Research to Support Appropriate Source Controls to Address Toxic Contaminants Found in Surfactants

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Executive Summary

Surface active agents (surfactants) are a class of chemicals which are used in a wide range of different industries, but their use in household cleaning and personal care products accounts for over 50% of all surfactant use. They are widely used for their cleaning properties in consumer detergents and personal care products including: laundry detergents, dish washing soap, shampoos, conditioners, and body washes. They are made up of a polar head and a nonpolar tail, and are broken down into four main classes based on the charge of the polar head: anionic (negatively charged), nonionic (no charge), cationic (positively charged), and amphoteric (charge changes depending on pH). Since the introduction of synthetic surfactants in the 1940s there have been multiple occurrences of negative environmental impacts associated with the disposal of surfactants or their metabolites in wastewater treatment plants (WWTPs). The most prominent of these being branched alkylbenzene sulfonates which caused contamination of drinking water and extensive foaming in lakes and rivers surrounding WWTPs, and nonylphenol ethoxylates which were shown to degrade into endocrine disrupting molecules. These chemicals are used extensively in down-the-drain products and are classified as high production volume (HPV) chemicals which indicates a significant potential for negative environmental impacts if WWTPs cannot properly remove them from the wastewater stream. In the last several decades many scientific and governmental agencies have been developed to research the use of specific surfactants and determine if any have the potential to cause environmental damage.

For this project, a literature review was first conducted on the current use of surfactants in commercial products. Next a database was developed based on inventories taken from grocery stores, pharmacies, and general stores around Metro Vancouver with a focus on down-the-drain products containing high concentrations of surfactants. The ingredients of each consumer product were classified into specific surfactant groups and analyzed for potential load on Metro Vancouver WWTPs, ecological toxicity, and methods for removing them from the wastewater stream.

By far the most abundant surfactants are anionic surfactants with the most important of these being linear alkylbenzene sulfonates (LAS), alkyl sulfates (AS), and alkyl ether sulfates (AES). The largest environmental concern for anionic surfactants is the use of LAS due to very high volume use and the inability to biodegrade under anaerobic conditions. The current nonionic and amphoteric surfactants in use are slightly toxic to the environment, but due to their rapid biodegradation under aerobic and anaerobic conditions they likely do not pose a serious threat to the environment. The class of cationic surfactants called quaternary ammonium compounds (QACs) are most commonly used in hair conditioners and are significantly toxic to the environment, do not biodegrade under anaerobic conditions, and can inhibit anaerobic biodegradation due to their antimicrobial activity. Of the other chemicals present in these consumer detergents and personal care products the most likely to cause environmental damage are parabens, optical brighteners, and triclosan. While they are not used in extremely high volumes, optical brighteners are very persistent in the environment and are significantly ecotoxic. Some of the chemicals belonging to the paraben class and triclosan have been identified as endocrine disruptors, are persistent in the environment, and are considerably toxic to aquatic organisms.

While some regulations surrounding the use of these chemicals have been passed and many manufacturers are voluntarily working with governing bodies to decrease their use of toxic chemicals, some source controls are still necessary to decrease the amounts of potentially toxic substances reaching the environment. My recommendations for methods to mitigate any environmental damage associated with the use of surfactants in consumer products are threefold:

1. Education: a public education campaign should be run outlining the benefits of using an automatic dishwasher instead of hand washing dishes, decreasing the amounts of consumer laundry detergents used or only using a single laundry pod, and decreasing the amounts of personal care products used with a specific focus on hair conditioners. These controls will decrease the load of surfactants reaching WWTPs. Additionally, I recommend that Metro Vancouver lobby for the federal government to follow the US in banning the use of triclosan in all antiseptic products as it has not been proven to be effective and is very toxic to the environment.
2. Treatment: the best method for dealing with the majority of these chemicals is through activated sludge secondary treatment in WWTPs. While the most effective method of minimizing environmental impacts is by decreasing surfactant load on WWTPs, it is also important to optimize treatment methods.
3. Ongoing Monitoring: many of the surfactants and other chemicals present in consumer detergents and personal care products adsorb to sludge in WWTPs or sediment in surrounding discharge areas. It is important to continually monitor these areas for buildup of these chemicals as they can cause environmental damage if high concentrations are reached. Specific attention should be given to linear alkylbenzene sulfonates (LAS), quaternary ammonium compounds (QAC), ethylenediaminetetraacetic acid (EDTA), parabens, stilbenes, and triclosan. As many of the chemicals discussed in this report require secondary treatment to fully biodegrade, ongoing monitoring of concentrations of these chemicals in effluents is very important.

While surfactants are not a major priority for environmental concern, as the population density increases in the Metro Vancouver area these recommendations would help ensure that ecological harm is not caused by the use of these chemicals.

Study Limitations

This study is limited by availability of accurate market data concerning exact amounts of surfactants used per capita by residents of the Metro Vancouver area in down-the-drain products. The majority of scientific studies focus on the very high production volume surfactants (anionic and nonionic), and more detailed market reports were not obtained for this study as they are very expensive. Additionally, not all manufacturers release detailed ingredient lists or safety data sheets for their products, so some data concerning surfactant concentrations and exact chemical names is missing from this study.

Current Metro Vancouver Wastewater Treatment Plants

Plant	Iona Island	Lions Gate	Annacis Island	Lulu Island	Northwest Langley
Treatment type	Primary	Primary	Secondary	Secondary	Secondary
Treatment Methods	• Influent Screens • Preaeration and grit removal • Primary sedimentation • Primary anaerobic digestion		• Influent Screens • Preaeration and grit removal • Primary sedimentation • Primary anaerobic digestion • Trickling filter/solids contact • Secondary clarification • Secondary anaerobic digestion		• Influent screens • Aerated flow equalization lagoon • Trickling filter/activated sludge-type secondary treatment • Secondary clarification

It is important to note that while the Lions Gate and Iona Island facilities are currently operating under primary treatment, they will be upgraded to secondary treatment by 2020 and 2030 respectively.

Introduction

Surface active agents (surfactants) are a group of chemicals which contain a hydrophilic (charged or uncharged) head and a hydrophobic tail. They are classified by the charge of the hydrophilic head as anionic (negatively charged), cationic (positively charged), nonionic (no charge), or amphoteric (can have positive, negative, or no charge depending on pH). Surfactants are widely used across many different industries for their ability to lower the surface tension of water by adsorbing at interfaces between water and air or water and other liquids. This enables improved efficiency for breaking down the interface between dirt or oils and water, and emulsification properties help to keep the dirt and oils in suspension for removal. For these reasons, surfactants are major components of most consumer detergents, personal care, and cleaning products. They are also used in lubricants, emulsion polymerization, textile processing, petroleum recovery, pesticides, and a wide variety of other applications.

The large scale production and use of surfactants puts them into the classification of high production volume (HPV) chemicals. This includes chemicals produced in amounts exceeding 1,000 tonnes per year by at least one member state of the Organization for Economic Co-operation and Development (OECD), which includes countries in North America, South America, Europe, Asia, and Australia. In 2014 the Canadian surfactant market annual demand was estimated at 300,000 to 400,000 tonnes, excluding imported formulated products containing surfactants [1]. The estimated pattern of demand (Figure 1) shows that the largest share of surfactants consumed in Canada is held by household products, and when combined with personal care products they account for over 50% of the Canadian surfactant market.

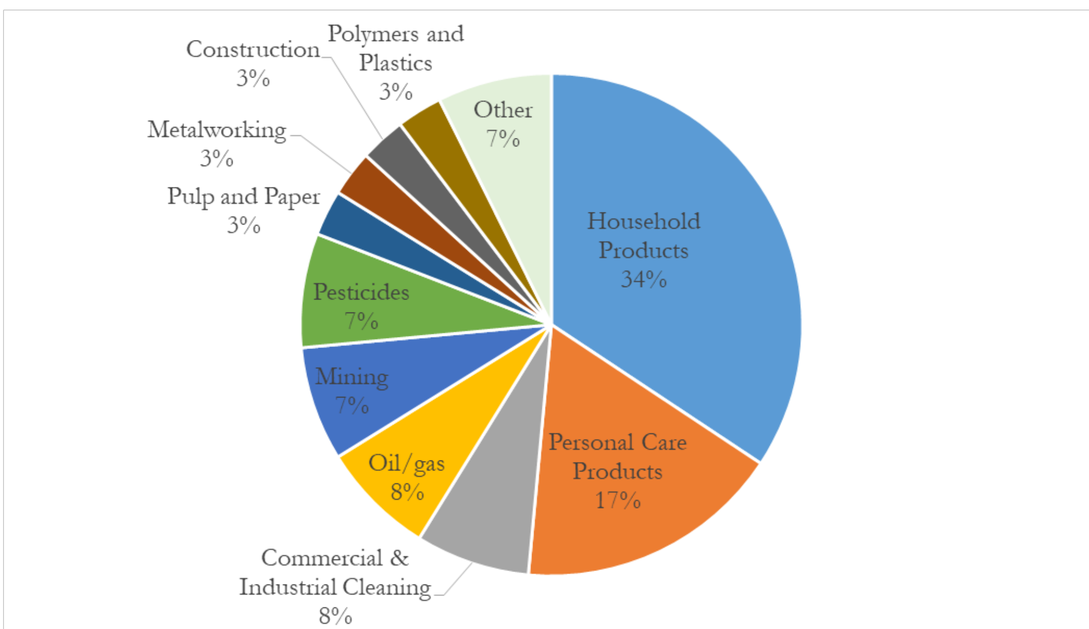

Figure 1: Estimated surfactant market segmentation in Canada in 2014 [1]

Of these household products the breakdown of surfactant use by functional use was estimated by Omni Tech to be [2]:

- Laundry detergents – 80%
- Dishwashing detergents – 10%
- Fabric Softeners – 7%
- Other – 3%

The breakdown of surfactant use in personal care products by functional use was estimated by Omni Tech to be [2]:

- Hair care – 35%
- Skin care – 20%
- Bar soaps – 20%
- Liquid soaps/body washes – 15%
- Other – 10%

In both of these industries the dominant type of surfactant used is anionic, with weight percentages ranging from 10 to 55% [2]. In the case of household detergents, nonionic surfactants make up the second largest amount of surfactant use due to their low sudsing, resistance to hard water, and ability to be combined with anionic surfactants. Nonionic surfactants have low use in personal care products due to their poor foaming abilities. Cationic surfactants are used mostly for hair conditioning or as fabric softeners, disinfectants, or sanitizers [3].

The extensive use of surfactants in down-the-drain consumer products results in high concentrations of these chemicals being delivered to wastewater treatment plants (WWTPs), so the treatment of wastewater in respect to surfactants is extremely important. When synthetic surfactants were first released in the 1940s, significant foaming began to occur in the rivers and lakes around WWTPs due to high concentrations of alkyl benzene sulfonates (ABS). This prompted scientific observation into the environmental effects of synthetic surfactants and how to properly treat them in wastewater. Since then many different institutions and agencies have been developed to properly analyze the environmental effects of surfactants including: the American Cleaning Institute® (ACI), the Council for LAB/LAS Environmental Research (CLER), the Soap and Detergent Association (SDA), and The Cosmetics Ingredients Review (CIR). They have contributed to producing research for environmental reviews for the United States Environmental Protection Agency (US EPA) and a voluntary industry program called the Human and Environmental Risk Assessment (HERA) on ingredients of household cleaning products along with detergent manufacturers. The CIR and European Chemicals Agency (ECHA) under the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation provide excellent resources for identifying chemicals of concern.

Research Methodology

To properly determine the surfactants of interest in consumer products in the Metro Vancouver area a literature review of current surfactants in use and their potential environmental impacts was first conducted. Next, site visits were conducted at local grocery stores and pharmacies to determine which products were most prevalent as determined by relative shelf space. Priority was given to high volume consumer products such as dish soap, shampoos, shower gels, conditioners, and laundry detergents based on the breakdown of home water use in the Metro Vancouver area (Figure 2). The most prevalent consumer products were included in a database, and surfactant ingredients were recorded (mainly from manufacturer websites or Safety Data Sheets) along with their designations in the European REACH registry and the US EPA Safer Chemical Ingredients List. Research was then conducted into the environmental impacts of the most common surfactants found in these consumer products along with other highly prevalent chemical ingredients.

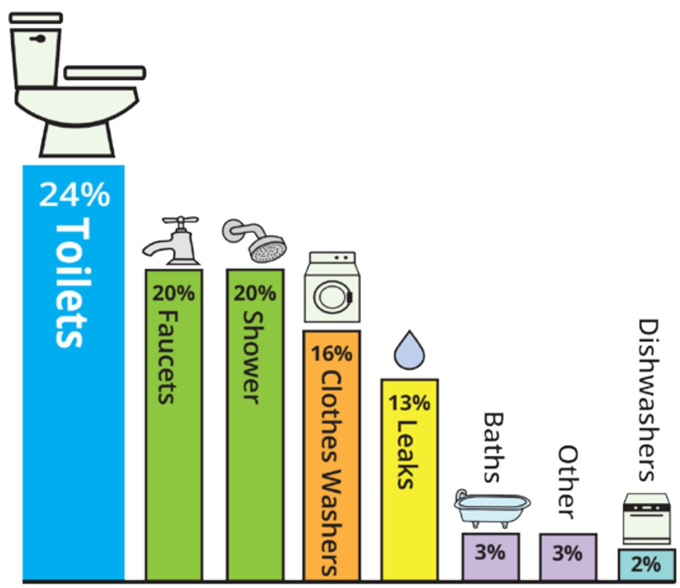

Figure 2: Water use in Metro Vancouver homes (figure from Metro Vancouver Tips to Conserve Water at Home public education campaign)

Findings

1 Anionic Surfactants

Anionic surfactants are the most commonly used surfactants in household detergents and personal care products. They are made up of a polar head which contains a negative charge and a hydrophobic tail (generally a hydrocarbon). The production of anionic surfactants accounts for about 60% of total worldwide surfactant manufacturing which results in significant amounts reaching the wastewater stream. There are many different types of anionic surfactants that are currently in use but the most widely used products include: alkylbenzene sulfonates (LAS), alkyl sulfates (AS), and alkyl ether sulphates (AES). Metro Vancouver GVS&DD Environmental Management and Quality Control reports indicate that the only wastewater samples that failed toxicity testing since 2012 have been due to the presence of anionic surfactants and have occurred at the Lions Gate WWTP. Anionic surfactants are used in the greatest quantity, so they have the highest potential impact for producing toxicity in the wastewater stream.

1.1 Linear Alkylbenzene Sulfonates

Linear alkylbenzene sulfonates (LAS) are widely used in most consumer detergents due to their low cost, excellent cleaning abilities, and high biodegradability. LAS has low compatibility with skin so it is rarely used in cosmetics, but it is the most commonly used surfactant in laundry detergents. It is generally combined with another anionic or nonionic surfactant [3]. It has been used effectively for more than 50 years and has been the focus of many different biodegradation and toxicity studies, including a full risk assessment produced by the Human and Environmental Risk Assessment (HERA) on ingredients of household cleaning products [4]. This risk assessment submitted in 2013 was conducted mainly by European researchers, and concluded that LAS is not harmful to the environment due to the high aerobic biodegradability. It is important to mention that LAS does not meet removal criteria under anaerobic digestion. LAS does have the capacity to damage the aquatic environment and fish gills when present in concentrations from 0.02 – 1.0 mg/L, so removal from the wastewater stream is important [5]. LAS also readily adsorbs to sediments in activated sludge (10 – 20%) and in sediment when discharged to the environment so it is important to periodically test sediments surrounding wastewater treatment plants (WWTPs) for LAS buildup. It has also been shown that biodegradation of LAS occurs at slower rates in saltwater and at lower temperatures.

After investigating the composition of major consumer products, it is clear that LAS is present in essentially all laundry detergent products, including single-use pods. There was significantly less LAS present in most dish soap or dishwashing detergents, however, the cheaper brands (e.g. Sunlight) seem to use significant amounts of LAS (concentrations up to 30%) as a replacement for alkyl ether sulfates and alkyl sulfates. In laundry detergents it is present at concentrations of 20 to 25% in pods and at 5 to 15% in liquid laundry detergents. It is also used in a few personal care products such as shampoos and bubble baths, but only at concentrations of 0.002 to 5%.

Methyl ester sulfonates (MES) have been gaining popularity as a replacement for LAS. MES have significantly lower environmental toxicity and are readily biodegradable under aerobic and anaerobic conditions (LAS is only biodegradable under aerobic conditions). Additionally, while LAS are produced from petro-chemicals, MES are produced from renewable plant and tallow resources [6]. Currently the major barrier for MES to replace LAS is cost driven, but as more MES plants are being built they could begin to replace LAS.

Overall, LAS is the most significant surfactant used in North America and results in the highest load on WWTPs. It is only biodegradable to around 30% with primary treatment, around 80% with trickling filter, and can be up to 99% with activated sludge or rotating biological contractor treatments [7]. In general, around 80 – 90% of LAS is biodegraded during treatment with the remaining 10 to 20% adsorbing into sludge, and around 1% being released in the effluent. In the Metro Vancouver region, this amounts to approximately 294 tonnes of LAS per year adsorbing into sludge and another 20 tonnes being released directly to the environment (Appendix A). Currently LAS use is not a major problem as it is biodegradable under the aerobic conditions being used at Metro Vancouver WWTPs, however, it could become more of an issue as population density increases. To decrease the amount of LAS reaching the environment my recommendations are to use aerobic activated sludge treatment in all facilities to ensure maximum removal, and to run a public education campaign aimed at teaching people about the benefits of reducing their use of laundry detergents. This campaign could be updated to include recommendations for using only one pod at a time or using half the amount of liquid or powder due to the high concentrations of LAS in these products. Metro Vancouver also has very soft water which does not require high amounts of laundry detergents. An additional public education campaign could be focused on educating about the benefits of using a dishwasher over hand washing dishes. Not only does this save significant amounts of water and energy, but would additionally reduce the use of LAS as these chemicals are not present in dishwasher tablets [8].

1.2 Alkyl Sulfates

Alkyl sulfates (AS) are generally used for their foaming and emulsifying qualities in both detergents and personal care products [3]. Alkyl sulfates like sodium lauryl sulfate (SLS) have also been evaluated for their environmental and human toxicological profile. Although SLS is classified as moderately toxic to aquatic life, they are considered environmentally safe due to the rapid biodegradation (>99%) under both aerobic and anaerobic conditions [9]. In the past SLS has been falsely associated with contamination by the potential carcinogen 1,4-dioxane. This is not likely as SLS is not an ethoxylated surfactant, however it is possible for cross contamination to occur through the use of common machinery. Overall, alkyl sulfates are not a significant environmental concern due to their rapid and complete biodegradation under both aerobic and anaerobic conditions. The Environment and Climate

Change Canada has also reviewed the environmental data submitted by the US CIR Expert Panel for SLS and considered it to be safe for use in consumer products.

Secondary alkane sulfonates (SAS) have also been investigated for their environmental toxicity. A risk assessment published by the HERA project has shown that these surfactants are removed primarily by aerobic biodegradation (84%) with the remaining concentration being removed by sorption to WWTP sludge [10]. The overall degradation of SAS in WWTPs utilizing activated sludge treatment systems occurred at over 99% allowing less than 1% to enter the environment. SAS was previously regarded as non-biodegradable under anaerobic conditions, but new studies have suggested that SAS can be degraded in marine sediments under anaerobic conditions after 166 days up to 98% [11].

Evaluation of consumer products has shown that alkyl sulfates are typically present in laundry detergents (especially powdered detergents) at concentrations of between 1 and 5% for powder and liquid detergents, and between 15 and 20% for laundry pods. They are also present in dish soaps at concentrations of 10 to 30%, and in person care products (shampoos, conditioners, and body washes) at concentrations of 5 to 10%. The most popular AS being SLS, which is also the surfactant of choice for toothpastes. These surfactants seem to be the surfactants of choice for higher end dish soaps, especially the eco brands like Seventh Generation, Green Works, and Mrs. Meyer's. This is likely due to the more complete biodegradation of SLS compared to LAS, and that SLS shows better skin compatibility. The average removal efficiencies for AS are very high ranging from 92% removal in trickling filter plants to up to 99% removal in activated sludge plants [7]. With usage of AS in Metro Vancouver being around 408 tonnes per year and a removal percentage of around 99%, only 4 tonnes of AS would be discharged to the environment per year (Appendix A). Additionally, AS has been shown to rapidly biodegrade under both aerobic and anaerobic conditions with a biodegradation half-life ranging from 0.3 to 1 day in surface waters, so it is unlikely that concentrations of AS would ever reach toxic levels. However, AS is still considered moderately toxic to the aquatic environment.

My recommendations for decreasing AS usage in Metro Vancouver would be an extension of a public education campaign aimed at educating people on the benefits of using a dishwasher over hand washing dishes. AS surfactants are generally contained in hand washing dish soap, but are absent from dishwasher detergents so this campaign would reduce the amounts of AS reaching WWTPs.

1.3 Alkyl Ether Sulfates

Alkyl ether sulfates like sodium lauryl ether sulfate (SLES) are the second most widely used anionic surfactant in household cleaners, dishwashing liquids, laundry care, and personal care products due to their resistance to hydrolysis [3]. They are more widely used than alkyl sulfates in laundry detergent and personal care products because they are milder to the skin and produce less foam. These surfactants are considered to be slightly less toxic to the environment than LAS and are very readily biodegradable under both aerobic and anaerobic conditions with ultimate biodegradation occurring to 98 – 99% [12]. The Canadian Department of the Environment has also reviewed the environmental data for α-olefin sulfonates (a type of alkyl ether sulfate) and considered them to be safe for use in consumer products.

Evaluation of consumer products has shown that alkyl ether sulfates are widely present in laundry detergents (liquids and pods) at concentrations ranging from 1 to 15% and in dish soaps at concentrations between 1 and 10%. They are also widely used in shampoos and body washes at concentrations between 5 and 15%. The AES surfactant of choice for consumer products is SLES. Removal efficiencies of AES from activated sludge treatment (AST) plants is generally between 98 and 99%, while the removal from trickling filter treatment (TFT) plants is around 83.5% [7]. AES are used in considerably higher quantities than AS with annual use being around 1,670 tons. At a removal efficiency of 99% this results in about 16.7 tons being released to the environment every year. However, AES are readily biodegradable under both aerobic and anaerobic conditions, as well as, quickly degrading in river water, so they are not likely to bioaccumulate. Additionally these surfactants are considered to be less toxic than LAS, so they are unlikely to cause a significant amount of environmental damage. However, since AES are ethoxylated surfactants, there is the possibility that they are contaminated with ethylene oxide (known carcinogen) and 1,4-dioxane (possible carcinogen) leftover from the ethoxylation process.

As AES are the second most used anionic surfactant, decreasing the use of AES would decrease the overall amount of anionic surfactants reaching WWTPs. My recommendation for decreasing the use of AES is centered around a public education campaign to reduce the use of laundry detergents or to only use one laundry pod as the majority of AES are used in laundry detergents. Another potential campaign could be aimed at decreasing the use of shampoos and body washes. However, I don't believe that this is fully necessary because AES are readily biodegradable and show low toxicity to aquatic organisms.

1.4 Other Anionic Surfactants

The main anionic surfactants used in household detergents and personal care products are LAS, AES, and AS, but there are a few other anionic surfactants used in consumer products. This includes fatty acid salts (soaps), alpha olefin surfactants, amino acid based surfactants, hydrotropes, and isethionic acids. Most of these surfactants are naturally based surfactants produced from coconut or palm oil, and are generally present in eco-friendly or high-end personal care products. They improve the foaming abilities of detergents and decrease skin irritation so their major use is in combination with other surfactants in products which come in contact with skin, so they are rarely seen in laundry or dish detergents [13]. These surfactants are generally considered readily biodegradable and non-toxic. Hydrotropes are known to biodegrade to approximately 87% in AST plants under aerobic conditions [14]. No data currently exists on the anaerobic biodegradation of hydrotropes, but their toxicity is quite low so bioaccumulation is unlikely.

Of this group only alpha olefins are known to not biodegrade under anaerobic conditions. In documents submitted under the REACH registration dossier for alpha olefin sulfonates, they are shown to biodegrade to over 99% after 28 days under aerobic conditions. While they are not biodegradable under anaerobic conditions, due to their rapid biodegradation under aerobic conditions bioaccumulation is not expected to occur. Although, the toxicity of alpha olefins is slightly higher than alkyl sulfates, their use is far less widespread than AS so Environment and Climate Change Canada has classified these surfactants as safe for use.

These surfactants are generally naturally derived and readily biodegradable. Additionally, they are used to far less of an extent than LAS, AS, and AES. My recommendation for the public education campaigns mentioned previously could have some effect on decreasing the overall amounts of anionic surfactants reaching the wastewater stream, but I think it is important to mainly focus on products containing LAS because it is reaching the wastewater stream in the largest amounts and is likely the biggest contributor to toxicity caused by anionic surfactants.

Surfactant	Approximate Usage in Metro Vancouver area	Concentration	Uses
Linear alkylbenzene sulfonates	1,960 tonnes/year	Dish soap: 30% Liquid laundry: 5-15% Laundry pods: 20-25%	Mainly laundry detergents with some use in dish soaps
Alkyl sulfates	408 tonnes/year	Dish soap: 10-30% Powder laundry: 1-5% Liquid laundry: 1-5% Laundry pods: 15-20% Personal care products: 5-10%	Present in majority of dish soaps, laundry detergents, and personal care products
Alkyl ether sulfates	1,670 tonnes/year	Dish soap: 1-10% Liquid laundry: 1-15% Laundry pods: 1-15% Shampoo/body wash: 5-15%	Present in majority of laundry detergents and is surfactant of choice in shampoos and body washes
Alpha olefin sulfonates	149 tonnes/year	Shampoos: 1-10%	Mainly used in shampoos and body creams
Hydrotropes	No data available	Dish soap: 3-5%	Used mainly in dish soaps, shampoos, and body washes

2 Nonionic Surfactants

The second major class of surfactants are nonionic surfactants. They are identified by their polar head which does not hold an electrical charge, which includes functional groups like alcohols, phenols, esters, ethers, or amides. These surfactants are most commonly used in household detergents and personal care products in combination with anionic surfactants because of their resistance to calcium and magnesium ions in hard water and their decreased foaming. Nonionic surfactants have received a significant amount of attention in the last 30 years since the discovery that the nonionic surfactants nonylphenol ethoxylate and octylphenol ethoxylate are toxic to aquatic organisms, and that their biodegradation products are significantly more persistent in the environment and act as estrogen mimics [15]. This research resulted in many countries designating these products as "toxic" and significantly limiting their use. The most commonly used nonionic surfactants include: alcohol ethoxylates (AE), alkylphenol ethoxylates (APEO), fatty alcohol ethoxylates (FAE), and alkyl polyglucosides (APG).

2.1 Alcohol Ethoxylates

Alcohol ethoxylates (AE) and fatty alcohol ethoxylates (FAE) are the most commonly used nonionic surfactants in North American consumer products [16]. The main use for these surfactants is in laundry detergents, with lesser use in household cleaners and personal care products. AE surfactants biodegrade rapidly under aerobic conditions and slower under anaerobic conditions. However, biodegradation of over 80% can still be achieved in anaerobic conditions after four weeks [7]. Removal of AE is accomplished at over 99% after treatment with activated sludge. AEs can be quite toxic to aquatic organisms, but because AE are highly biodegradable and aquatic organisms can metabolize AE, they are considered safe for use. FAE have also been evaluated for their biodegradation and toxicity, and have shown comparable results to AE. FAE also show a lower amount of bioaccumulation than AE due to their low solubility, so they are also considered safe for use [17].

Evaluation of consumer products has shown that AE are the only surfactant used in dishwasher detergent pods at concentrations of 5 to 10%. Dishwasher detergents utilize enzymes rather than anionic surfactants to remove food and grease from dishes. AE have been shown to degrade to over 99% in activated sludge, trickling filter, oxidation ditch, lagoon, and rotating biological contractor plants [7]. However, with primary treatment alone only 18 to 20% of AE are removed from the wastewater stream. These nonionic surfactants are biodegradable under aerobic and anaerobic conditions, have a much lower foaming ability, and lower toxicity than the majority of anionic surfactants used in hand dishwashing soap. Due to the added efficiency of automatic dishwashers, it is also possible to use less overall surfactants than hand dishwashing. AE are also present in essentially all laundry detergents as the nonionic surfactant of choice at concentrations of 10 to 20% in laundry pods and 1 to 10% in liquids, and are used in a few shampoo or conditioner products. While AE are the most widely used nonionic surfactant, the estimated use in consumer products in the Metro Vancouver region is around 1,200 tons per year. At an average removal efficiency of 99% that leaves around 12 tons per year reaching the environment (Appendix A).

Concerning the use of AE, I recommend that some form of secondary treatment is necessary for removal from the wastewater stream. Additionally, I recommend that public education campaigns should be implemented detailing the benefits of using an automatic dishwasher over hand washing dishes, and decreasing the amounts of laundry detergents used. Because AE are present at higher levels in laundry detergents than in dishwasher detergents, overall amounts of AE reaching the wastewater stream would be decreased.

2.2 Alkyl Phenol Ethoxylates

Alkyl phenol ethoxylates (APEO) such as nonylphenol ethoxylate (NPEO) and octylphenol ethoxylate (OPEO) have received significant attention due to their high toxicity and estrogen-like qualities of their metabolites. During biodegradation NPEO and OPEO break down to nonylphenol (NP) and octylphenol (OP) respectively. These degradation products are significantly more environmentally persistent than NPEO or OPEO and show endocrine disrupting characteristics. Due to the high toxicity of these products their use is highly regulated and they have been banned in several European countries and Canada [18]. Many manufacturing companies and governing bodies have come together to mostly phase out the use of APEO in consumer detergents. However, these regulations do not apply to commercial laundry detergents. A 96% reduction in the use of these chemicals has been observed since Canada placed NPEO and NP on the list of toxic substances in 2002 [19]. While the United States has no direct regulations around the use of NP and NPEO, the US EPA proposed a Significant New Use Rule (SNUR) in 2014 which would require manufacturers to obtain permission from the agency to begin or resume production of NP or NPEO. No additional regulations were implemented around the use of NP or NPEO in the US, but manufactures participated in a voluntary phase-out of these chemicals so they are rarely found in consumer products. During the investigation of the surfactants contained in consumer products in the Metro Vancouver region, not a single product was found to contain NP, NPEO, OP, or OPEO.

2.3 Alkyl Polyglucosides

Alkyl polyglucosides (APG) are an emerging type of surfactant produced from starch or sugars and fatty alcohols. They exhibit good foaming properties and skin tolerance. Their main uses include dishwashing and laundry detergents and mild personal care products [18]. They have been shown to be readily biodegradable under aerobic conditions, although degradation under anaerobic conditions only occurs to 40% [20]. Toxicity of APG is slightly lower than AE, and due to the rapid biodegradation under aerobic conditions these surfactants are considered safe.

Investigation of consumer products has revealed that APG are used almost exclusively in eco-friendly brands of products which require high foaming capabilities like dish soaps (e.g. Seventh Generation and Green Works) and shampoos (e.g. Live Clean). Usual concentrations of APG in products ranges from 1 to 7%. They are produced mostly from plant-derived starches and fats, and considered safe for sensitive skin. Due to their rapid biodegradation, limited usage, and very low toxicity they are not likely to cause bioaccumulation or environmental toxicity.

Surfactant	Approximate Usage in Metro Vancouver area	Concentration	Uses
Alcohol ethoxylates	1,200 tonnes/year	Dishwasher pods: 5-10% Liquid laundry: 1-10% Laundry pods: 10-20%	Nonionic surfactant of choice for dishwasher and laundry detergents
Alkyl phenol ethoxylates	Toxic substance banned in consumer products	Banned in consumer products	Was previously the nonionic surfactant of choice in laundry detergents, still allowed in commercial laundry detergents
Alkyl polyglucosides	No data available	Dish soap: 1-7%	Used as the major eco-friendly surfactant in dish soap and shampoo

3 Cationic Surfactants

Cationic surfactants are identified by their polar head which holds a positive charge. They are produced in far smaller amounts than anionic or nonionic surfactants due to their high cost. Their main use is as broad spectrum biocides and antistatic agents due to their ability to adsorb to negatively charged surfaces like glass, hair, fibers, metals, and plastics. They mainly consist of nitrogenated compounds like quaternary ammonium compounds (QACs) and esterquats, and their main applications are as hair-conditioning shampoos, conditioners, disinfectants, sanitizers, and fabric softeners [3]. Cationic surfactants tend to be more ecotoxic than anionic or nonionic surfactants, and cannot be combined with anionic surfactants due to the formation of insoluble complexes. Total Canadian imports of cationic surfactants would result in 330 tonnes per year usage in the Metro Vancouver area, but actual usage in down-the-drain products is significantly less.

3.1 Quaternary Ammonium Compounds

Quaternary ammonium compounds (QAC) are the dominant form of cationic surfactants used in hair conditioners. Their positive charge allows them to quickly adsorb to negatively charged sewage sludge, soil, and sediments. They are considered to be readily biodegradable in aerobic activated sludge WWTPs with potential removal rates above 90%. However, biodegradation is significantly hampered by the adsorption of QAC which often exceeds biodegradation. For this reason concentrations of QAC in activated sludge should be closely monitored. These surfactants are considered antimicrobial and could negatively affect organisms present in WWTPs due to their resistance to the denitrification process. QAC also do not degrade under anaerobic digestion due to inhibition of methanogenesis, and at high concentrations they can decrease COD removal efficiency [21]. These cationic surfactants are also considered toxic to both aquatic and terrestrial organisms. Additionally, QAC have been shown to decrease fertility in mice [22]. While QAC only account for a small amount of overall surfactant use and biodegrade in aerobic conditions, they are the most toxic surfactants. Therefore, QAC use and removal from wastewater needs to be carefully monitored.

QAC are the dominant surfactant used in hair conditioners in consumer products in the Metro Vancouver region. They are generally present in these products at concentrations between 1 and 5%. The most popular QACs currently in use are: behentrimonium chloride, behentrimonium methosulfate, cetrimonium chloride, and dicetyldimonium chloride. These surfactants mainly feature a quaternary nitrogen group connected to a long hydrocarbon tail, the difference being the choice of salt to neutralize the nitrogen group. Studies submitted in the REACH dossier for QAC with chloride or methosulfate salts show that biodegradation is possible up to 80% after 28 days in an AST reactor under aerobic conditions. However, they are not degradable under anaerobic conditions and can even inhibit degradation under anaerobic conditions due to their biocidal effects. While these surfactants are significantly toxic to the environment and do not biodegrade to the extent of most other surfactants, significantly smaller quantities of cationic surfactants are used compared to anionic or nonionic surfactants. Additionally, cationic surfactants used in hair conditioners are positively charged and quickly adsorb onto hair proteins and don't completely wash out, resulting in even less of these chemicals reaching the wastewater stream.

While these surfactants have the most potential for environmental harm, the quantity of them reaching the wastewater stream is significantly less than that of anionic or nonionic surfactants, so they are unlikely to cause significant environmental damage. My recommendation for decreasing the amount of these surfactants reaching WWTPs is to include hair conditioners in a public education campaign aimed at decreasing overall use of surfactants in personal care products (hair conditioners, shampoos, body washes).

3.2 Esterquats

Esterquats consist of quaternary ammonium salts with ester links in the hydrophilic moiety of the molecules [23]. The most common esterquats used commercially are triethanol amine quat (TEAQ), diethyloxyester dimethylammonium chloride (DEEDMAC), and Hamburg Esterquat (HEQ) [24]. Like QAC, esterquats are positively charged surfactants and largely adsorb to negatively charged sewage sludge, soil, and sediments. Esterquats are also readily biodegradable in aerobic systems ranging from 60 to 100%. Unlike QAC, esterquats are also biodegradable in anaerobic systems allowing for higher removal percentages. Biodegradation of esterquats has also been evaluated in the soil compartment via agricultural use of digester sludge and the half-life has been determined to be 18 days. Esterquats are not as environmentally toxic as QAC and combined with their ability to readily biodegrade under aerobic and anaerobic conditions, they are considered safe for use [24].

The QAC ditallow dimethyl ammonium chloride (DTDMAC) was the primary cationic surfactant used in fabric softeners until research was published in the 1990s showing that this chemical did not biodegrade at all and was causing significant environmental damage. When this work was published it sparked a voluntary phase-out of DTDMAC in Europe which extended into North America in favor of esterquats. Now the majority of surfactants used in fabric softeners are esterquats, specifically diethyl ester dimethyl ammonium chloride, at concentrations between 5 and 10%. These surfactants are readily biodegradable and significantly less toxic to the aquatic environment than QAC. My recommendation is that these products are safe to use and should be encouraged over QAC as they are not very toxic and are quickly broken down in the wastewater stream.

Surfactant	Approximate Usage in Metro Vancouver area	Concentration	Uses
Quaternary ammonium compounds	No data available	Hair conditioner: 1-5%	Almost exclusively hair conditioners
Esterquats	No data available	Fabric softener: 5-10%	Almost exclusively fabric softeners

4 Amphoteric Surfactants

Amphoteric surfactants contain both positive and negative charges in their polar head, and are capable of switching overall charge based on the pH of their surroundings. The cationic portion of the head is generally comprised of an amine containing compound while the anionic portion can include sulfonates, carboxylates, or other oxygen containing compounds. Amphoteric surfactants generally show excellent resistance to Mg and Ca ions present in hard water, impart viscosity to a solution, and are skin compatible [3]. The main amphoteric surfactants in commercial use are amine oxides (AO) and betaines. These surfactants tend to be almost as ecotoxic as cationic surfactants, but also tend to be much more biodegradable.

4.1 Amine Oxides

Amine oxide (AO) surfactants are sometimes classified as nonionic surfactants although they exhibit both nonionic and cationic properties depending on pH. They are classified as high production volume chemicals and have been investigated for their environmental safety. These surfactants are generally used in combination with anionic surfactants in formulations for shampoos, detergents, and antistatic preparations [3]. AO toxicity for aquatic organisms varies considerably among different organisms, but in general these surfactants are classified as quite toxic to the aquatic environment [18]. However, AO surfactants are very readily biodegradable under both aerobic and anaerobic conditions with ultimate degradation up to 99% [25]. Under anaerobic conditions the naturally derived AO can be biodegraded, but the synthetically produced AOs show very little degradation [26]. One relevant contribution to the removal of AO is "pipe-loss" (degradation of AO before WWTP treatment). Significant degradation of AO (up to 98%) has seen in pipe-loss studies in the US and Netherlands although it is difficult to directly calculate [25]. Although AO exhibits high aquatic toxicity, due to the rapid degradation of these chemicals under aerobic, anaerobic, and in environmental conditions this surfactant is considered safe for use.

AO are present in a significant number of consumer products sold in the Metro Vancouver region. They are used in many brands of dish soaps (1 to 10%), laundry detergents (1 to 10%), and personal care products like shampoos, conditions, and body washes (1 to 5%). The most common AO used are lauramine oxides, stearamidopropyl dimethylamine, and cocamide salts (generally monoethanolamine). They are far more prevalent in personal care products than in detergents, although their concentration in personal care products is lower than in detergents. These surfactants are used in significantly lower quantities than anionic or nonionic surfactants, and data presented in the REACH registration dossier show that they are readily biodegradable at an average of 95.2% in activated sludge treatment (AST) reactors. Additionally, bioaccumulation is not expected for these surfactants. Cocamide MEA seems to be the AO of choice for the eco-friendly and high-end brands of shampoos, while synthetic AO tend to be present in hair conditioners, laundry detergents, and dish soap. Cocamide MEA is derived from coconut oil and has been show to readily biodegrade under anaerobic and aerobic conditions, while synthetic AO only biodegrade under aerobic conditions.

While these surfactants are slightly ecotoxic, they are used in low overall amounts and are readily biodegradable. My recommendation for decreasing the discharge of these surfactants from WWTPs to the environment is advising AST at all surrounding WWTPs. A public education campaign aimed at decreasing the use of laundry detergents and the benefits of using an automatic dishwasher over hand washing dishes would decrease the amounts of synthetic AO reaching the wastewater stream. My additional recommendation for decreasing the amounts of synthetic AO reaching WWTPs is including hair conditioners in a public education campaign aimed at decreasing the use of down-the-drain personal care products.

4.2 Betaines

Betaine based surfactants like cocamidopropyl betaine (CAPB) are used as mild surfactants in a range of personal care products (including baby shampoos) and cosmetics because they are inherently mild to the skin and eyes and show strong anti-irritant properties when combined with anionic surfactants [23]. The CAPB surfactants are derived from coconut oil and are compatible with both anionic and cationic surfactants. These surfactants exhibit slight toxicity to aquatic organisms with the alkyl imidazoline derivatives exhibiting the least amount of toxicity [27]. However, these surfactants are very readily biodegradable under both aerobic and anaerobic conditions, so they are considered safe for use.

CAPB is used along with an anionic surfactant as the major amphoteric surfactant in shampoos and body washes in the Metro Vancouver region at concentrations between 1 and 5%. It is present in essentially every shampoo and body wash included in this study. While CAPB is considered moderately toxic to aquatic life, it readily biodegrades under both aerobic and anaerobic conditions [27]. Based on the low overall concentrations of CAPB in products and the high levels of biodegradation under aerobic and anaerobic conditions I recommend the CAPB does not need to be prioritized for targeted source control initiatives aimed at decreasing surfactant use. My recommendation for the implementation of a public education campaign aimed at decreasing the use of personal care products like shampoos, hair conditioners, and body washes would also decrease the overall amount of CAPB reaching WWTPs, although it is not a priority.

Surfactant	Approximate Usage in Metro Vancouver area	Concentration	Uses
Amine oxides	No data available	Dish soap: 1-10% Liquid laundry: 1-10% Laundry pods: 10-15% Personal care products: 1-5%	Used as amphoteric surfactant of choice in many different products, primarily cleaning products
Betaines	No data available	Shampoo/body wash: 1-5%	Used as the amphoteric surfactant of choice in shampoos and body washes

5 Other Chemicals of Interest

While surfactants are the major component of household detergents and personal care products, these products also contain many other chemicals that also end up in WWTPs and are potentially more hazardous to the environment. The main chemicals of interest due to ecological toxicity include: formaldehyde releasing preservatives, ethylenediaminetetraacetic acid (EDTA), parabens, optical brighteners, and triclosan.

5.1 Formaldehyde Releasing Preservatives

Certain preservatives present in personal care products like shampoos, body washes, and hair conditioners constantly release small amounts of formaldehyde (a known carcinogen). These chemicals usually include: quaternium-15, imidazolidinyl urea, diazolidinyl urea, polyoxymethylene urea, sodium hydroxymethylglycinate, and DMDM hydantoin [28]. Reviewing personal care products available to consumers in the Metro Vancouver region has shown that DMDM hydantoin is the most commonly used formaldehyde releasing preservative present in these products. DMDM hydantoin classifies as moderately toxic to the aquatic environment, however, it readily biodegrades in an AST reactor under aerobic conditions up to 95% after 28 days [29]. Although formaldehyde is considered a human carcinogen, the amounts released from these products are so small that they are very unlikely to cause any damage. Additionally, due to the high biodegradability of these chemicals it is unlikely that they would result in any bioaccumulation. My recommendations are that these chemicals are not a priority for targeted source control initiatives as these preservatives and are unlikely to cause any environmental harm if WWTPs are operated with activated sludge treatment.

5.2 EDTA

Ethylenediaminetetraacetic acid (EDTA) is generally used to sequester metal ions, and is used in detergents and personal care products mainly to improve their stability in air. Four main substances are classified under EDTA and were evaluated by Environment and Climate Change Canada as priorities for assessment. These chemicals includes ethylene diaminetetraacetic (EDTA) or edetic acid, tetrasodium EDTA, ferric monosodium EDTA, and ferric ammonium EDTA. The most commonly used chemical in this group being tetrasodium EDTA. Data presented in the REACH final registration dossier for EDTA shows that in activated sludge treatment under neutral to acidic pH EDTA degrades very slowly or not at all, while at higher pH it degrades to over 80%. EDTA is not expected to adsorb onto sludge so it is important to monitor the amounts of EDTA in the effluent as 100% will be released to the environment if it is not degraded. Additionally, EDTA is not biodegradable under anaerobic conditions. However, the final risk assessment for EDTA published by Environment Canada in May 2018 classified EDTA as low risk to the environment, and will not include it under CEPA as these chemicals are not entering the environment in significant amounts.

My recommendations for decreasing the amount of EDTA reaching the environment is to run activated sludge treatments at higher pH (around 8 or 9) if possible, and to closely monitor effluent for EDTA concentrations. Additionally, public awareness campaigns aimed at reducing the amount of laundry detergents and personal care products (shampoos, conditioners, body washes) used would also greatly contribute to decreasing the amount of EDTA reaching the environment.

5.3 Parabens

Parabens are chemicals present in significant numbers of personal care products (max 0.4% each or 0.8% in combination) and pharmaceutical products (max 1%) for their preservative and antimicrobial qualities. These chemicals have been receiving a lot of attention recently due to their potential link to breast cancer and potential classification as endocrine disruptors. The European Scientific Committee on Consumer Safety (SCCS) has classified propylparaben, butylparaben, methylparaben, and ethylparaben as safe for use in low levels. However, they have banned the use of isopropylparaben, isobutylparaben, phenylparaben, benzylparaben and pentylparaben. Due to the wide-spread use of parabens in consumer products their release to the environment is constant. Removal efficiencies of around 90% are seen at most WWTPs practicing activated sludge treatment, however, parabens are always found in effluent and have been detected in surface waters and swimming pools [30]. Additionally, parabens can react with chlorine in aquatic environments to form chlorinated parabens which could be more persistent in the environment. Parabens have been listed on Canada's priority substances, but currently no regulations have been made around the use of these chemicals in Canada.

However, significant numbers of manufacturers have begun to label their products as paraben-free, so voluntary removal of parabens may already be occurring.

Parabens seem to be weak endocrine disruptors, and have already seen regulations surrounding their use in Europe. While manufacturers are starting to voluntarily decrease the use of parabens in commercial products, my recommendations is to carefully monitor paraben concentration in WWTP effluents. I think including a short excerpt about the dangers of parabens to human health and the environment should be added to a public education campaign aimed at decreasing the amounts of personal care products (shampoos, conditioners, body washes) used in the Metro Vancouver area.

5.4 Optical Brighteners

Optical brightening agents are common additives in Canadian liquid laundry detergents (at a concentration of 0.80%) and powdered laundry detergents (0.067 – 0.54%), generally without the actual chemical name listed under the ingredients. The most commonly used optical brighteners are part of a chemical family called stilbenes. They are a class of chemicals which absorb ultraviolet light and re-emit light in the blue region which makes washed clothes appear cleaner. A report on the safety of two major stilbenes was released by Environment and Climate Change Canada along with Health Canada in September 2017 which details the human and environmental risks associated with these chemicals. They found that the Fluorescent Brightener FWA-1 was being imported into Canada at 42,344 kg per year and C.I. Fluorescent Brightener 28, disodium salt was being imported at 10,000 to 100,000 kg per year, however recent commercial changes have resulted in a decrease in imports of this chemical. Both Fluorescent Brightener FWA-1 and C.I. Fluorescent Brightener 28, disodium salt were found to have moderate ecological risks and long overall persistence in the environment. However, it was determined that these chemicals are not reaching the environment in large enough levels to be of high concern. A study conducted by the Swiss Federal Institute of Technology found that in WWTPs up to 85% of FWA-1 adsorbs onto sludge. Additionally, lake monitoring has shown that FWA-1 is broken down by photolysis up to 50% and each 25% adsorption and flushing over a period of 12 months with no observed bioaccumulation.

While these chemicals do not rapidly biodegrade in the environment and are moderately toxic to aquatic life, they have not been classified as a high risk to human health or the environment. My recommendation for decreasing the amounts of these chemicals being discharged to the environment is close monitoring of stilbene concentrations in WWTP effluent to ensure significant amounts are not being discharged to the environment. Additionally, a public education campaign aimed at decreasing the amounts of laundry detergent used in the Metro Vancouver area would also decrease the amounts of these chemicals reaching WWTPs and the environment.

5.5 Triclosan

Triclosan (5-chloro-2-(2,4-dichlorophenoxy)) is an antimicrobial found in some antiseptic consumer detergents and personal care products. Triclosan was banned in the European Union in 2015 and in September 2016 the FDA issued a final rule which found that products containing triclosan were no more effective antimicrobials than the soaps alone. Canada added triclosan to Schedule 1 under CEPA in July 2018, but has only restricted the allowable concentrations of triclosan in consumer products to 0.03% in mouthwashes, 1.0% in non-prescription drugs, and 0.3% in cosmetics and natural health products. Triclosan has been shown to be a weak endocrine disruptor and is very persistent in the environment which poses a significant environmental threat. Data submitted under the REACH registration dossier for triclosan indicates that it will settle into sediment and only degrade up to 78% after 104 days, and will inhibit respiration in activated sludge at concentrations of 11 mg/L or higher. Other studies have shown triclosan removal from WWTPs of around 95% in activated sludge plants, but only 50 to 80% removal in trickling filter plants [31]. It is also not biodegradable under anaerobic conditions. Concerns have also been raised about the potential for the use of triclosan to propagate drug-resistant bacteria, however, the Canadian risk assessment found no clear link between triclosan and increased antimicrobial resistance. Triclosan is classified as toxic to aquatic bacteria, highly toxic to aquatic algae, and has a high potential for bioaccumulation when converted to methyl-triclosan.

While many manufacturers have voluntarily removed triclosan from their formulations, my recommendation is that Metro Vancouver should lobby the federal government to follow the US in banning triclosan in consumer antiseptic products. Consumer products must already indicate if they contain triclosan, but I recommend an additional public awareness campaign on the dangers of triclosan including associated actions such as avoiding the use of these products, and the high probability of environmental damage associated with the use of this chemical.

Conclusions and Recommendations

Overall the majority of surfactants currently in consumer products seem to be safe for use and discharge to the environment after treatment at a WWTP using an aerobic activated sludge system. For the majority of the surfactants primary treatment is not enough to degrade or remove them from the system and aerobic secondary systems must be used. Anionic surfactants make up the majority of the market (although current and reliable market data is difficult to obtain) with LAS and AES being used in the largest amounts. LAS are readily biodegradable under aerobic conditions, but do not degrade under anaerobic conditions so they can persist among sediment and anoxic compartments. Additionally, LAS easily adsorbs onto sediment and can persist in this manner so it is important to occasionally test sediment surrounding WWTPs for LAS buildup. All other anionic surfactants discussed in this review seem to be acceptable for use due to their rapid biodegradation.

Nonionic surfactants of the past (NPEO and OPEO) were of extreme environmental concern due to their degradation into endocrine disrupting compounds (NP and OP). Due to regulations imposed by many countries (including Canada) and voluntary discontinuation by manufacturers these compounds are no longer present in consumer products in North America, however, they are still available in commercial detergents. The replacements for these chemicals (alcohol ethoxylates) are still toxic to aquatic species, but readily biodegrade under both aerobic and anaerobic conditions so they likely do not pose a threat to the environment.

Cationic surfactants, especially QAC, appear to be of the most concern for environmental considerations. They are highly toxic to aquatic organisms and quickly adsorb to sediments and WWTP sludge which inhibits biodegradation. These surfactants make up the smallest market share of surfactants so the environmental concern is not extremely high, but their use should be monitored. They are mainly present in personal care products like shampoos and conditioners, but have been replaced by esterquats in fabric softeners which are more readily biodegradable.

The amphoteric surfactant AO seems to be one of the more toxic surfactants currently in use, although they biodegrade very quickly and almost completely. The exposure of these surfactants is still a concern depending on relative amounts being discharged to the environment. The major amphoteric surfactant of use in combination with anionic surfactants in personal care products is CAPB. CAPB is moderately toxic to aquatic organisms, but readily biodegrades under both aerobic and anaerobic conditions so it is unlikely to cause environmental harm.

The current use of surfactants in personal care products and household detergents seems to be fairly environmentally conscious. The majority of surfactants in use are classified as moderately toxic to aquatic organisms, but are readily biodegradable to over 90%. The major areas of concern and where further research should be conducted include: the removal efficiencies and accumulation of LAS in sediment, the use of QAC surfactants and relative amounts reaching WWTPs, and the overall amounts of AO being discharged to the environment.

The current preservatives of use in consumer detergents and personal care products seem to follow the same pattern as the surfactants. The formaldehyde releasing preservatives and EDTA are moderately toxic to aquatic organisms but are readily biodegradable under the correct conditions. The major areas of concern are in the use of parabens, optical brighteners, and triclosan. Parabens are weak endocrine disruptors and have been classified as safe for use in Canada and the US, while specific parabens have been banned or regulated by the European Union. However, the major parabens being used in commercial products (methylparaben and propylparaben) are considered safe for use in Canada, the US, and the EU. Optical brighteners, while considered persistent and moderately toxic, are still considered safe for use by Canada which could potentially cause environmental damage if use increases. By far the largest area of concern is the use of triclosan in consumer products. It is very persistent in the environment, is highly toxic to aquatic organisms, and is classified as a weak endocrine disruptor. The US has banned its use in antiseptic soaps and detergents, while Canada has only specified allowable concentrations in personal care products and detergents.

My first recommendation for decreasing the use of surfactants and other harmful chemicals in personal care products and household detergents is that Metro Vancouver should lobby the federal government to follow the US in banning the use of triclosan in antiseptic products. Metro Vancouver does not have the authority to ban these products, but would have to lobby the federal government. There is no significant evidence that suggests that triclosan-containing products are significantly more effective than soaps and detergents alone. Additionally, the environmental damage caused by triclosan is cause enough to restrict its use in antiseptic formulations. My recommendations for methods to decrease the overall load of surfactants and other harmful chemicals from reaching the environment are threefold:

Education: My first recommendation is that a public education campaign should be conducted similarly to the one in the early 2000s aimed at decreasing the amount of laundry detergents reaching the Lions Gate WWTP. This new public education campaign should include advising people to use less laundry detergents, or only one laundry pod at a time due to the high concentrations of surfactants contained in the pods and the fact that Metro Vancouver has very soft water. This section of the campaign could also include the dangers of optical brighteners which are often present in laundry detergents. The next section of the public education campaign should include decreasing the current use of personal care products with a specific focus on hair conditioners. The final section of this campaign should include the benefits of using an automatic dishwasher over hand washing dishes. Automatic dishwashing pods contain far less harmful chemicals than hand dishwashing soaps, and automatic dishwashers are now significantly more efficient than hand washing which saves water and energy. This campaign would decrease the overall amount of surfactants reaching the Metro Vancouver WWTPs.

Treatment: Overall, the surfactants and other chemicals discussed in this study cannot be fully removed by primary treatment. Some form of secondary treatment is necessary to fully remove the majority of these chemicals from the wastewater stream. My recommendation is that all plants in the Metro Vancouver area utilize activated sludge treatment as their secondary treatment option because this method is the most effective option for treatment of the contaminants discussed in this study. Additionally, for the removal of ethylenediaminetetraacetic acid (EDTA) it is important to run activated sludge treatment at higher pH (around 9) to ensure complete biodegradation.

Ongoing Monitoring: One of the major removal methods of these surfactants and other chemicals in WWTPs is adsorption onto sludge present in the reactor or sediment in surrounding discharge areas. It is important to continually monitor these areas for buildup of these chemicals as they can cause environmental damage if high concentrations are reached. Specific attention should be given to linear alkylbenzene sulfonates (LAS) in both sludge and surrounding sediment as it reaches the environment in fairly high quantities due to its extensive use in consumer detergents. LAS is known to adsorb onto sediment surrounding discharge areas and degrades slowly at low temperatures and in salt water. Ongoing monitoring should be conducted to ensure proper removal of LAS. Quaternary ammonium compounds (QAC), ethylenediaminetetraacetic acid (EDTA), parabens, stilbenes, and triclosan should be continuously monitored mainly in treatment sludge as they can adsorb at very high levels. It is very important to conduct extensive monitoring to ensure that treatment methods are working adequately and large amounts of chemicals are not being discharged to the environment.

While these surfactants are not currently a huge problem, as population density increases in Metro Vancouver more of these chemicals will enter the wastewater system, and potentially reach the environment where they can cause toxicity. The source controls outlined in this study should help to ensure that extensive environmental damage does occur due to the use of these chemicals.

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Appendix A

All current surfactants in use in the Metro Vancouver area are based off the attached excel sheet: Database of Surfactants in Consumer Detergents and Personal Care Products.

Calculations:

Table 1: Per capita use (g/cap/d) of surfactants in North America [7]

Parameter	Alcohol Ethoxylates	Alkyl Sulfates	Alkyl Ether Sulfates	Linear Alkylbenzene Sulfates
Per capita use (g/cap/d)	1.35	0.454	1.86	2.18
Metro Vancouver Use (tonnes per year)	1,213.86	408.22	1,672.42	1,960.15
Discharged to Environment (tonnes)	1% (12.14)	1% (4.1)	1% (16.7)	1% (19.6)

Metro Vancouver population (2016 census): 2,463,431

$$Surfactat\ use = Per\ capita\ use\ \left(\frac{g}{cap * d}\right) * population(cap) * 365d$$