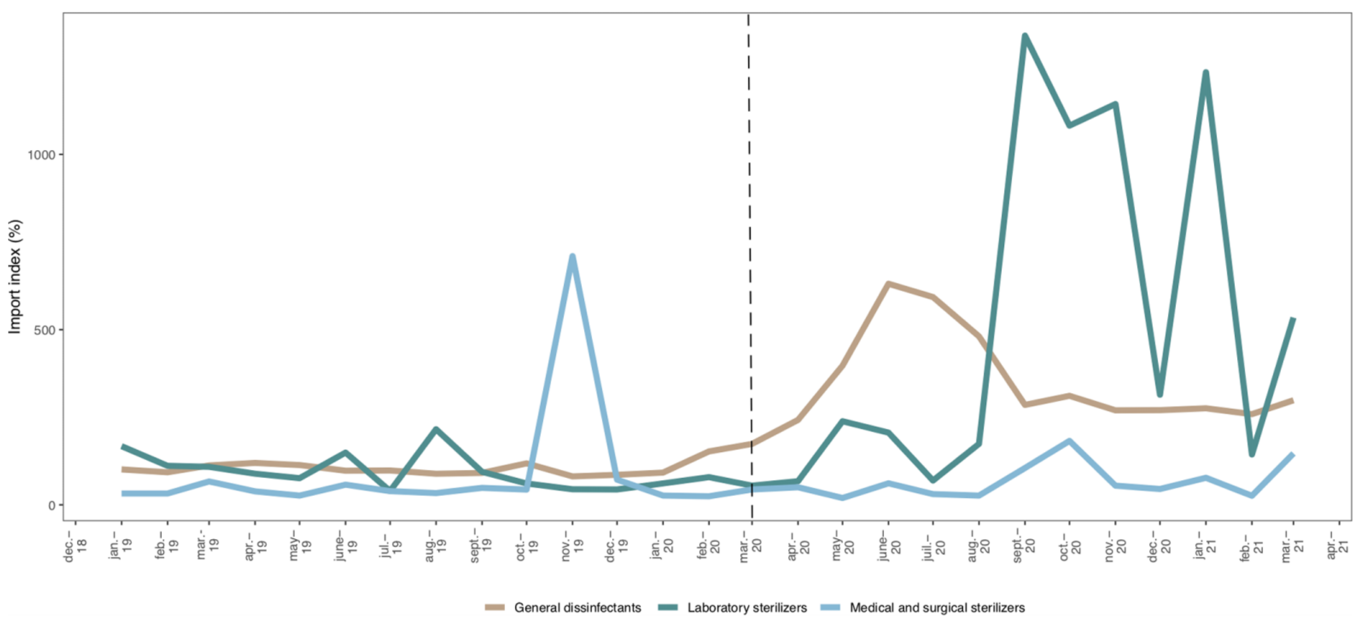


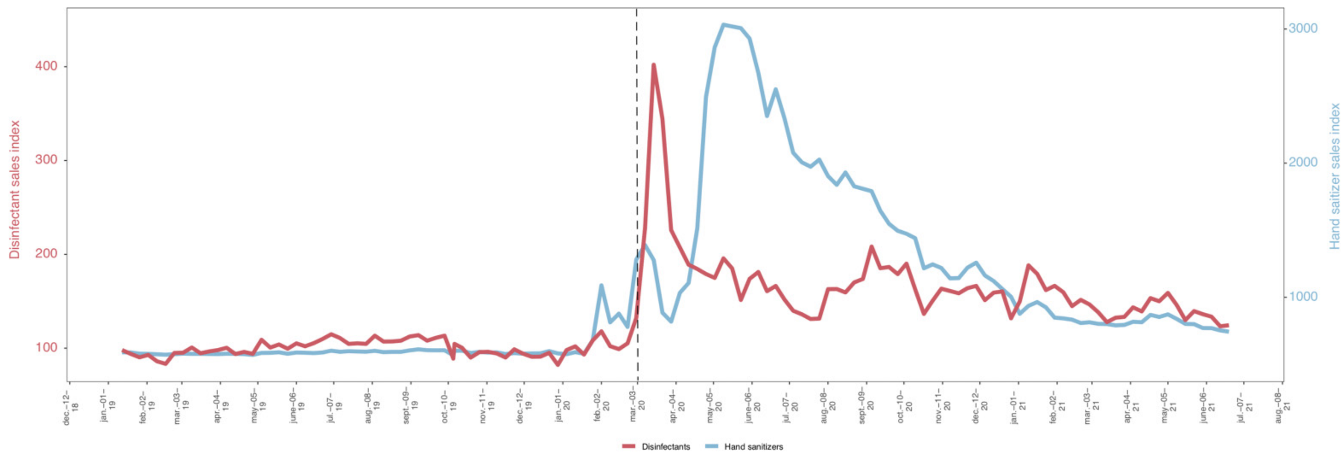
Fig. 4. Index of monthly import quantities (kg) for general disinfecting products one year before and one year after the pandemic began in Canada (March 2020, dashed line), captured under international Harmonized Item Description Coding System (HS). Data were obtained from the Canadian International Merchandise Trade Program at Statistics Canada. Import index = monthly imports in kilograms × 100/average monthly imports in 2019 (see Table 1 for HS codes). For a monochromatic version of this figure, see the Supplementary Material.



additional to those found in registered health products were bromoethane and bromochloromethane (the former being used for fumigation pesticide purposes rather than surface disinfection; PubChem 2022).

For all imports generally, monthly indices in 2019 did not vary greatly from the average for that same year (i.e., it remained close to 100%), suggesting a consistent demand during that recent prepandemic year in most months (Figs. 3

Fig. 5. Index of weekly grocery store retail sales of disinfectants or hand sanitizers (an order of magnitude higher), one year before and one year after the pandemic began in Canada (March 2020, dashed line). Data from Statistic Canada, Consumer Prices Division. Sales index (%) = weekly sales in Canadian dollars × 100/average weekly sales in 2019; raw data were unavailable due to privacy concerns. For a scatter plot visualization (Supplementary Fig. S2) and monochromatic versions of these figures, see the Supplementary Material.



and 4). Once the pandemic began (March 2020), the relevant HS codes that saw the greatest increases were propanol-2 as a single compound, which saw a large spike at the onset and then levelled off between 200% and 400% of the 2019 monthly average around July 2020 (Fig. 3; see Table 1 for annual totals), and disinfectants containing bromoethane or bromochloromethane, which were increasingly imported at 200%–600% of the 2019 monthly average in most months during the first year of the pandemic (Fig. 3), albeit in much smaller quantities (Fig. 3 and Table 1). Ethyl alcohol imports also rose by 50% fairly consistently (Fig. 3; Table 1). All of these products showed significant monotonically increasing trends (propanol-2: Mann−Kendall tau = 0.47, $p < 0.001$; bromoethane/bromochloromethane: tau = 0.38, $p < 0.01$; ethyl alcohol: tau = 0.50, $p < 0.001$). Imports of quaternary ammonium salt and hydroxides and hydrogen peroxide showed significant decreasing trends (tau = −0.60, $p < 0.00001$ and tau = −0.45, $p < 0.001$, respectively), while cationic surfactants (which may include QACs) and hypochlorites showed no significant trend (tau = 0.01, $p = 0.967$ and tau = 0.1, $p = 0.478$, respectively; Fig. 3).

3.2. Estimated domestic demand for disinfectants

3.2.1. Imports into Canada

Similar to some products with chemical specificity, general disinfectants also saw a sharp increase in import quantities into Canada at the start of the pandemic (600% of the 2019 monthly average), which settled to a steady level of 300% of 2019 imports after September 2020 (Fig. 4) and were monotonically increasing (Mann−Kendall tau = 0.45, $p < 0.001$). Though in considerably smaller quantities, import mass of laboratory sterilizers also increased monotonically (tau = 0.31, $p = 0.02$), albeit with visible large fluctuations (200%−1300% of 2019 imports), while medical sterilizers showed no increasing trend (tau = 0.15, $p = 0.27$; Fig. 4).

3.2.2. Retail sales within Canada

In 2019, similar to imports, monthly grocery store sales indices for hand sanitizers and disinfectants did not vary greatly from the average for that same year, suggesting a consistent prepandemic baseline demand (Fig. 5). During the COVID-19 pandemic in Canada (beginning March 2020), the sales indices for these products revealed that purchase for home-use rose considerably, mirroring import trends and supporting the assumption that these products have increased greatly in use. As occurred with numerous consumer products (Statistics Canada 2020), sales rose sharply at the onset of the pandemic in Canada, but once they levelled (April 2020 for disinfectants and December 2020 for hand sanitizers; Fig. 5 and Supplementary Fig. S2), they consistently remained close to 150% and 300% of the 2019 weekly average for disinfectants and hand sanitizers respectively, up to at least March 2021 (hand sanitizers Mann−Kendall tau = 0.37, $p < 0.0001$; disinfectants tau = 0.40, $p < 0.0001$; Fig. 5 and Supplementary Fig. S2). Supply chain issues and greater than usual inflation of prices (5% in 2020 for cleaning products: Statistics Canada 2021) likely factored into the dollar-value sales numbers in the peak seen in the months immediately following the inception of the pandemic in Canada; however, the effects of both of these factors dissipated quickly according to analyses conducted by Statistics Canada (2021). Thus, it is likely that the ongoing increased sales do not merely reflect price increases and suggest that these products continued to be purchased and used more frequently, including following any early stockpiling. That hand sanitizer sales in grocery stores increased much more than disinfectant sales is not surprising as disinfection in homes is less necessary than it is in public spaces. This highlights one limitation of these data, as the use of disinfectants in public or workplace settings would likely have increased considerably more than home use; however, this was more broadly captured by imports into Canada described above (see also Section S1 of the Supplementary Material).

3.3. Candidate antimicrobial contaminants

Several identified antimicrobials were eliminated from the list of candidates for further consideration for aquatic environmental implications. These included (*i*) all alcohols (propanol-2, ethyl, and anhydrous), (*ii*) bromochloromethane, bromoethane, and chlorine dioxide due to their high likelihood of evaporating quickly following application (NCBI 2022*a*, 2022*b*; Supplementary Table S1), (*iii*) hydrogen peroxide due to its high instability in water (readily breaks down into hydrogen and oxygen; NCBI 2022*c*), (*iv*) sodium hypochlorite (PMRA 2021*a*) and sodium dichlorocyanurate (NCBI 2022*d*), which are also used as chlorine, and (*iv*) sodium chloride (also used as road salt). It should be noted, however, that the chemical properties used as elimination criteria were not available for all identified antimicrobials (Supplementary Table S1). Two identified antimicrobials were not searchable as named and thus not included in our final list for consideration. These included "octyl dimethyl ammonium chloride" and "dimethyl benzyl ammonium chloride". These are likely related to other identified QACs; however, we decided not to assume which ones, and since this only involved two product entries in total we simply removed them from further consideration. These eliminations resulted in a refined list of 32 candidate antimicrobials, most of which could be broadly categorized as QACs ($n = 8$), acids ($n = 8$), phenols ($n = 7$), or salts ($n = 4$) along with a few others ($n = 5$; Table 2 and Supplementary Table S1). These candidate antimicrobials were found in a total of 1534 product entries (sanitizers and disinfectants), 85% of which ($n = 1302$ entries) were QACs. The candidate antimicrobial found in the most products was benzalkonium chloride (624 entries) followed by four other QACs (Table 2 and Supplementary Table S1). Phenols were found in the second highest number of product entries, albeit an order of magnitude lower ($n = 148$; 10%), and triclosan was the top used phenol, and the sixth most prominent candidate antimicrobial overall ($n = 70$ products), followed by chloroxylenol ($n = 32$; Tables 2 and Supplementary Table S1). While several salt and acid antimicrobials were identified in total, compared with these other two groups, they were used in only a small proportion of product entries each (3% and 2%, respectively), suggesting a lower prominence (Table 2 and Supplementary Table S1).

3.4. Environmental concentrations and toxicity to aquatic biota

Reports of environmental concentrations in Canada of candidate antimicrobial contaminants were sparse. None of the candidate antimicrobials were previously included in Canada's National Long-term Water Quality Monitoring Program which mainly tracks pesticides, persistent organic pollutants, metals, and polycyclic aromatic hydrocarbons (GoC 2016) nor were they included in CMP's Wastewater Monitoring Program which additionally tracks major ions, nitrogen, ammonia, and numerous other compounds (GoC 2019*a*). This is unsurprising for candidates that may have known low environmental risk or are newly emerging, but for some it may also be related to the lack of standard analytical methods for their detection (as noted for other contaminants: Anderson et al. 2021). Studies reporting environmental concentrations of candidate antimicrobials in aquatic habitats in Canada were also rare and for most, our search string yielded no relevant results. The more general search terms yielded several reports of PPCPs in wastewater or relevant environmental compartments. However, all were heavily focused on other pharmaceuticals (including antimicrobial drugs, i.e., antibiotics), and of the few disinfecting antimicrobials included, only triclosan and triclocarban were reported (Lapen et al. 2008; Couperus et al. 2016; de Solla et al. 2016; Krogh et al. 2017; Srain et al. 2021). Furthermore, there is a lack of established water quality guidelines for all but two of the candidate antimicrobials: triclosan (0.47 μg/L; GoC GoC 2018) and one QAC (didecyl dimethyl ammonium chloride; 1.5 μg/L; CCME's Water Quality Guidelines database) GoC 2017). Notwithstanding 19 of the candidate antimicrobials are classified as hazardous to aquatic biota (fish, crustaceans, and (or) algae or aquatic plants) based on the acute and chronic toxicity thresholds of the GHS (Tables 2 and S1). Only triclosan is currently managed and is listed on Canada's Schedule 1 of CEPA, the List of Toxic Substances based on its potential to enter aquatic environments at concentrations with potential to elicit immediate or long-term harmful effect on the environment or biodiversity. As a result, risk management actions have been taken to reduce the quantities of triclosan released to the environment (GoC 2018). Chlorhexidine and its salts (which includes chlorhexidine gluconate) are proposed for addition to Schedule 1, also based on the results of a final screening assessment which concluded that immediate or long-term harmful effect on the environment or its biological diversity were possible (GoC 2019*b*) and risk management actions have been proposed (GoC 2022*b*).

4. Discussion

4.1. Evaluation of proxy evidence for antimicrobial identification and use

The three lines of proxy evidence we consulted (retail sales of sanitizers and disinfectants and imports of disinfectants and related product codes and drug registrations) varied in their usefulness to respond to our objectives of identifying antimicrobial chemicals and estimating Canadian use trends. The assessments of domestic grocery store retail sales as well as imports into Canada were useful to confirm the assumption that demand for disinfecting personal care products increased in Canada from the onset of pandemic restrictions (March 2020) and in the year that followed. These observed increasing trends were likely coupled with increased use, thus elevating the potential for antimicrobial active ingredients to enter the aquatic environment through wastewater effluents (or other pathways). Of all three proxy lines of evidence,

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Table 2. Active antimicrobial ingredients identified in hand sanitizers and surface disinfectants approved for use against SARS-CoV-2 and other registered disinfectants up until May 2021 to be considered for implications for aquatic biota.

Rank	Antimicrobial active ingredient	CAS No.	Group	Total no. of products	GHS
1	Alkyl dimethyl benzyl ammonium chloride (benzalkonium chloride)	63449-41-2	QAC	624	H400, H410
2	Alkyl dimethyl ethylbenzyl ammonium chloride	85409-23-0	QAC	227	H410
3	Didecyl dimethyl ammonium chloride	7173-51-5	QAC	204	–
4	Octyl decyl dimethyl ammonium chloride	32426-11-2	QAC	112	H400
5	Dioctyl dimethyl ammonium chloride	5538-94-3	QAC	107	H400
6	Triclosan*	3380-34-5	Phenol	70	H400, H410
7	Chloroxylenol	88-04-0	Phenol	32	–
8	Chlorhexidine gluconate*	18472-51-0	Salt	29	H400, H410
9	Benzyl dimethyl trimethylpentan phenoxy ethodyethan ammonium chloride (benzethonium chloride)	121-54-0	QAC	22	H400, H410
10	Thymol	89-83-8	Phenol	18	H401, H411
11	Citric acid	77-92-9	Acid	14	–
12	Hypochlorus acid	7790-92-3	Acid	10	–
12	P-*tert*-pentylphenol	80-46-6	Phenol	10	H410, H411
13	Clorophene	120-32-1	Phenol	9	H400, H410
14	2-Phenylphenol (*O*-phenylphenol)	90-43-7	Phenol	7	H400
15	Peracetic acid	79-21-0	Acid	5	H400
16	Alkyl dimethyl benzyl ammonium saccarinate (myristalkonium saccharinate)	68989-01-5	QAC	4	–
16	Hydrochloric acid	7647-01-0	Acid	4	–
17	Potassium peroxymonosulfate	10058-23-8	Salt	3	–
18	Acetic acid	64-19-7	Acid	2	–
18	Didecyl dimethyl ammonium carbonate/bicarbonate	148788-55-0	QAC	2	–
18	Dodecyl benzene sulfonic acid	27176-87-0	Acid	2	H411
18	Glycolic acid	79-14-1	Acid	2	–
18	Iodine	7553-56-2	Other	2	H400
18	Lactic acid	50-21-5	Acid	2	–
18	Phenol	108-95-2	Phenol	2	–
18	Phenolate sodium/sodium phenoxide	139-02-6	Salt	2	–
18	Silver dihydrogen citrate	None	Other	2	–
18	1-Vinyl-2-pyrrolidinone (within polymers)	88-12-0	Other	1	–
18	Bronopol	52-51-7	Other	1	H400
18	Gluteraldehyde	111-30-8	Other	1	H400, H411
18	Potassium iodide	7681-11-0	Salt	1	H411

Note: Toxicity classification by the Globally Harmonized System (GHS): very toxic, H400: $LC_{50} < 1$ mg/L; toxic, H401: $LC_{50} = 1 - 10$ mg/L), or chronic toxicity (very toxic, H410: no observable effect concentration, NOEC < 0.01 mg/L; toxic, H411: NOEC < 0.1 mg/L; or harmful, H412: NOEC < 1 mg/L) toxicity (UNECE 2019). References: NCBI's PubChem database was searched to identify CAS No., all available chemical information (basic and properties related to evaporation potential) and GHS toxicity classification (https://pubchem.ncbi.nlm.nih.gov/).
Antimicrobials are listed from highest to lowest for the total number of products (sanitizers and surface disinfectants) that they were identified in. Identified antimicrobials unlikely to reach aquatic systems due to evaporation or instability in water were not included in this list nor were those related to available chlorine (Supplementary Table S1).
*Listed or proposed for Schedule 1 List of Toxic Substances under the Canadian Environmental Protection Act, CEPA for environmental reasons (reference: https://pollution-waste.canada.ca/substances-search/substance).

the analysis of products approved for use against SARS-CoV-2 was the most successful in identifying the widest variety of antimicrobial chemicals. It was easier to extract information from these lists of products than the permanent searchable database of all current disinfectant registrations, as not all active ingredients are immediately displayed in the latter. However, using the regular drug database may become necessary for any similar future analyses if the COVID-19 approved product lists are not maintained indefinitely. Furthermore, it is also of note that many of the disinfectant registrations are not new, indicating that these products were in use prior to the pandemic, and their registration date could be a useful data point to explore in a temporal context.

Our assumption that products approved for use against SARS-CoV-2 are also those in greatest use was well supported by the increased retail sales and import trends. Of these sets of economic data, some chemical specificity could only be obtained from the import data. Thus, for future objectives, retail sales may be of limited use. Though we were unsuccessful in identifying candidate antimicrobials additional to those found in registered sanitizers and disinfectants from imports, further detail on the types of products was useful.

The study of imports into Canada, though affected by numerous factors (see the Supplementary Material, Section S1), thus represents a useful line of evidence for estimating the current use of these and other HS-coded classes of products or chemicals that can make their way indirectly into the environment. One of the great benefits of these data is that they are historically and continually available with monthly updates (by mass or dollars) that can be purchased from Statistics Canada or annual values that can be obtained online (in dollars; exports or imports, etc.: https://www.ic.gc.ca/app/scr/tdst/tdo/crtr.html). Both long-term trends and current imports could be assessed and (or) regularly monitored for chemicals with a lack of central sales monitoring (i.e., unlike pesticides: Anderson et al. 2021). This was particularly useful in the present work because there can be large delays in accessing contaminant concentrations in the environment due to the time it takes to collect and analyse samples followed by publication timeframes. In the present pandemic situation, this was further compounded by the restrictions on in-person work both in the field and laboratory in Canada. The use of these proxies has enabled us to rapidly highlight contaminants of potential concern and to provide a list of compounds for environmental monitoring studies that may not otherwise have been included. Comparing imports of chemicals with environmental concentrations over time would be a worthwhile exercise to validate this approach for antimicrobials or other chemicals. For researchers in other countries, similar lines of evidence may be available and worth exploring to respond to similar questions regionally.

4.2. Candidate antimicrobials for ecotoxicological consideration

This exercise has revealed that a wide variety of candidate antimicrobial active ingredients are currently included in sanitizing and disinfecting products in Canada, that their use has drastically increased during the COVID-19 pandemic, and that most would be considered as novel environmental contaminants if they are reaching aquatic environments. These findings align with our predictions and exemplify the circumstances of most classes of PPCP chemicals. Furthermore, while leave-on hand sanitizers contain mainly alcohols as active ingredients, antimicrobial soaps and surface disinfectants are dominated by candidate antimicrobial contaminants. The majority of these candidates fell into the categories of QACs, acids, phenols, and then salts, with QACs and phenols being the most prominent, and there may be varying environmental implications for each of these groups.

4.2.1. Quaternary ammonium compounds

A key finding of our review was the heavy emphasis on QAC antimicrobials in current-use products. These antimicrobials held the top five positions for the most prominent active ingredients in sanitizing and disinfecting products approved for use against SARS-CoV-2 by Health Canada and were present in the vast majority of product entries in our refined list of candidate antimicrobials for further environmental consideration. This finding reflects their dominance in the global market where 31% of all cleaning products contained them in 2020 (CMI 2020; GVR 2021). QACs are cationic surfactants (i.e., compounds with hydrophobic and hydrophilic components) that reduce surface tension and have an additional biocidal capacity. They are used in household, commercial, and medical settings for surface disinfection (reviewed in Pereira and Tagkopoulos 2019) including for deactivating SARS-CoV-2 (Celina et al. 2020; Wu et al. 2020) with proven effectiveness (e.g., didecyl dimethyl ammonium chloride; Xiling et al. 2021). QACs function by disrupting lipid bilayers of microorganisms (reviewed in Nagai et al. 2003) and lipid bilayers that surround enveloped viruses (including coronaviruses; Falk 2019), properties that are potentially harmful to a range of aquatic species.

Our understanding of QACs as environmental contaminants remains limited. Reports on environmental concentrations of QACs are sparse, particularly in Canada; however, those from other industrialized nations may be comparable. Although a significant portion of QACs are removed from waste streams via wastewater treatment facilities (e.g., 90%, Zang et al. 2015), predominantly through sorption to organic solids and biodegradation, they are still measured in downstream aquatic systems (Hora et al. 2020). For example, a 2018 study of wastewater effluent in Minneapolis, USA, showed that QAC concentrations ranged from 0.4 to 8.3 μg/L (sums) and that individual QAC concentrations in regional lake surface sediments ranged from 14 to 436 ng/g dry weight (including one site in Lake Superior; Pati and Arnold 2020). Benzalkonium chloride, the most prominent antimicrobial in current use products identified in the present work, has been detected in effluent and surface waters at maximal concentrations ranging from 0.01 to 99.6 μg/L in various locations in Korea, the USA, and Europe (reviewed in Kim et al. 2020).

The toxicity of QACs has also yet to be well characterized, but their broad presence in aquatic systems and toxicity to a range of aquatic species, from microorganisms to fish, is concerning (Zang et al. 2015). The only QAC on our candidate list that has an established water quality guideline is didecyl dimethyl ammonium chloride (which is likely related to its additional and possibly more widespread use as a wood preservative: NCBI 2022*e*), which was the third most prominently used QAC in current disinfectants (freshwater, long-term exposure: 1.5 μg/L; CCME 2021). However, no data are available for the determination of other thresholds for this compound, including short-term freshwater exposure, marine exposure, and sediment concentrations (CCME 2021). We found that several of the identified QAC antimicrobials are classified as toxic to aquatic biota (GHS, Tables 2 and S1; see Section 2.2.3.), underscoring the need to determine to what degree they are reaching downstream aquatic ecosystems in Canada, and their relative persistence and bioaccumulation potential. Additional research on the bioavailability of QACs in aquatic ecosystems is also needed. Early studies that have shown that QACs readily sorb to particulates making them less bioavailable compared to the freely dissolved form which is primarily responsible for aquatic toxicity (Hora et al. 2020).

How this varies between individual QACs under a range of conditions and the impact for water column versus sediment-dwelling biota is needed. Though the degree to which individual QACs are used varies, it is likely important to increase our knowledge on these compounds in general and inferences may ultimately be made between those with similar chemistry. The dearth of knowledge on QACs has been acknowledged by Canada's Chemicals Management Plan which has identified them as highly hazardous and has indicated that further review could be challenging due to a lack of ecotoxicological information and the difficulty in their testing and modelling (GoC 2019*c*; data gathered to date: GoC 2020*c*). As such, timely studies on these chemicals also stand to be highly informative for regulatory purposes.

4.2.2. Phenols

The next most prominent group of candidate antimicrobials were phenols, and though there appears to be a considerably lower emphasis on their use compared to QACs, it remains important to consider their potential environmental impacts. Phenols are chemicals that may arise from both natural (e.g., decomposition) and anthropogenic sources (e.g., oil and gas, pesticides), and their toxicity varies with their degree of hydrophobicity, ability to form free radicals, and the type and position of halogen atoms (e.g., chlorine; reviewed in Michalowicz and Duda 2007). In their use against target species, they can penetrate cell membranes where electrophilic metabolites may bind to enzymes and (or) DNA and can elicit mutagenic or carcinogenic effects and histological changes in tissues (reviewed in: Michalowicz and Duda 2007). Triclosan, the top phenol in the present exercise, is also the only established, or legacy, environmental antimicrobial contaminant (Abbott et al. 2020) among our candidates. It has had a broad range of uses associated with multiple antimicrobial mechanisms of action (Russell 2004; Lubarsky et al. 2012). Though human health risks were deemed low, risk assessment conducted by the Canadian Government revealed that triclosan poses a risk to the environment because it adversely affects aquatic biota at low concentrations (GoC 2018). The use of triclosan for pest control in Canada ceased in 2014, added to Schedule 1 in 2020, and under the Food and Drugs Act (R.S.C., 1985, c. F-27), Canada regulates its use in cosmetics, nonprescription drugs, and natural health products with maximum allowable concentrations of 0.03% in mouthwashes, 1.0% in nonprescription drugs, and 0.3% in cosmetics and natural health products (GoC 2018).

In the most recent (and still prepandemic) reports, the presence of triclosan in wastewater effluent ranged from 10.3 to 1390 ng/L across 13 different treatment facilities in 2011–2014; removal of triclosan ranged from 40% to 100% depending on the type of water treatment method (Guerra et al. 2019). In Canadian surface waters from 44 locations sampled between 2012 and 2018, triclosan was detected in 25% of samples (<6–874 ng/L; mean 52.84 ng/L), and in three samples, concentrations were above the water quality guideline of 470 ng/L (Lalonde et al. 2018). Concentrations of triclosan in water were higher in locations situated downstream of wastewater treatment effluent but overall showed no temporal trend during the sampling period (Lalonde et al. 2018). There is also some evidence for bioconcentration or bioaccumulation of triclosan and other phenols in aquatic biota, and mussels located close to wastewater effluent release showed 96.3 $\pm$ 48.1 ng/g wet weight (ww) of triclosan in tissue compared with 12.5 $\pm$ 27.9 ng/g ww farther downstream (de Solla et al. 2016). Environmental concentrations of other phenols were not found for Canadian locations; however, 2-phenylphenol has been detected in 82% of freshwater fish and prawn samples (median concentration of 7 ng/g lipid weight) in China (Peng et al. 2018), suggesting that it can enter the environment and be taken up by aquatic biota as well.

4.2.3. Others

Aside from QACs and phenols, a variety of other antimicrobial active ingredient types were identified. Though most were generally present in small numbers of products each, we have used these numbers as a proxy for use, and it may remain worthwhile to further consider the potential of some of them to enter aquatic environments. With respect to acid antimicrobials, their mechanisms of action include disrupting membranes, inhibiting metabolic reactions, altering pH, and promoting build-up of toxic anions (e.g., weak organic acids: Arshad and Batool 2017). Many of the acid antimicrobials identified are naturally occurring compounds, with well-characterized roles in biological processes (e.g., hydrochloric, lactic, acetic, citric, glycolic, hypochlorous; Tables 2 and S1) which may influence ecotoxicological considerations. Hypochlorous acid (endogenous in mammals and effective for virus inactivation: Block and Rowan 2020) is formed when sodium hypochlorite dissolves in water and is the intermediate in the production of available chlorine (Severing et al. 2019). Thus, ecotoxicological considerations of hypochlorous acid may be related to chemicals used as chlorine. However, as it is listed on Canada's Non-domestic Substances List and thus requires regulatory review in Canada (GoC 2022*a*), we have maintained it on our list of candidates for now. A number of candidate salt antimicrobials were identified in a small proportion of products. The antimicrobial ability of salts has long been known and they mainly function by desiccation or by physical damage to cells during recrystallization (e.g., Quan et al. 2017). The most prominent among the candidate antimicrobials in the present work was chlorhexidine gluconate, which has recently been evaluated in Canada and proposed for addition to Schedule 1 List of Toxic Substances under CEPA, under the category of "chlorhexidine and its salts". The review concluded that releases of chlorhexidine moiety in the aquatic environment from the industrial formulation of chlorhexidine-based products pose a risk to aquatic and benthic organisms; and we refer readers to the screening assessment for further information (GoC 2019d). As a result of this assessment, on 14 February 2022, the government published a proposed *Environmental Performance Agreement for the Formulation of Chlorhexidine Products* for a 60-day public comment period (GoC 2022*b*). The purpose of this proposed agreement is to protect the aquatic environment by minimizing participating companies' releases of chlorhexidine and its salts, from their facilities that formulate chlorhexidine-based products.

Only five candidate antimicrobials were identified that did not fall into one of the four main groups, and each was present in one or two products only (iodine, silver dihydrogen citrate, 1-vynyl-2-pyrrolidinone, bronopol, and glutaraldehyde). Though aldehyde-based products are considered a major class of cleaners (GVR 2021), that only glutaraldehyde was identified in the present exercise and only in one product suggests that they are not prominent in these types of registered health products. However, further consideration for environmental impacts may be warranted due to their use in cleaning products.

4.3. Recommendations

4.3.1. Environmental monitoring

The analysis that we have completed has revealed a number of antimicrobial chemicals in current, and likely increased, use for sanitizing and disinfecting purposes that have potential to enter the environment. The first step in determining how prominent they are (or may become) as contaminants will be to begin biotic and abiotic monitoring efforts for these compounds in a wide variety of aquatic ecosystems. This information is important to better document environmental concentrations and trends and to increase our understanding of their fate within aquatic compartments and uptake into biota. This is particularly important for regulators, such as Environment and Climate Change Canada and Health Canada, to understand risk when they are assessing these substances and setting control measures. The fact that we were unable to find Canadian aquatic environmental concentrations for any of the identified antimicrobials other than triclosan, using our directed literature search string, underscores this recommendation. However, we acknowledge that a deeper dive into the literature or other sources might be beneficial to uncover more reports. Though triclosan is generally considered a legacy antimicrobial (Abbott et al. 2020) that is already regulated in Canada (GoC 2018) and elsewhere, some environmental monitoring to ensure it remains under the water quality benchmark despite possible increased use in response to the COVID-19 pandemic may be beneficial, along with efforts to monitor other phenols. However, a shift away from using triclosan and triclocarban (used in cleaning products (GoC 2020*d*), but not identified in disinfectants herein) as the only exemplary, or sentinel, disinfecting antimicrobials in monitoring studies is warranted due to the variety of compounds we have found to be in use, and inclusion of QACs in particular would be a beneficial addition. We recognize that the lack of environmental concentrations could also be related to the lack of analytical techniques for the detection of some of the candidates. Nontarget analysis may be a useful approach in the immediate future, and where applicable, a focus on analytical method development where needed could be important. On a broad note, in these efforts, we appeal to researchers conducting environmental monitoring studies to incorporate reconciliation with Indigenous peoples. Towards this goal in Canada, we highlight the advice laid out in the ten Calls to Action for natural sciences (Wong et al. 2020). Additionally, we recommend consideration for the cultural significance of aquatic species and ecosystems under study (e.g., Whyte et al. 2016) and that the personal implications of contaminants research for Indigenous peoples be observed (Liboiron 2021).

While we present a specific case study, using Canada as an example, we encourage researchers in other countries to consider the same recommendations. That few reports on environmental concentrations of candidate antimicrobials were available from other regions as well highlights the fact that the need to determine their significance is global. It would be beneficial for researchers in other nations or regions to search out and examine similar sources of information to determine whether these, or other antimicrobial active ingredients, are in current use to ensure that local monitoring efforts are relevant.

Though the scope of this study was to identify antimicrobial compounds that are likely receiving increased use (largely based on active ingredients in products approved for use against SARS-CoV-2), there may be other antimicrobials of concern. For example, these may be commonly used in household products that do not require drug registration (e.g., cleaning products), and products for other disinfecting purposes, and for researchers in other countries there may be additional compounds approved for this use. Though drastic increased importation of general cleaning products was not evident in the first year of the pandemic (Supplementary Fig. S1), imports of a variety of general cleaning products are considerably higher than any disinfecting or sanitizing product categories (Supplementary Fig. S1), and thus their use and potential release are likely greater. In addition, it is important to note that the reviewed products contain numerous inactive ingredients (e.g., other surfactants, gels, scents, nonylphenol ethoxylates, etc.). The fate of these compounds may be of environmental concern should they evade water treatment processes and enter aquatic environments and are a consideration for all sanitizing and disinfecting products irrespective of the likelihood for the active antimicrobial ingredient to reach aquatic environments. Future work includes identifying these compounds and assessing their risk through desktop reviews, lab studies, and environmental monitoring, where necessary, to improve our understanding of individual and chemical mixture concentrations in the environment that could induce negative health effects in aquatic species. Further work to determine what some of these additional antimicrobials and nonactive ingredients may be and (or) including them in environmental monitoring efforts when possible would be complementary, as they may have similar effects to the present compounds discussed and (or) could contribute to environmental mixtures of chemicals.

It may be predicted that ongoing increased disinfection relative to prepandemic levels is likely to persist while the pandemic is active or outbreaks reoccur; however, the reasonable question does arise as to how long exaggerated use of decontaminants will persist and thus how long study of these antimicrobials should be prioritized thereafter. We recognize that scientific knowledge on SARS-CoV-2 transmission has

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increased rapidly and evidence is mounting for low transmission from surfaces (Pitol and Julian 2021). Notwithstanding, surface or hand decontamination practices remain recommended (GoG 2020*a*: last reviewed March 2022; WHO 2020), and recent findings indicate that some newer variants may last longer on surfaces (Chin et al. 2022). This suggests that increased sanitization and disinfection is likely to persist, certainly in high-risk settings such as health care facilities, and hand sanitization remains important (Pitol and Julian 2021). In addition, aside from the COVID-19 pandemic, we believe that disinfecting chemicals will remain important as emerging environmental contaminants, firstly because many of the candidate antimicrobials were already in use and some were detected in aquatic environments before the pandemic began (e.g., Guerra et al. 2019; Pati and Arnold 2020), and thus further understanding their impacts is not a new requirement. Secondly, the global market for disinfecting and cleaning products has been projected to grow by 6%−20% per year with QACs showing the fastest increases (2020–2028; CMI 2020; GVR 2021). Indeed, initially the COVID-19 pandemic is estimated to contribute to this growth; however, on a more prolonged basis, the increased prevalence of numerous other pathogens (e.g., antibiotic-resistant bacteria in hospitals) and the expansion of the disinfectant market to countries where use has been less widespread to date are expected to continue driving this growth worldwide (CMI 2020; GVR 2021).

4.3.2. Policy implications

While in the wake of an emergency the use of all available tools was critical, as the crisis abates, it is important to begin considering the environmental implications of antimicrobial use. Propanol-2 (70%–100% concentration), ethanol (62%–71%), hydrogen peroxide (0.5%), and sodium hypochlorite (0.1%) are all capable of quickly deactivating SARS viruses (reviewed in: Rabenau et al. 2005; Kampf et al. 2020) including SARS-CoV-2 (Gerlach et al. 2020; Hirose et al. 2021), and with greater efficacy than some other tested compounds (e.g., benzalkonium chloride 0.05%–0.2% and chlorhexidine gluconate 0.02%; Hirose et al. 2021). These represent options for both hand sanitizing and surface disinfection and could be promoted immediately based on their low likelihood of reaching aquatic systems or better characterized environmental impacts, in the place of less well-understood antimicrobials or those determined to be toxic to aquatic biota at environmentally relevant levels. As research is conducted on the antimicrobials identified in the present work, other safer options may also become apparent. In addition, though we have acknowledged our assumption that not all products imported into Canada may be used immediately (Section S1), which certainly impacts how much of these compounds may be currently entering the aquatic ecosystems, the presence of surplus disinfectants (both in homes and commercial settings) may also pose an environmental concern and policy surrounding their safe disposal will be critical when considering the hazards for aquatic biota. Finally, if domestic production of sanitizers and disinfectants increases, release during manufacturing may become a larger contributing factor.

5. Conclusions

During the COVID-19 pandemic, there has been an increased use of sanitizing and disinfecting products to curb the spread of the SARS-CoV-2 virus, and the prolonged rise in retail sales and imports in Canada highlighted herein supports our hypothesis and common assumptions. It is likely that currently employed antimicrobials and use trends are similar in many other nations for which this work may provide an example, as the market for these types of disinfectants is global (CMI 2020; GVR 2021). This may be particularly true for drug-standardization partner nations including in the USA (Canada–United States Regulatory Cooperation Council: www.trade.gov/cc) as well as Europe, and several countries in Asia, South America and beyond (International Council for the Harmonization of Technical Requirements for Pharmaceuticals for Human Use: www.ich.org/page/members-observers).

Several trends on the use of antimicrobials in Canada in response to the COVID-19 pandemic became evident. To begin with, we can reliably conclude that alcohol-based antimicrobials were favoured for leave-on hand sanitizers, based on their presence in approved products and increased imports into the country, which is in line with recommendations by WHO (2020) and Government of Canada (2020*a*). This is a positive finding from an aquatic environmental standpoint due to their rapid evaporation following application (e.g., Macinga et al. 2014) and thus low likelihood of reaching aquatic environments through wastewater treatment systems or other pathways. Conversely, there was no evidence for increased use of long-standing antimicrobials with low likelihood of reaching aquatic environments (hydrogen peroxide) or well-characterized environmental implications (hypochlorites/chlorine, e.g. bleach)—they were not employed as active ingredients in high proportions of approved sanitizers or disinfectants, nor did their imports increase. As these compounds are effective in deactivating SARS-CoV-2 (reviewed in: Rabenau et al. 2005; Kampf et al. 2020; and as evidenced by presence as single active ingredients in industry-tested products), and may pose low environmental concern (PMRA 2005, 2017), this may have been a missed opportunity to employ antimicrobials for which environmental risks are better understood, and this could be considered moving forward. Thirty-two other nonalcohol−nonchlorine-based antimicrobial chemicals were collated into our list of candidates for consideration for aquatic environmental implications. These were used particularly in antiseptic soaps and surface disinfectants, which may be concerning for potential entry into aquatic systems, and they were dominated by QACs (followed by several phenols, acids, salts, and others).

Following this process, we want to stress that environmental monitoring for candidate antimicrobials is the main recommendation for immediate further empirical research. While herein we highlight which antimicrobials are likely receiving the most use, that alone cannot indicate which compounds have the greatest potential to emerge as environmental contaminants. To begin with, numerous other factors will be at play including their transformation and environmental fate. The next step in the present project is thus to conduct a deeper review of candidate antimicrobials to include chemical properties related to persistence, bioaccumulation, and toxicity to aid in further determining which should be prioritized for ecotoxicological studies as well.

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References

Abbott, T., Kor-Bicakci, G., Islam, M., and Eskioglu, C. 2020. A review on the fate of legacy and alternative antimicrobials and their metabolites during wastewater and sludge treatment. Int J Mol. Sci. **21**: 9241. doi:10.3390/ijms21239241.

Anderson, J.C., Marteinson, S.C., and Prosser, R.S. 2021. Prioritization of pesticides of risk to aquatic ecosystems in Canada and identification of knowledge gaps. *In* Reviews of environmental contamination and toxicology (Continuation of Residue Reviews). Vol. 259. *Edited by* P. de Voogt. Springer, Cham, pp. 171–231.

Arshad, M.S., and Batool, S.A. 2017. Natural antimicrobials, their sources and food safety. *In* Food additives. *Edited by* D.N. Karunaratne and G. Pamunuwa. Ch. 4. IntechOpen, Croatia.

Block, M.S., and Rowan, B.G. 2020. Hypochlorous acid: a review. J Oral Maxillofacial Surg. **78**(9): 1461–1466. doi:10.1016/j.joms.2020.06.029.

CCME, Canadian Council of Ministers of the Environment. 2021. Canadian Water Quality Guidelines (CEQGs); summary table. Available from https://ccme.ca/en/summary-table. [Accessed September 2021.]

Celina, M.C., Martinez, E., Omana, M.A., Sanchez, A., Wiemann, D., Tezak, M., and Dargaville, T.R. 2020. Extended use of face masks during the COVID-19 pandemic-thermal conditioning and spray-on surface disinfection. Polymer Degrad Stabil. **179**: 109251. doi:10.1016/j.polymdegradstab.2020.109251.

Chalew, E., and Halden, R.U. 2009. Environmental exposure of aquatic and terrestrial biota to triclosan and triclocarban. J. Am. Water Works Assoc. **45**(1): 4–13. doi:10.1111/j.1752-1688.2008.00284.x. PMID: 20046971.

Chin, A.W.H., Lai, A.M.Y., Peiris, M., and Poon, L.L.M. 2022. SARS-CoV-2 omicron variant is more stable than the ancestral strain on various surfaces. Emerg Infect Dis. **28**(7): 1515–1517. doi:10.3201/eid2807.220428. PMID: 35550234.

CMI, Coherent Marketing Insight. 2020. Disinfectants market analysis. 2021. Sample available from https://www.coherentmarketinsights.com/market-insight/disinfectants-market-256. [Accessed December 2021.]

Couperus, N.P., Pagsuyoin, S.A., Bragg, L.M., and Servos, M.R. 2016. Occurrence, distribution and sources of antimicrobials in a mixed-use watershed. Sci. Total Environ. **541**: 1581–1591. doi:10.1016/j.scitotenv.2015.09.086. PMID: 26512947.

da Silva, C.F., Deutschendorf, C., Nagel, F.M., Dalmora, C.H., Dos Santos, R.P., and Lisboa, T.C. 2021. Impact of the pandemic on antimicrobial consumption patterns. Infect Control Hosp. Epidemiol. **42**(9): 1170–1172. doi:10.1017/ice.2020.1227.

de Solla, S.R., Gilroy, E.A.M., Klinck, J.S., King, L.E., McInnis, R. Struger, J., et al. 2016. Bioaccumulation of pharmaceuticals and personal care products in the unionid mussel *Lasmigona costata* in a river receiving wastewater effluent. Chemosphere, **146**: 486–496. doi:10.1016/j.chemosphere.2015.12.022. PMID: 26741555.

Dhama, K., Patel, S.K., Kumar, R., Masand, R., Rana, J. Yatoo, M., et al. 2021. The role of disinfectants and sanitizers during COVID-19 pandemic: advantages and deleterious effects on humans and the environment. Environ. Sci. Pollut. Res. **28**(26): 34211–34228. doi:10.1007/s11356-021-14429-w.

Ebele, A.J., Abdallah, M.A.-.E., and Harrad, S. 2017. Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment. Emerg Contam. **3**(1): 1–16. doi:10.1016/j.emcon.2016.12.004.

Evariste, L., Barret, M., Mottier, A., Mouchet, F., Gauthier, L., and Pinelli, E. 2019. Gut microbiota of aquatic organisms: a key endpoint for ecotoxicological studies. Environ. Pollut. **248**: 989–999. doi:10.1016/j.envpol.2019.02.101. PMID: 31091643.

Falk, N.A. 2019. Surfactants as antimicrobials: a brief overview of microbial interfacial chemistry and surfactant antimicrobial activity. J. Surfactants Deterg. **22**(5): 119–1127.

Gerlach, M., Wolff, S., Ludwig, S., Schäfer, W., Keiner, B., Roth, N.J., and Widmer, E. 2020. Rapid SARS-CoV-2 inactivation by commonly available chemicals on inanimate surfaces. J. Hosp. Infect. **106**(3): 633–634. doi:10.1016/j.jhin.2020.09.001.

GoC, Government of Canada. 2014. Archived guidance document—management of disinfectant drug applications [online]. Available from https://www.canada.ca/en/health-canada/services/drugs-health-products/drug-products/applications-submissions/guidance-documents/disinfectants/management-disinfectant-drug-applications.html#b2. [Accessed December 2020.]

GoC, Government of Canada. 2016. National long-term water quality monitoring data. Available from https://open.canada.ca/data/en/dataset/67b44816-9764-4609-ace1-68dc1764e9ea. [Accessed November 2021.]

GoC, Government of Canada. 2017. Canadian Environmental Protection Act, 1999 federal environmental quality guidelines triclosan. Available from https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/cepa-tricosan-guidelines.html. [Accessed June 2021.]

GoC, Government of Canada. 2018. Triclosan - information sheet. Available from https://www.canada.ca/en/health-canada/services/chemical-substances/fact-sheets/chemicals-glance/triclosan.html. [Accessed June 2021.]

GoC, Government of Canada. 2019*a*. CMP wastewater monitoring program. Available from https://open.canada.ca/data/en/dataset/c6bbdf52-e5e4-43db-b1be-813bb4651ba3. [Accessed January 2022.]

GoC, Government of Canada. 2019*b*. List of substances in the third phase of CMP (2016-2021): July 2019 update. Available from https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/cmp-third-phase-update.html. [Accessed November 2021.]

GoC, Government of Canada. 2019*c*. IRAP, Identification of risk assessment priorities—results of the 2017-18 review. Available from https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/identification-risk-assessment-priorities-irap-2017-18.html.

GoC, Government of Canada. 2019*d*. Screening assessment; chlorhexidine and its salts. Environment and Climate Change Canada and Health Canada. Available from https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/screening-assessment-chlorhexidine-salts.html.

GoC, Government of Canada. 2020*a*. COVID-19: Main modes of transmission. Government of Canada. Available from https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection/health-professionals/main-modes-transmission.html. [Accessed September 2022.]

GoC, Government of Canada. 2020*b*. Hard-surface disinfectants and hand sanitizers *(COVID-19)*. Government of Canada. Available from https://www.canada.ca/en/health-canada/services/drugs-health-products/disinfectants/covid-19.html. [Accessed January 2022.]

GoC, Government of Canada. 2020*c*. Information received in response to quaternary ammonium compounds—phase 1. Available from https://open.canada.ca/data/en/dataset/b82332e6-3ed3-41f0-af1c-4d173d6e903e. [Accessed March 2022.]

GoC, Government of Canada. 2020*d*. Tricolocarban – information sheet. Available from https://www.canada.ca/en/health-canada/services/chemical-substances/fact-sheets/chemicals-glance/triclocarban.html. [Accessed January 2022.]

GoC, Government of Canada. 2021*a*. Drug product database. Available from https://www.canada.ca/en/health-canada/services/drugs-health-products/drug-products/drug-product-database.html. [Accessed November 2021.]

GoC, Government of Canada. 2021b. Chemical substances. https://www.canada.ca/en/health-canada/services/chemical-substances.html. [Accessed September 2021.]

GoC, Government of Canada. 2022*a*. Non-domestic substances list. Available from https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/substances-list/non-domestic.html. [Accessed March 2022.]

GoC, Government of Canada. 2022*b*. Proposed environmental performance agreement for the formulation of chlorhexidine products. Available from https://www.canada.ca/en/environment-climate-change/corporate/transparency/consultations/environmental-performance-agreement-chlorhexidine/proposed-agreement.html.

Guerra, P., Teslic, S., Albert, A., Gewurtz, S.B., and Smyth, S.A. 2019. Occurrence and removal of triclosan in Canadian wastewater systems. Environ. Sci. Pollut. Res. **26**: 31873–31886. doi:10.1007/s11356-019-06338-w.

GVR, Grand View Research. 2021. Surface disinfectant market size, share & trends analysis report by product type (chemical, biophased), by form (liquid, wipes sprays), by application, by end use, by region and segment forecasts, 2021−2028. Sample available from https://www.grandviewresearch.com/industry-analysis/antiseptics-and-disinfectants-market. [Accessed March 2022.]

Hirose, R., Bandou, R., Ikegaya, H., Watanabe, N., Yoshida, T. Daidoji, T., et al. 2021. Disinfectant effectiveness against SARS-CoV-2 and influenza viruses present on human skin: model-based evaluation. Clin Microbiol. Infect. **27**(7): 1042.e1–1042.e4. doi:10.1016/j.cmi.2021.04.009.

Hora, P.I., Pati, S.G., McNamara, P.J., and Arnold, W.A. 2020. Increased us of quaternary ammonium compounds during the SARS-CoV-2 pandemic and beyond: consideration of environmental implications. Environ. Sci. Technol. Lett. **7**: 622–631. doi:10.1021/acs.estlett.0c00437.

Kampf, G., Todt, D., Pfaender, S., and Steinman, E. 2020. Persistence of coronaviruses on inanimate surfaces and their inactivation with biocidal agents. J Hosp. Infect. **104**(3): 246–251. doi:10.1016/j.jhin.2020.01.022.

Kim, S., Ji, K., Shin, H., Park, S., Kho, Y. Park, K., et al. 2020. Occurrences of benzalkonium chloride in streams near a pharmaceutical manufacturing complex in Korea and associated ecological risk. Chemosphere, **256**: 127084. doi:10.1016/j.chemosphere.2020.127084. PMID: 32460158.

Krogh, J., Lyons, S., and Lowe, C. 2017. Pharmaceuticals and personal care products in municipal wastewater and the marine receiving environment near Victoria Canada. Front. Mar. Sci. **4**: 415. doi:10.3389/fmars.2017.00415.

Lalond, B., Garron, C., Dove, A., Struger, J., Farmer, K. Sekela, M., et al. 2018. Investigation of spatial distributions and temporal trends of triclosan in Canadian surface waters. Arch Environ. Contam Toxicol. **76**: 231–245. doi:10.1007/s00244-018-0576-0.

Lapen, D.R., Topp, E., Metcalfe, C.D., Li, H., Edwards, M. Gottschall, N., et al. 2008. Pharmaceutical and personal care products in tile drainage following land application of municipal biosolids. Sci. Total Environ. **399**: 50–65. doi:10.1016/j.scitotenv.2008.02.025. PMID: 18455753.

Liboiron, M. 2021. Pollution is colonialism. Duke University Press, Durham, NC.

Liboiron, M., Ammendolia, J., Winsor, K., Zahara, A., Bradshaw, H. Melvin, J., et al. 2017. Equity in author order: a feminist laboratory's approach. Feminism Theory Technosci. **3**(2): 1–17. doi:10.28968/cftt.v3i2.28850.

Lubarsky, H.V., Gerbersdorf, S.U., Hubas, C., Behrens, S., Ricciardi, F., and Paterson, D.M. 2012. Impairment of the Bacterial Biofilm Stability by Triclosan. PLoS One. https://doi.org/10.1371/journal.pone.0031183.

Luo, Y., Guo, W., Ngo, H.H., Nghiem, L.D., Hai, F.I. Zhang, J., et al. 2014. A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. Sci. Total Environ. **473**: 619–641. doi:10.1016/j.scitotenv.2013.12.065. PMID: 24394371.

Macinga, D.R., Schumaker, D.J., Werner, H.-P., Edmonds, S.L., Leslie, R.A., Parker, A.E., and Arbogast, J.W. 2014. The relative influences of product volume, delivery format and alcohol concentration on dry-time and efficacy of alcohol-based hand rubs. BMC Infect. Dis. **14**: 511. doi:10.1186/1471-2334-14-511. PMID: 25238976.

McLeod, A.I. 2011. Kendall: Kendall rank correlation and Mann-Kendall trend test. R package version 2.2. Available from https://CRAN.R-project.org/package=Kendall.

Michalowicz, J., and Duda, W. 2007. Phenols – sources and toxicity. Pol. J. Environ. Stud. **16**(3): 347–362.

Nagai, K., Murata, T., Ohta, S., Zenda, H., Ohnishi, M., and Hayashi, T. 2003. Two different mechanisms are involved in the extremely high-level benzalkonium chloride resistance of a pseudomonas fluorescent strain. Microbiol. Immunol. **47**(10): 709–715. doi:10.1111/j.1348-0421.2003.tb03440.x. PMID: 14605437.

NCBI, National Center for Biotechnology Information. 2022*a*. PubChem compound summary for CID 6323, Bromomethane. Available from https://pubchem.ncbi.nlm.nih.gov/compound/Bromomethane. [Accessed 23 March 2022.]

NCBI, National Center for Biotechnology Information. 2022*b*. PubChem compound summary for CID 6333, bromochloromethane. Available from https://pubchem.ncbi.nlm.nih.gov/compound/Bromochloromethane. [Accessed 23 March 2022.]

NCBI, National Center for Biotechnology Information. 2022*c*. PubChem compound summary for CID 784, hydrogen peroxide. Available from https://pubchem.ncbi.nlm.nih.gov/compound/Hydrogen-peroxide. [Accessed 23 March 2022.]

NCBI, National Center for Biotechnology Information. 2022*d*. PubChem compound summary for CID 517121, sodium dichloroisocyanurate. Available from https://pubchem.ncbi.nlm.nih.gov/compound/Sodium-dichloroisocyanurate. [Accessed 23 March 2022.]

NCBI, National Center for Biotechnology Information. 2022*e*. PubChem compound summary for CID 23558, didecyldimethylammonium chloride. Available from https://pubchem.ncbi.nlm.nih.gov/compound/Didecyldimethylammonium-chloride. [Accessed 30 March 2022.]

Pastorino, B., Touret, F., Gilles, M., de Lamballerie, X., and Charrel, R.N. 2020. Prolonged infectivity of SARS-CoV-2 in fomites. Emerg. Infect. Dis. **26**(9): 2256. doi:10.3201/eid2609.201788.

Pati, S.G., and Arnold, W.A. 2020. Comprehensive screening of quaternary ammonium surfactants and ionic liquids in wastewater effluents and lake sediments. Environ. Sci.: Processes Impacts. **22**: 430–444.

Peng, X., Zheng, K., Liu, J., Fan, Y., Taing, C., and Xiong, S. 2018. Body-size-dependent bioaccumulation, tissue distribution and trophic and maternal transfer of phenolic endocrine-disrupting contaminants in a freshwater ecosystem. Environ. Chem. **37**: 1811–1823. doi:10.1002/etc.4150.

Pereira, B.M.P., and Tagkopoulos, I. 2019. Benzalkonium chlorides: uses, regulatory status, and microbial resistance. Appl. Environ. Microbiol. **85**(13): e00377–e00319. PMID: 31028024.

Pitol, A.K., and Julian, T.R. 2021. Community transmission of SARS-CoV-2 by surfaces: risks and risk reduction strategies. Environ. Sci. Technol. Lett. **8**(3): 263–269. doi:10.1021/acs.estlett.0c00966.

PMRA, Pest Management Regulatory Agency. 2005. Sodium and calcium hypochlorite. Re-evaluation decisions document RRD2005-09. Health Canada. Available from https://publications.gc.ca/site/eng/9.559490/publication.html. [Accessed November 2021.]

PMRA, Pest Management Regulatory Agency. 2017. Proposed re-evaluation decision PRVD2017-12, hydrogen peroxide and its associated end-use products. Health Canada. Available from https://www.canada.ca/en/health-canada/services/consumer-product-safety/pesticides-pest-management/public/consultations/proposed-re-evaluation-decisions/2017/hydrogen-peroxide/document.html. [Accessed June 2021.]

PMRA, Pest Management Regulatory Agency. 2018*a*. Re-evaluation decision RV2018-14, isopropyl alcohol and its associated end-use products. Health Canada.Available from https://www.canada.ca/en/health-canada/services/consumer-product-safety/reports-publications/pesticides-pest-management/decisions-updates/reevaluation-decision/2018/isopropyl-alcohol.html. [Accessed June 2021.]

PMRA, Pest Management Regulatory Agency. 2018*b*. Re-evaluation decision RV2018-25, ethyl alcohol and its associated end-use products. Health Canada. Available from https://www.canada.ca/en/health-canada/services/consumer-product-safety/reports-publications/pesticides-pest-management/decisions-updates/reevaluation-decision/2018/ethyl-alcohol.html. [Accessed June 2021.]

PMRA, Pest Management Regulatory Agency. 2021*a*. Pest control products sales report for 2019. Available from https://publications.gc.ca/collections/collection_2021/sc-hc/H111-3-2019-eng.pdf.

PMRA, Pest Management Regulatory Agency. 2021*b*. Re-evaluation note REV2021-03, Pest Management Regulatory Agency re-evaluation and special review work plan 2021-2026. Available from https://www.canada.ca/en/health-canada/services/consumer-product-safety/reports-publications/pesticides-pest-management/decisions-updates/reevaluation-note/2021/special-review-work-plan-2021-2026.html. [Accessed March 2022.]

PubChem. 2022. National Library of Medicine (US), National Center for Biotechnology Information; 2004-. PubChem Compound Summary for CID 6332, Bromoethane. Available from https://pubchem.ncbi.nlm.nih.gov/compound/Bromoethane. [Accessed September 2022.]

Quan, F.S., Rubino, I., Lee, S.H., Koch, B., and Choi, H.-J. 2017. Universal and reusable virus deactivation system for respiratory protection. Sci. Rep. **7**: 39956. doi:10.1038/srep39956. PMID: 28051158.

Rabenau, H.F., Cinatl, J., Morgenstern, B., Bauer, G., Preise, W., and Doerr, H.W. 2005. Stability and inactivation of SARS coronavirus. Medic Microbiol Immunol. **194**: 1–6. doi:10.1007/s00430-004-0219-0.

Russell, A.D. 2004. Whither triclosan? J. Antimicrob. Chemother. **53**(5): 693–695. doi:10.1093/jac/dkh171. PMID: 15073159.

Salimi, M., Esrafili, A., Gholami, M., Jafari, A.J., Kalantary, R.R. Farzadkia, M., et al. 2017. Contaminants of emerging concern: a review of new approach in AOP technologies. Environ Monitor Assess. **189**: 414. doi:10.1007/s10661-017-6097-x.

Senta, I., Terzic, S., and Ahel, M. 2013. Occurrence and fate of dissolved and particulate antimicrobials in municipal wastewater treatment. Water Res. **47**(2): 705–714. doi:10.1016/j.watres.2012.10.041. PMID: 23186859.

Severing, A.L., Rembe, J.-.D., Koester, V., and Stuermer, E.K. 2019. Safety and efficacy profiles of different commercial sodium hypochlorite/hypochlorous acid solutions (NaClO/HClO): antimicrobial efficacy, cytotoxic impact and physicochemical parameters in vitro. J. Antimicrobial Chemother. **74**(2): 365–372. doi:10.1093/jac/dky432.

Srain, H.S., Beazley, K.F., and Walker, T.F. 2021. Pharmaceuticals and personal care products and their subtle and lethal effects in aquatic organisms. Environ. Rev. **29**: 142–181. doi:10.1139/er-2020-0054.

Statistics Canada. 2020. Canadian consumers prepare for COVID-19. Prices analytical series. Released April 8, 2020. ISBN 978-0-660-34425-6. Available from https://www150.statcan.gc.ca/n1/pub/62f0014m/62f0014m2020004-eng.htm.

Statistics Canada. 2021. The consumer price index and COVID-19: a one year retrospective. Released May 2021. ISBN 978-0-660-38885-4. Available from https://www150.statcan.gc.ca/n1/en/pub/62f0014m/62f0014m2021010-eng.pdf?st=GcAuD6Ve.

Szklarek, S., Górecka, A., and Wojtal-Frankiewicz, A. 2022. The effects of road salt on freshwater ecosystems and solutions for mitigating chloride pollution—a review. Sci. Total Environ. **805**: 150289. doi:10.1016/j.scitotenv.2021.150289. PMID: 34536879.

UNECE, United Nations Economic Division of Europe. 2019. Globally harmonized system of classification and labelling of chemicals (GHS). 8th ed. United Nations, New York. Available from https://unece.org/fileadmin/DAM/trans/danger/publi/ghs/ghs_rev08/ST-SG-AC10-30-Rev8e.pdf.

US EPA, Environmental Protection Agency. 2015. Sustainable Futures / P2 Framework Manual 2012 EPA-748-B12-001. Ch. 5: Estimating physical / chemical and environmental fate properties with EPI Suite TM. https://www.epa.gov/sites/default/files/2015-05/documents/05.pdf.

US EPA, United States Environmental Protection Agency. 2021. National recommended water quality criteria—aquatic life criteria table. Available from https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table. [Accessed September 2021.]

Van Doremalen, N., Bushmaker, T., Morris, D.H., Holbrook, M.G., Gamble, A. Williamson, B.N., et al. 2020. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. New Engl. J. Med. **382**(16): 1564–1567. doi:10.1056/NEJMc2004973.

WHO, World Health Organization. 2020. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public. [Accessed 30 December 2020; July 2022.]

Whyte, K.P., Brewer, J.P., and Johnson, J.T. 2016. Weaving indigenous science, protocols and sustainability science. Sustainability Sci. **25**: 25–32. doi:10.1007/s11625-015-0296-6.

Wilkinson, J.L., Boxall, A.B.A., Kolpin, D.W., and Teta, C. 2022. Pharmaceutical pollution of the world's rivers. Proc. Natl. Acad. Sci. U. S. A. **118**(8): e2113947119. doi:10.1073/pnas.2113947119.

Wong, C., Ballgooyen, K., Ignace, L., Johnson, M.J., and Swanson, H. 2020. Towards reconciliation: 10 calls to action to natural scientists working in Canada. Facets, **5**: 769–783. doi:10.1139/facets-2020-0005.

Wu, Y.C., Chen, C.S., and Chan, Y.J. 2020. The outbreak of COVID-19: an overview. J. Chin. Med. Assoc. **83**(3): 217. doi:10.1097/JCMA.0000000000000270.

Xiling, G., Yin, C., Ling, W., Xiansong, W., Jingjing, F. Xiaoyan, Z., et al. 2021. In vitro inactivation of SARS-CoV-2 by commonly used disinfection products and methods. Sci. Rep. **11**: 2418.

Zang, C., Cui, F., Zeng, G.-m., Jiang, M., Yang, Z.-z. Yu, Z.-g., et al. 2015. Quaternary ammonium compounds (QACs): a review on occurrence, fate and toxicity in the environment. Sci. Total Environ. **518-519**: 352–362. doi:10.1016/j.scitotenv.2015.03.007.