APPENDIX C

FINAL REPORT

Biosolids Land Application – An Updated Review of Human Health and Environmental Risks

Version 2.0

December 12, 2024

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1 Introduction

Municipal wastewater treatment yields two primary byproducts: treated wastewater and solid residue, or biosolids. Soil application of biosolids as an organic fertilizer is economic way to beneficially use the carbon and nutrient contents in biosolids to promote soil fertility. A substantial body of research has explored the risks and benefits associated with the land application of biosolids, including numerous studies focused on contaminants, including heavy metals, pathogens, and contaminants of emerging concern (COECs) (Hydromantis Inc., 2010; McCarthy et al., 2015; LRCS Land Resource Consulting Services, 2016; Pozzebon and Seifert, 2023; BC ENV 2024).

There are many benefits associated with the land application of biosolids. Benefits include the addition or organic matter to soil and the associated increase in soil water retention and reduction in soil erosion, as well as the addition of essential nutrients for plant growth. Biosolids can provide a natural alternative to synthetic fertilizers and can store carbon in soil and reduce greenhouse gas emissions (LRCS Land Resource Consulting Services, 2016' BC ENV, 2024). These benefits have been well documented by others and are not the focus of this review. The objective of this report is to build on previous literature reviews assessing potential human health and environmental risks through a comprehensive scan of the recent primary scientific literature and other relevant studies.

As background, the British Columbia Organic Matter Recycling Regulation (OMRR) (available at https://www.bclaws.gov.bc.ca/OMRR) provides a regulatory framework for the production, quality, and application of organic matter products, including biosolids. Its purpose is to ensure that biosolids and other organic materials are used in a way that protects human health and the environment while promoting sustainable resource use. The OMRR was developed based on a review of the available scientific literature in the late 1990s and implemented in 2002. The OMRR has undergone several regulatory reviews, with additional amendments proposed which are noted to include provisions to enable the BC Ministry of Environment and Climate Change Strategy to require sampling and analysis for COECs (BC ENV, 2024). Currently, while the OMRR includes requirements for vector (i.e., rodents, birds and insects) attraction reduction processes, and limits for pathogens and heavy metals, the regulation does not include limits for several key COECs including per- and polyfluroalkyl substances (PFAS), pharmaceuticals and personal care products (PPCPs), and microplastics. While it is acknowledged that the derivation of limits for some of the COECs is complicated by the limited available toxicological data, the importance of recommending limits based on the best available science is essential for the protection of human health and the environment.

In response to concerns over the land application of biosolids, the BC government has convened two technical working groups (TWGs), one in 2015 and a second in 2022, to review scientific information on biosolids production and waste management practices. A summary of the findings of the reports produced by the two TWGs follows.

The findings of the 2015 Technical Working Group were presented in the report titled *A literature review of risks relevant to the use of biosolids and compost from biosolids with relevance to the Nicola Valley, BC* (LRCS Land Resource Consulting Services, 2016). The review focused on risks not addressed by the existing regulatory framework for biosolids management in Canada, including the issue of COECs. Primary environmental and human health risks identified included the potential contamination of ground and surface water by COECs, seasonal risks due to groundwater recharge and runoff following biosolids application, and the potential for livestock and wildlife to be directly exposed to contaminants in biosolids via ingestion of biosolids during foraging, as well as the ingestion of plants that have accumulated the contaminants. Several knowledge gaps were identified, including:

- Insufficient empirical data to conduct detailed human health and ecological risk assessments.

- Lack of data on the ever-expanding list of emerging contaminants of concern present in biosolids.
- Lack of research on the potential synergistic effects of contaminants present in biosolids.
- Limited field studies on biosolid impacts on ground and surface water and subsequent effects in aquatic receiving environments.
- Limited studies assessing the effects of the land application of biosolids on wildlife at all trophic levels.
- Gaps in the understanding of the ability of treatment processes to reduce toxic loading to environmental media and biota.

The report presented several recommendations, including implementing routine public reporting on biosolid composition, focusing on contaminants, including COECs, conducting quantitative risk assessments to address area-specific exposures and associated risks, revising regulations to increase setback distances from watercourses for Class B biosolids and enhanced monitoring programs, to further evaluate the effectiveness of composting and thermal treatment to reduce COECs and to develop public education and source reduction programs to reduce the introduction of contaminants into wastewater systems.

The 2022 TWG provided recommendations in a report titled Organic Matter Recycling Regulation, Technical Working Group Report 2024. The scope of the 2022 TWG was limited and focused on identifying new scientific information on biosolids and compost constituents and management, and on new information on COECS in biosolids and compost since the 2015 TWG. BC ENV (2024) provides the following key messages derived from the TWG findings:

- Each compost and biosolids product is unique to their origin. For example, wastewater treatment plants vary in their input sources (e.g., industrial vs. residential) and may use different treatment processes. Further, the land to which the biosolids (and compost) are applied have unique characteristics. As such, an OMRR application plan specific to the source and the application site should be prepared.
- The importance of source control as the quality of the biosolids (and compost) is directly related to their inputs. The 2022 TWG therefore advocated for regulations that focus on preventing contamination at the source.
- Our understanding is constantly evolving as science advances, and it is challenging to keep pace with evolving science. The 2022 TWG therefore recommended that the ministry devote resources to monitoring the scientific literature and be transparent regarding the research that is used to inform policy.
- To identify and manage COECs it was recommended that the BC ENV develop a comprehensive and transparent strategy that should include not only the presence of COECs, but associated risk. The TWG recommended that the ENV focus on the results of field-based, vs. laboratory-based, studies.
- Provision of context for clear, factual and easily understood information, including providing plain language information on the BC ENV website for why we compost and use biosolids.

Given the large body of scientific literature on the benefits and risks of biosolids that exists, as well as the work conducted by the TWGs convened by the BC ENV, this review is focused on the scientific literature and other relevant reports that have been produced over the last two years (2023 and 2024), with the objective to provide up to date information on the following:

- The human health and environmental risks of both legacy contaminants and COECs, with consideration of environmental conditions typical of the BC south coast.
- Contaminant concentrations in biosolids relative to levels of exposure in general society.
- The limitations of extrapolating lab-based toxicity testing to observations in the environment.
- A summary of the areas of uncertainty in biosolids land application risk, including a summary of relevant techniques for evaluating and addressing uncertainty.
- A summary of biosolids land application techniques that can reduce risk and/or address uncertainty.
- A summary of the risks and concerns that have resulted in land application bans elsewhere.
- An assessment of the overall risks of biosolids land application considering the intent of the Precautionary Principle (Rio Declaration, 1992 and subsequent derivations).

2 Contaminants Present in Biosolids and Associated Risks

Previous studies have identified the presence of numerous contaminants in biosolids. These include legacy contaminants such as heavy metals (Sloan et al., 1997; Evanylo et al., 2006; LRCS Land Resource Consulting Services, 2016; Marchuk et al., 2023) and persistent organic pollutants like polychlorinated biphenyls (PCBs), dioxins and furans (PCDD/Fs) and polycyclic aromatic hydrocarbons (PAHs) (Furr et al., 1976; Bergh and Peoples, 1977). In addition, several COECs have been identified in biosolids, including PFAS (LRCS Land Resource Consulting Services, 2016; Wang et al., 2020; Moodie et al., 2021), microplastics (Crossman et al., 2020; Mohajerani and Karabatak, 2020), PPCPs (LRCS Land Resource Consulting Services, 2016; Mohajerani and Karabatak, 2020; Kinney and Heuvel, 2020) and industrial contaminants such as plasticizers, surfactants and brominated flame retardants. The USEPA (https://www.epa.gov/biosolids/basic-information-about-biosolids) reports that more than 700 contaminants have been identified in biosolids (in at least one instance) since 1993, with the contaminants present in biosolids varying between wastewater treatment plants (WWTPs) depending on inputs to the facilities.

Regulatory agencies, including the BC ENV, have established limits for metals in biosolids, as well as for pathogens. These contaminants are routinely monitored in biosolids prior to land application. Further, as the toxicity of the legacy organic pollutants (e.g., PCBs, PCDD/F, PAHs) is well understood, many of them have existing standards or criteria in Canada and internationally. A sampling program conducted by the BC ENV (2019) indicated that the concentrations of metals, pathogens and legacy organic pollutants were less than the applicable standards/guidelines for biosolids in samples collected from two WWTPs in the province. Further, previous assessments (Smith, 2009; Eriksen et al., 2009; Jensen et al., 2012; WEAO 2001 and 2010; Higgin et al., 2010) have evaluated risks associated with these contaminants in biosolids. These previous studies have indicated a negligible to low potential for risk to human health and the environment. As the use of some of these chemicals have been phased out overtime, concentrations of these contaminants in wastewater (and biosolids) have also decreased overtime. Despite having a good understanding of the potential risks associated with legacy contaminants in biosolids on an individual level, many of the uncertainties discussed throughout this report, including the lack of understanding of the potential for additive and synergistic effects of contaminants in biosolids, also apply to legacy contaminants.

Contaminants of emerging concern are those that have been identified in recent years, primarily due to advancements in laboratory methodologies and the associated reduction in laboratory detection limits. As they are relatively new contaminants, with limited toxicological data, regulatory agencies typically have not derived environmental quality standards for COECs. Further, due to the same limitation as well as a lack of understanding of the fate of these contaminants following land application of biosolids, a limited number of risk assessments have been conducted to assess the potential for COECs in biosolids to adversely impact human health and the environment. Those available (Eriksen, 2009; Smith, 2009; Jensen et al., 2012; Higgens et al., 2010; Kennedy/Jenks, 2017) have concluded that the contaminants generally represent a low risk to human and environmental health based on the low concentrations of most of the COECs identified in biosolids. Further studies (Higgins et al., 2010; Clarke and Smith, 2011; TCEQ , 2021; Warke and McAvoy, 2024) have attempted to prioritize or rank COECs in biosolids, but have encountered similar challenges due to the paucity of toxicity data for many of the COECs.

A review of the recent (2023-2024) literature pertaining to COECs in biosolids indicates that the scientific understanding of select COECs in biosolids is evolving at a rapid rate, with many recent studies focused on PFAS, microplastics and PPCPs. Research focused on the prevalence of these and other COECs in biosolids, their fate following land application, and their toxicities is being undertaken across the globe, including in Canada. This research has highlighted the existing data gaps and uncertainties in our understanding of COECs in biosolids owing to the complex mixture of contaminants present in biosolids, the variability in the contaminant profile observed between sources depending on inputs, and the potential for these contaminants to act additively or synergistically.

With the objective of this report to update previous studies regarding human health and ecological risks from the land application of biosolids, a summary of the recent literature and other information (e.g., regulatory decisions) pertaining to PFAS, microplastics and PPCPs follows. Recent data on the concentrations of PFAS in Canadian biosolids was identified, including from the Capital Regional District (CRD), and has been used to conduct a screening level human health and ecological risk assessment of select PFAS with available toxicological data (Section 2.1.1), as well as a comparison of exposures of PFOA and PFOS in CRD biosolids relative to typical daily exposures intakes of PFOA and PFOS (Section 2.1.2). Additionally, a summary of a 2024 study conducted to rank unregulated organic compounds (UOCs) identified in biosolids is also provided (Warke and McAvoy, 2024) (Section 2.4).

2.1 PFAS

Per- and polyfluorinated alkyl substances (PFAS) are a group of over 4700 aliphatic compounds containing at least one carbon-fluorine (C-F) bond. Due to environmental concerns, North America, Europe, and Australia voluntarily phased out long-chain PFAS (≥8 carbons) in the early 2000s, replacing them with shorter-chain versions. These shorter-chain PFAS are less prone to soil absorption and bioaccumulation, yet they are more environmentally mobile. Despite their reduced bioaccumulation, short-chain PFAS still persist in the environment and can pose risks to human health and the environment (Pozzebon and Siefert, 2023).

Although toxicity and effects data only exist for a small number of PFAS, the health effects of this class of chemicals are well documented. Exposure to PFAS, even at low concentrations, can have significant adverse health effects and effect multiple organs and systems, including liver, kidney and thyroid function, as well as the immune, nervous and reproductive systems (https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/water-quality/water-talk-per-polyfluoroalkyl-substances-drinking-water.html). Additionally, in the environment, PFAS exposures have been linked to negative impacts on the immune and nervous systems of wildlife, as well as effects on growth, reproduction, and development (ECCC, 2023 and 2024).

In May 2023, Environment and Climate Change Canada and Health Canada published the Draft State of PFAS Report (Government of Canada, 2023), providing a qualitative assessment of the fate, sources, occurrence, and potential impacts of PFAS on the environment and human health. The report highlights the extreme stability of PFAS in the environment, often referred to as "forever chemicals”. The report also emphasizes the potential for cumulative effects from co-exposure to multiple PFAS, which may lead to adverse environmental and health outcomes. In July 2024, an updated draft report (Government of Canada, 2024) was issued which incorporated new information and public comments. The updated report continues to underscore the environmental persistence and potential human health and environmental risks associated with PFAS, and reinforces the need for comprehensive management strategies to mitigate their impact. Additionally, in alignment with the Government of Canada’s 2021 notice of intent to address PFAS as a class of chemicals (https://www.canada.ca/en/health-canada/services/chemical-substances/other-chemical-substances-interest/per-polyfluoroalkyl-substances.html), in August 2024, Health Canada published an objective for Canadian Drinking Water Quality for PFAS of 30 nanograms/L (ng/L) for the sum of 25 PFAS (Health Canada, 2024a).

PFAS have been identified in biosolids globally, and while concentrations of PFAS in biosolids are influenced by inputs to WWTPs, treatment methods, and sludge stabilization techniques, studies have confirmed their presence in biosolids in Canada nationwide (McCarthy, 2015; Letcher et al., 2020; Lakshminarasimman et al., 2021 and Gewurtz et al., 2024).

In response to growing concerns over PFAS in biosolids, in June 2024 the Canadian Food Inspection Agency (CFIA) recommended an interim standard for PFAS in commercial biosolids of 50 part per billion (ppb) of perfluorooctane sulfonate (PFOS) on a dry weight basis (Canada Food Inspection Agency trade memoranda T-4-132 available at https://inspection.canada.ca/en/plant-health/fertilizers/trade-memoranda/t-4-132-commercial-biosolids), with enforcement of the standard to begin as of October 18, 2024. CFIA (2024) indicates that the available data suggest that approximately 92% of Canadian biosolids contain PFOS at concentrations below 50 ppb (ng/g). Data provided by the Capital Regional District (CRD) indicates that the average concentration of PFOS in biosolids from the region is 5.4 ppb (ng/g) and is nearly an order of magnitude below the CFIA limit (see data in Table 1).

The US EPA has prioritized research, restriction, and remediation of PFAS in the environment, including in biosolids, and has defined a PFAS Strategic Roadmap which includes a risk assessment for perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) in biosolids. The assessment is currently underway and is anticipated to be completed by the end of 2024 (https://www.epa.gov/biosolids/and-polyfluoroalkyl-substances-pfas-biosolids). During the completion of the assessment, the US EPA has advised states to monitor biosolids for PFAS contamination, identify suspected industrial discharges and implement pre-treatment requirements where appropriate to reduce concentrations of PFAS in biosolids. The US EPA has indicated that if the risk assessment determines that PFOA or PFOS in biosolids may adversely affect public health or the environment, that risk managers will consider options for numerical limitations and best management practices for these compounds.

Additionally in the USA, several states have responded to concerns regarding PFAS in biosolids by enacting rules that limit the concentration of PFAS in biosolids, with Maine (in 2022) and Connecticut (in 2024) implementing bans on the use or sale of PFAS-containing biosolids.

Key findings of recent scientific studies that have evaluated PFAS in biosolids include the following:

1. As the quality of biosolids is dependent on the contaminants present in raw wastewater, it is important to consider upstream controls and monitoring to minimize the input of PFAS-containing wastes into wastewater treatment systems (BC ENV, 2024; Tansel et al., 2024; Gewurtz et al., 2024). In their review of PFAS concentrations in influent, effluent and biosolids samples collected from 27 wastewater treatment plants (WWTPs) across Canada, Gewurtz et al. (2024) identified that PFAS concentrations are the highest in samples from plants that receive landfill leachate.

2. PFAS concentrations in biosolids in the US have not decreased despite the phasing out of the longer chain PFAS in the early 2000s (Pozzebon and Siefert, 2023; Borthakur et al., 2022; Gewurtz et al., 2024). In a study of biosolids sourced from Canadian WWTPs, Gewurtz et al. (2024) reported that except PFOS, the concentrations of long-chain PFAS have generally decreased overtime; however, they remain at measurable concentrations. Further, Gewurtz et al. (2024) found that the replacement of long-chained PFAS with short-chain PFAS has resulted in concentrations of short-chain PFCAs in wastewater influent and effluent increasing over the period of 2009 and 2021, with the short-chain PFAS less frequently detected in biosolids.

3. Recent evidence suggests that PFAS are transformed during the wastewater treatment process. Studies (Helmer et al., 2022; Tansel et al., 2024; Behnami et al., 2024) indicate that some PFAS precursors transform during treatments like anaerobic digestion, potentially altering contaminant profiles and increasing certain PFAS concentrations post-treatment. PFAS not degraded during aerobic and anaerobic digestion will instead become concentrated during treatment (Lakshminarasimman et al., 2021; Gewurtz et al., 2024; Tansel et al., 2024). Carbon chain length significantly affects PFAS partitioning, with longer chain PFAS adsorbed to sludge, and shorter chain PFAS partitioning to the wastewater (Behnami et al., 2024; Gewurtz et al., 2024).

2.1.1 Screening Level Human Health and Ecological Risk Assessment for PFAS in Biosolids

Data collected from 29 Canadian wastewater treatment plants, as summarized in Zhou et al. (2024) from

Letcher et al. (2020) and Lakshminarasimman et al. (2021) indicate that PFOS was the most prevalent PFAS (<0.49–50.4 ng/g dw) in collected biosolids, followed by PFDA (0.11–53 ng/g dw) and PFOA (<0.07–23 ng/g dw) (Zhou et al., 2024; Letcher et al., 2020; Lakshminarasimman et al., 2021).

Gewurtz et al. (2024) summarized data for 42 PFAS in samples collected in 2021 from 27 WWTP across Canada, and reviewed trends in concentrations overtime. The 2021 results were consistent with the previous studies, indicating PFOS is the most prevalent, with concentrations ranging from <0.32 to 96 ng/g dw.

Gerwurtz et al. (2024) reported that the PFAS with the highest concentrations in Canadian biosolids (2018 to 2021) were PFOS, PFBA and the short-chain precursor 5:3 FTCA. Long-chain PFCAs, PFOS, FOSA, the long-chain intermediate transformation products *N*-methylperfluorooctanesulfonamidoacetic acid (MeFOSAA) and N-ethylperfluorooctanesulfonamidoacetic acid (EtFOSAA), PFHxA, and 5:3 FTCA were frequently (in >60 % of the samples) over this period, with the long-chain PFAS likely detected more frequently due to their greater tendency to sorb to solids (Gewurtz et al., 2024; Helmer et al., 2022).

The below table summarizes the concentrations of select PFAS identified in Canadian biosolids (from Letcher et al., 2020; Lakshminarasimman et al., 2021 and Gewurtz et al., 2024). In addition, average PFAS concentrations measured in CRD biosolids (n=3) have been provided for comparative purposes.

PFBA (C4)	**PFPeA (C5)**	**PFHxA (C6)**	**PFHpA (C7)**	**PFOA (C8)**	**PFNA (C9)**	**PFDA (C10)**	**PFUnA (C11)**	**PFDoA (C12)**	**PFBS (C4)**	**PFHxS (C6)**	**PFOS (C8)**
Letcher et al., 2020											
<0.48-3.0	<0.28-6.0	0.17-4.65	<0.08-1.53	<0.07-11.5	0.09-4.72	0.11-23.4	0.19-7.49	0.19-6.09	<0.14-3.48	<0.06-2.43	0.49-**50.4**
Lakshminarasimman et al., 2021											
<2.06	<2.06-14	<2.06-8.3	<2.06-5.2	<2.06-23	<2.06-20	<2.06-53	<2.06-7	<2.06-10	<4.11-11	<**4.11**	<4.11-**27**
Gewurtz et al., 2024 (2021 data)											
<1.3-200	<0.64-12	<0.32-7.9	<0.32-2.6	<0.32-42	<0.31-8.8	<0.31-27	<0.31-3.5	<0.31-7.6	<0.32-7.5	<0.32-**5.4**	<0.32-**96**
Capital Regional District Biosolids											
<1.50	1.28	2.02	0.96	1.11	0.37	1.80	0.738	1.34	0.474	2.2	5.35
Health Canada SSVs (HC, 2019), BC CSR Standards and CCME Soil Quality Guidelines, Residential/Agricultural Land Use, Human Health Protection											
114,000[a]	800[a]	800[a]	800[a]	700[a]	800[a]	NA	NA	NA	61,000[a] 300,000[b]	2,300[a]	2,100[a] 1000[b] 2,000[c]
Grippo et al., (2021), BC CSR Standards and CCME Soil Quality Guidelines, Residential/Agricultural Land Use, Ecological Protection											
2,980[d]	NA	6,200[d]	NA	3,840[d]	24.2[d]	67.7[d]	NA	NA	817[d]	2.8[d]	70,000[b] 10[c] 8.7[d]

Table 1: Concentrations of PFAS reported in biosolids from WWTPs in Canada (in ng/g) (from Letcher et al., 2020; Lakshminarasimman et al., 2021 and Gewurtz et al., 2024) compared to Health Canada SSVs (2019) and BC CSR soil standards for residential and agricultural land use. NA: Not Applicable, [a] Health Canada SSV, [b] BC CSR soil standard, [c] CCME soil quality guideline, [d] Grippo et al. (2021) ESV, **Bold** – concentration exceeds ecological protection guidelines/standards.

Following the land application of biosolids, there is the potential for human and ecological receptors to be exposed to the biosolids, and thus the contaminants, including PFAS, present in the biosolids. Depending on the land application technique used (e.g., injection, incorporation into surface soils, amendments), the biosolids and COECs may be 'diluted'. For this screening exercise, it has been conservatively assumed that there is the potential for human and ecological receptors to be exposed directly to the PFAS concentrations measured in Canadian biosolids. In practice, biosolids are mixed with other materials prior to land application; for example the CRD uses a mixing ratio of 18:1 (5 parts sand, 13 parts wood and 1 part biosolids, or approximately 6% biosolids by volume).

Per standard risk assessment methodologies, including those recommended in guidance from the BC ENV

(2023a), Health Canada (2024b) and the CCME (2020), the concentrations of PFAS presented in Table 1 have been compared to guidelines/standards derived to be protective of human health and ecological direct contact exposures, including for human health, incidental ingestion of soil, and for ecological receptors, direct contact, and for wildlife, soil and food ingestion.

Soil guidelines/standards derived to be protective of human health are available for select PFAS from Health Canada (2019), the BC Contaminated Sites Regulation (CSR) (BC, 2023b) and the CCME (2021). Health Canada recommends human health protective soil screening values (SSVs) for 11 select PFAS including PFOS, PFOA, PFBA, PFBS, PFHxS, PFPeA, PFHxA, PFHpA, PFNA and two fluorotelomer sulfonates (6:2 FTS and 8:2 FTS). The SSVs also consider the potential for PFOS and PFOA to act additively, with an SSV of < 1 for the sum of the ratio of the [PFOS]/SSV_{PFOS} and the [PFOA]/SSV_{PFOA}. Using the maximum concentration of PFOS and PFOA reported in Table 1 (PFOS = 96 ng/g and PFOA = 42 ng/g), the ratio is < 1 and thus meets the SSV. In addition, the BC CSR provides human health protective soil standards for PFOS and PFBS, and the CCME provides a human health soil quality guideline for PFOS. A comparison of the maximum concentrations of the PFAS measured in Canadian biosolids to the Health Canada SSVs, as well as the BC CSR and CCME human health protective soil standards (See Table 1) indicates that the measured concentrations are well below the SSVs, standards and guidelines, with the average concentrations of PFAS measured in CRD biosolids (n=3) well below the Canadian maximum concentrations and all available SSVs, standards and guidelines. As noted, the direct comparison of measured concentrations in biosolids to the standards and guidelines is highly conservative given the mixing that occurs prior to land application. For example, applying the 18:1 mixing ratio used by the CRD, the concentrations of PFAS in Table 1 would be divided by a factor of 18 to provide a resulting exposure concentration. Applying this ratio, the maximum exposure concentration of PFOS (the PFAS measured at the highest concentration) in CRD biosolids would be 0.3 ng/g compared to the lowest standard for human health protection of 1000 ng/g and the lowest standard for ecological health protection of 8.7 ng/g (protective of food chain exposures).

Soil guidelines and standards in BC and available from the CCME for the protection of the environment, are limited to PFOS only. On behalf of the US Department of Energy, Grippo et al. (2021) developed ecological screening values (ESVs) to support screening-level ecological risk assessments at U.S. Air Force (Air Force), Navy, Army, and other U.S. Department of Defense (DOD) sites PFAS have been detected in soils and surface waters. A comparison of the maximum concentrations of PFAS measured in Canadian biosolids to the ESVs and CSR/CCME guidelines/standards for PFOS is provided in Table 1. As presented, concentrations of select PFAS, including PFOS and PFHxS exceed the guidelines for environmental protection, and specifically the CCME soil quality guideline and the Grippo et al. (2021) EVS for soil and food ingestion. Concerning the Grippo et al. (2021) ESV that is exceeded, it is specific to soil and food ingestion of mammalian ground insectivores. Further, concentrations of PFOS exceed the CCME guidelines protective of soil leaching to groundwater for the protection of potable groundwater (10 ng/g) and aquatic life (10 ng/g).

The below discussion considers screening quotients (SQs) for select PFAS; SQs were calculated as the [PFAS] / guideline (or standard or screening value).

The above screening exercise indicates that the concentrations of individual PFAS in both Canadian biosolids, including those from the CRD, for which there is available toxicity data to derive soil guidelines are less than the guidelines derived to be protective of human health (maximum SQ of 0.06 for PFOA), and thus, exposure to these individual PFAS in biosolids, as well as combined exposures to PFOS and PFOA, are not anticipated be associated with risks to human health. As noted the comparison of measured concentrations is highly conservative as amendment would occur prior to application.

The comparison of the PFAS concentrations measured in Canadian biosolids, as reported by Letcher et al., 2020; Lakshminarasimman et al., 2021 and Gewurtz et al., 2024 exceed ecological health guidelines for select individual PFAS including PFOS (maximum SQ =11) and PFHxS (maximum SQ = 1.9). On this basis, there is the potential for the highest concentrations of these PFAS measured in Canadian biosolids to pose a risk to ecological receptors and specifically wildlife exposed via soil and food ingestion. Further, as the maximum PFOS concentrations exceed of soil guidelines protective of drinking water and aquatic life (maximum screening quotient of 9.6), there are potential for risks to both human health and the environment associated with soil leaching to groundwater. The average concentrations of PFAS in the CRD biosolids were all below the available SSVs, ESVs, as well as the CCME guideline and CSR standard for PFOS (i.e., all SQs are well below 1).

The findings of the above screening exercise must be interpreted in the context that guidelines are only available for a small number of the 4700 PFAS known to exist, and that the individual guidelines may not consider the combined toxicity of the PFAS mixture present in biosolids. Further, as PFAS are persistent and accumulate in soils, following the repeated application of biosolids to land, the concentrations of PFAS have the potential to increase overtime.

2.1.2 Estimated Daily Intakes of PFOS and PFOA

As PFAS are ubiquitous in the environment, humans are exposed daily to PFAS from a variety of sources (i.e., consumer products, diet, air, water and soil). Limited data exists on Canadian's exposure to PFAS; however, biomonitoring data indicates that PFAS are present at measurable concentrations in the blood of most Canadians (Government of Canada, 2024).

Using summary statistics from secondary sources for concentrations of PFOA and PFOS in indoor and outdoor air, water and dust in the US, as well as European dietary intake estimates to estimate exposures from food, East et al. (2023) estimated exposure to adults and children over the period of 2011 to 2017. Daily intake estimates for adults were estimated to be 40 ng/day PFOA and 40 ng/day PFOS, and rates for young children (toddlers) were estimated to be 14 ng/day PFOA and 17 ng/day PFOS. A comparison of these estimates using a first-order pharmacokinetic model indicated that the results were aligned with serum concentration measurements from the National Health and Nutrition Examination Survey over the same time period (East et al., 2023), providing evidence that the modeled daily intakes are reasonable. It is noted that although not discussed by East et al. (2023), it is assumed that exposures to PFAS in biosolids would be accounted for in the measured serum contributions in areas where biosolids are applied and represent a potential source.

As measured levels of PFAS in blood in Canada and the US are reportedly similar (Public Health Ontario, 2023), the results of East et al. (2023) have been considered here in an assessment of potential PFAS exposures for Canadians, and a comparison to potential exposures to PFOS and PFOA measured in Canadian biosolids.

Using Health Canada (2024b) exposure equations for the direct soil exposure pathways (i.e., incidental ingestion, dermal contact and inhalation of soil particulate) and receptor characteristics for an adult and a toddler, with the average PFOS and PFOA concentrations in CRD biosolids from Table 1 used as exposure point concentrations, exposure intakes associated with exposures to PFOA and PFOS in CRD biosolids were estimated. A summary of the results summed with the estimates from East et al. (2023) and compared to the Health Canada tolerable daily intakes (TDIs) for PFOA and PFOS are presented in Table 2.

PFAS	Background EDI (East et al., 2023) (ng/day)		EDI from CRD biosolids (ng/day)		Total Exposure Estimate (ng/day)		Total Exposure Estimate (ng/kg-bw/day)		Health Canada Tolerable Daily Intakes (ng/kg-bw-day)
	Toddler	Adult	Toddler	Adult	Toddler	Adult	Toddler	Adult	
PFOA	14	40	0.09	0.03	14.09	40.03	0.85	0.57	60
PFOS	17	40	0.44	0.14	17.44	40.14	1.06	0.57	21

Table 2. Estimated daily intakes for PFOA and PFOS (from East et al., 2023) and from exposures to PFOA and PFOS in biosolids using the maximum PFOA and PFOS concentrations in Table 1. Total exposure estimates are the sum of the EDIs from East et al., 2023 and the EDIs from biosolids.

The total exposure estimates (the sum of the estimated daily intakes from East et al., 2023 and those from CRD biosolids) in ng/kg-bw-day are well below the Health Canada (2021) tolerable daily intakes (TDIs), suggesting that exposures for PFOA and PFOS in biosolids in the CRD, combined with background exposures, are unlikely to represent a health risk. The estimated exposures from the CRD biosolids are conservative as they are based on concentrations measured in the CRD biosolids, which as noted, would be reduced by a factor of 18 following the amendment of the biosolids prior to application.

As with the results of the screening assessment presented in Section 2.1.1, the above evaluation does not consider exposures to the mixture of PFAS in biosolids, which has the potential to act additively with one another as well as with other contaminants in biosolids, and thus is likely an underestimate of total risks associated with PFAS exposures. Despite this, the potential contribution of exposures to PFOS and PFOA from biosolids from the CRD to overall exposures of these PFAS is low, and when amendment of the biosolids is considered, is likely to be negligible.

2.2 Microplastics

Microplastics are pieces of plastic less than five millimeters in diameter and while some microplastics are intentionally manufactured (e.g., microbeads in beauty products), they generally result from the degradation of plastic debris. Microplastics have been identified to be present in biosolids around the globe, including in Canada (Crossman et al., 2020; Gies et al., 2018; Lavoy and Crossman, 2021; Savarajah et al.; 2023). Further, biosolids have been identified as an important pathway for microplastics to enter the environment (Crossman et al., 2020) and agricultural lands where biosolids have been applied are one of the largest reservoirs of microplastics (Pozzebon and Siefert, 2023). Due to their emerging nature, there are no regulations pertaining to microplastics in biosolids (or from other sources) in Canada.

While the studies assessing the prevalence of microplastic in biosolids in Canada were previously limited, Sivarajah et al., (2023) quantified microplastics in biosolids from 22 WWTPs located in nine Canadian provinces. Microplastics were identified in all samples, at concentrations ranging from 228 to 1353 particles per gram dry weight (dw) (median = 636 particles per gram dw). These concentrations are orders of magnitude greater than those reported from previous investigations of microplastics in biosolids in 4 other WWTP in Canada, as well as in other countries (Sivarajah et al., 2023). Importantly, despite the large variation in the concentrations of microplastics observed across the samples from the 22 WWTPs, the investigators did not find a significant difference in the concentrations based on region, the type of WWTP or the sludge treatment type. The results for the Pacific region (n=4) were the highest, with a median concentration of 914 particles per gram dw.

The effects of microplastics on humans and the environment remain largely uninvestigated. In recognition of this, in January 2024 the Government of Canada announced funding of $2.1 million over four years to three academic institutions for the research of microplastics and their potential to impact human health (https://www.canada.ca/en/health-canada/news/2024/01/government-of-canada-funding-research-on-the-health-risks-of-microplastics.html). While there is limited data on health effects, the inhalation of microplastics has been identified as a concern, with the inhalation of microplastics associated with oxidative stress in lung tissues and general inflammation responses in airways (Pozzebon and Siefert, 2023).

Microplastics are highly persistent, resistant to degradation and can accumulate in soils (Xu et al., 2019; Pozzebon and Siefert, 2023). This is of specific concern in areas where there is repeated land application of biosolids. Contrary to the benefits of the land application of biosolids, microplastics from biosolids and their accumulation in soil compromises soil structure and affects nutrient availability, water retention and aeration (Xu et al., 2019). They can also be toxic to soil organisms and thus reduce the beneficial effects these organisms have on soil fertility and structure (Xu et al., 2019). Evidence also suggests the potential for the chemical constituents in mircroplastics to leach into soil and groundwater, and for plants to absorb microplastic particles, serving as a pathway for microplastics to enter the food chain (Xu et al., 2019; Pozzebon and Siefert, 2023).

A recent study (Wang and Good, 2024) identified that microplastics in biosolids can act as vectors for the long-range transport of PFAS, including atmospheric deposition in aquatic systems. The authors indicate that microplastics enriched with PFAS are an important concern due to the ubiquitous nature of both microplastics and PFAS globally, but also their co-occurrence in biosolids and the potential for combined toxicity (Wang and Good, 2024).

The presence of microplastics in biosolids, and the early evidence of effects to both human health and the environment, highlights the need for further research and the implementation of measures to prevent the further introduction of microplastics to the environment. Recent policies limiting single use plastics, along with existing regulations banning use of polymeric microbeads in cosmetics and personal care products, are likely to have resulted in a reduction in microplastics entering WWTPs. Despite this, the laundry of synthetic clothing will continue to contribute to the load of microplastics in biosolids (Crossman et al., 2020); however, the use of microfibre filters in washing machines would reduce microplastics sourced from laundering clothing.

2.3 Pharmaceuticals and personal care products

Pharmaceutical and personal care products (PPCPs) include prescription and over the counter medications and supplements, as well as pharmaceuticals used in agriculture to promote growth and health of livestock (Pozzebon and Siefert, 2023; Hydromantis Inc., 2010; McCarthy, 2015). PPCPs also include other products used for health and cosmetic purposes (e.g,, fragrances). Sub-categories of PPCPs include antibiotics, antimicrobials, steroidal chemicals, fragrances, alkylphenolics, and other PPCPs such as analgesics, antidepressants, antifugals, anti-inflammatories and diuretics, to name a few.

Traditional WWTPs are generally ineffective at removing PPCPs, which often persist through the treatment process. The land application of biosolids has been identified as the primary way that PPCPs enter the environment (Brown et al., 2019; Kinney and Vanden Heuvel, 2020; Pozzebon and Siefert, 2023).

Data indicate that most PPCPs degrade within months after being introduced to the environment; however, some studies indicate that select PPCPs can persist (Garcia-Santiago et al., 2016; McCarthy, 2015; Kinney and Vanden Heuvel, 2020). Further, many PPCPs are considered "pseudo-persistent" as they are continuously introduced to the environment (Pozzebon and Siefert, 2023). The potential for PPCPs to accumulate in soil and transfer to soil invertebrates and plants, as well as to leach to groundwater has been demonstrated (Garcia-Santiago, 2016), although limited data exists on the ecotoxicity of PPCPs, especially in terrestrial systems (Pozzebon and Siefert, 2023). Given the low doses of many PPCPs required to elicit a response in humans, PPCPs are likely to cause a variety of effects on biota if they accumulate in the environment. PPCPs contain endocrine disruptors which have the potential to interfere with human and animal hormonal systems even at low concentrations. Reproductive failure associated with exposure to endocrine disrupting contaminants has been well documented in aquatic systems (Pozzebon and Siefert, 2023).

Further, some antibiotics persist in the environment after land application, affecting soil microbial communities and potentially altering ecosystem functions. They can promote the growth of antibiotic-resistant bacteria, and may disrupt the balance of beneficial soil microorganisms, affecting nutrient cycling and soil health (Black et al., 2019; Pozzebon and Siefert, 2023). Antibiotic resistance has been defined by the World Health Organization as a global threat to health and food security. The promotion of antibiotic-resistant bacteria by PPCPs will contribute to this threat and is specifically concerning given the co-occurrence of antibiotic-resistant bacteria and pathogens in biosolids (Pozzebon and Siefert, 2023). Hung et al. (2022) found that biosolid samples contained significantly higher concentrations of antibiotic-resistant genes when compared to raw agricultural soils, as well as the potential for the airborne spread of the genes. The authors emphasized the importance of their findings to the global concerns regarding antibiotic resistance.

Previous studies (Garcia-Santiago et al., 2016; Kennedy/Jenks, 2017) have conducted preliminary evaluations of the potential effects and risks associated with PPCPs. Additionally, McCarthy (2015) summarized the results of previous risk assessments including those for PPCPs. Overall, the assessments suggest that the potential for human health risks from exposure to individual PPCPs in biosolids is likely low, however, there are limitations and uncertainties in the previous assessments, including the consideration of a small number of PPCPs and the lack of accounting for potential additive and synergistic effects.

Garcia-Santiago et al. (2016) conducted a screening level risk assessment to assess the potential for human exposure to PPCPs measured in biosolids to exceed one therapeutic dose. The study focused on PPCPs shown to persist in WWTPs including carbamazepine, fluoxetine, triclosan, miconazole and ciprofloxacin, and Naproxen. Total exposures via the direct soil exposure pathways, as well dietary exposures, were evaluated. The results of the assessment indicated total hazard quotients (HQs) were less than an HQ of 1.0 (i.e., total exposures were less than one therapeutic dose), with most PCPPs having HQ values of less than 0.1, except for triclosan which has been shown to bioaccumulate, which had an average HQ of 0.28 and a 95% UCLM HQ of 0.95, indicating a potential risk to human health. The mean triclosan concentration reported by Garcia-Santiago et al. (2016) was 5,890 (SD = 3,870) ng/g, while the concentration of triclosan measured in CRD biosolids (n=1) is 1,870 ng/g.

Kennedy/Jenks Consultants (Kennedy/Jenks, 2017) completed a biosolids risk assessment on behalf of Metro Vancouver. A quantitative human health risk assessment was conducted for a small group of COECs detected in biosolids including over the counter pain medications (analgesics) and non-steroidal anti-inflammatory drugs, antidepressants, antibiotics, antimicrobials, plasticizers, and flame retardants. The results of the risk assessment suggested that the concentrations of the COECs in biosolids from the Metro Vancouver region were unlikely to result in adverse health effects to exposed individuals, including children. The assessment further demonstrated that it would take a minimum of a decade and up to one billion years of exposures to the COECs in biosolids to equal a single therapeutic dose of the PPCPs.

The number of PPCPs identified in biosolids continues to grow and there is a general lack of data on the effects of these chemicals in the environment. Given that many of them act via the same mode of action (e.g., endocrine disruptors) and/or belong to the same classes (e.g., antibiotics, SSRIs) it is essential that future assessments consider the combined effect of the mixture of these PPCPs on human health and the environment.

2.4 Prioritization of Unregulated Organic Chemicals in Biosolids (Warke and McAvoy, 2024)

While acknowledging the benefits of the land application of biosolids, Warke and McAvoy (2024) conducted a literature review to compile a database of all reported unregulated organic chemicals (UOCs) present in biosolids. Where data gaps were identified, predictive modelling and an extensive literature search were conducted to determine values for persistence, mobility, bioaccumulation, and toxicity. The prioritization process used these characteristics to rank the UOCs according to their potential impact on human health.

Of 906 chemicals identified in biosolids, 124 were categorized as either high or low priority. Among these, 13 chemicals were classified as carcinogenic, and 22 as endocrine disruptors. Notable examples of endocrine-disrupting chemicals included N-nitrosodimethylamine, cashmeran, nonylphenol, bisphenol A, and several PBDEs. Potential carcinogens identified included 1,2-dichloropropane, 1,4-dioxane, di(2-ethylhexyl)-phthalate, and trichloroethylene.

The priority UOCs were further ranked using scoring based on combinations of mobility, persistence, bioaccumulation, and toxicity. This analysis added eight additional compounds to the high-priority list, resulting in a total of 46 high-priority compounds, with the remaining 78 classified as low priority. The high priority UOCs included several carcinogens (e.g., N-nitrosodiethylamine), endocrine disruptors (e.g., BDE 99, estrone), PPCPs (e.g., fluoxetine, bisphenol-A, carbamazepine, triclosan) and industrial solvents (e.g., trichloroethylene)

Comparison of the Warke and McAvoy (2024) results to those from other studies ranking UOCs in biosolids identified similarities. Of the 46 high-priority UOCs identified by Warke and McAvoy (2024), 38 were also present in other priority lists, including 20 in from Higgins et al. (2010), 14 in a study conducted on behalf of Scottish EPA (WCA, 2019), and 12 in a study conducted by the Texas Commission on Environmental Quality (TCEQ, 2021).

Of the high-priority UOCs identified, several including: bisphenol-A, triclosan, nonylphenol, N-nitrosodimethylamine, 4-chloraniline, triphenyltin (TPhT), and several polybrominated diphenyl ethers (PBDEs) such as BDE 209, BDE 47, and BDE 99, have been associated with effects ranging from endocrine disruption to carcinogenic effects (Warke and McAvoy, 2024). Additionally, triclosan, is known to disrupt thyroid function, may cause reproductive and developmental toxicity and N- nitrosodimethylamine has been linked to neurological, gastrointestinal, and developmental disorders (Warke and McAvoy, 2024).

As noted, previous risk assessments for biosolids-amended soil indicate that most UOCs are below threshold levels for human exposure pathways (HQ < 1). However, Warke and McAvoy (2024) emphasized that preliminary data for pathways involving soil organisms and aquatic systems suggest the potential for HQ values exceeding 1 for certain UOCs including triclocarban, ciprofloxacin, and azithromycin, and that further study is needed for these pathways. Further, while some compounds like caffeine pose minimal risks to humans, they can significantly impact aquatic and soil organisms and antibiotics like ciprofloxacin and azithromycin, as well as fluoroquinolones, have been identified as photosynthetic inhibitors in plants and present potential risks to soil and aquatic ecosystems (Warke and McAvoy, 2024).

While the available data generally support that the measured concentrations of PCPPs in biosolids are low and for the most part do not represent a risk to human health and the environment, the results of Warke and McAvoy (2024) further highlight the number of contaminants in biosolids, and gaps where further research is required to understand potential risks to human health and the environment.

3 Fate and Transport of Contaminants in Biosolids and Considerations of Conditions Typical of the BC South Coast

In sensitive coastal environments, like those present in southern BC, the fate and transport of contaminants, is complex. As discussed throughout this report, land application of biosolids can result in the introduction of a range of contaminants, which may disperse in the environment through soil leaching, erosion, and runoff. This issue is exacerbated by heavy precipitation which can enhance the mobilization of contaminants. Precipitation infiltrates the soil and can leach soluble contaminants into groundwater. In agricultural and rural areas, where biosolids are most likely to be applied, the use of groundwater as a source of drinking water, irrigation water or livestock water, is more likely. Thus, the contamination of groundwater has the potential to result in human health exposures via potable water, as well as livestock and crop exposure. Further, groundwater impacted with contaminants from biosolids can migrate to nearby aquatic systems and result in effects to aquatic ecosystems, as well as entry into the human food chain via seafood consumption.

Heavy rainfall or snowmelt can also create surface runoff, which has the potential to mobilize contaminants from application areas, resulting in impacts to adjacent lands, or migration to nearby water bodies. For example, Crossman et al. (2020) suggested that heavy rainfall may result in the mobilization of microplastics from agricultural soils. The risk of contaminant mobilization via surface runoff is especially high prior to the incorporation of applied biosolids into the soil matrix (LRCS Land Resource Consulting Services, 2016).

Further, prolonged or intense precipitation can saturate soils, resulting in decreased soil adsorption of contaminants and subsequent leaching, as well as soil erosion. Eroded soils carrying adsorbed contaminants may be redistributed across the landscape onto adjacent lands or to nearby waterbodies. Additionally, natural processes such as freeze-thaw and drying cycles can release fine particles from biosolids, facilitating the movement of contaminants into subsurface soils and groundwater.

Tansel et al. (2024) discussed that PFAS persistence and mobility are dependent on soil interactions and precipitation events. Leaching, which is influenced by soil type and water infiltration rates, with higher infiltration rates in areas with high precipitation levels, facilitates PFAS migration to groundwater and surface water. PFAS compounds with long fluoroalkyl chains tend to bind more strongly to solid phases, while shorter-chain PFAS are soluble and prone to leaching and transport. Consistent with other studies (Blake and Fenton, 2020; Drew et al., 2021), Tansel et al. (2024) identified the potential for plant uptake of PFAS from biosolid-amended soils, raising concerns about bioaccumulation in food chains and ecosystems.

PCPPs in biosolids can similarly migrate, with pharmaceuticals showing potential to leach into groundwater (Santiago et al., 2016; Kinney et al., 2006). Gottschall et al., (2012) detected pharmaceuticals and personal care products (PPCPs) in groundwater following biosolids land application. While many PPCPs dissipate within a few months, others, particularly those embedded in biosolid aggregates, can persist for over a year (Kinney and Heuvel, 2020).

Some COECs, due to their persistence and bioaccumulation potential, can be transported long distances. For example, microplastics in biosolids exhibit hydrophobic characteristics, allowing them to adsorb other contaminants. These particles may then be subject to long-range transport (Carbery et al., 2018). Studies (Wang et al., 2024, Strynar et al., 2011) indicate that long-chain PFAS can attach to microplastics or dust and become airborne. These findings raise concerns regarding the multiple contaminant types present in biosolids and their influence not only on the fate and transport of such contaminants, but also on their combined toxicities.

While the science on the fate and transport of COECs in biosolids in advancing, further research is required to fully understand the behaviour of these contaminants in the environment. Field studies in BC that evaluate seasonal influences, such a precipitation levels, on the environmental fate and transport of COECs in biosolids would provide valuable insight, including how the co-occurrence of numerous contaminants impact migration patterns and ultimately exposure pathways for human and ecological receptors.

4 Techniques to Reduce Risks in Biosolids Land Application

Numerous studies have emphasized the importance of government oversight and regulation to limit the risks associated with the land application of biosolids; however, as discussed, available regulations are limited due to the paucity of toxicity data for COECs. This gap, and the uncertainties discussed in Section 6, highlight the critical need for further research, source control to limit the entry of COECs into WWTPs, the development of treatment technologies that degrade COECs in biosolids, and standardized requirements for monitoring COECs in biosolids.

4.1 Recent Research on Treatment Technologies

Recognizing the critical problem that contaminants, and specifically COECs, in biosolids present, recent research has focused on treatment technologies that remove COECs. As noted, conventional WWTPs were not designed to remove COECs and thus, these contaminants will continue to persist in inputs to WWTPs.

Much recent research has been focused on technologies that destroy PFAS. An PFAS Innovative Treatment Team was formed by the USEPA is 2020 to investigate and develop innovative tools and methods to break the carbon fluorine (C-F) bonds in PFAS-containing waste. Four emerging technologies were identified by the team with a technology's suitability dependent on waste characteristics, processing requirements, and potential byproducts, as well as considerations for energy consumption, costs, and system mobility (Berg et al., 2022). Berg et al. (2022) also indicated that additional pretreatment and post-treatment steps may be necessary to enhance effectiveness and manage byproducts, such as volatile PFAS emissions.

The four emerging technologies were summarized by Berg et al. (2022) and include:

- Mechanochemical destruction (MCD), which has been shown to result in over 99% PFAS destruction in laboratory settings. The authors note that this technology requires further study for commercial-scale application.
- Electrochemical oxidation (EO), which uses electrical currents to break C-F bonds in PFAS, has shown successful bench and pilot-scale results, but faces challenges in scaling up.
- Supercritical water oxidation (SCWO) treats waste at high temperatures and pressures, producing heat that can sustain the process, but requires managing acidic byproducts and salt precipitation.
- Pyrolysis and gasification decompose materials at high temperatures, potentially destroying PFAS, and produce useful byproducts like char and syngas. Further research on this technology was noted to be required.

Research briefs on these technologies are available on the PITT's website, providing detailed information on benefits and areas needing further research available at https://www.epa.gov/chemical-research/pfas-innovative-treatment-team-pitt. Each of these technologies were noted by US EPA to be under evaluation, with further pilot-testing and reporting of the results planned for 2021; however, no further updates on these technologies were identified on the above webpage. While showing promise, the technologies are not yet commercially available.

Keller et al. (2024) pyrolyzed biosolid samples from a WWTP in Southern California at temperatures ranging from 400 to 700 °C for two hours. The study evaluated contaminant removal, with most contaminants being eliminated entirely and only minimal residuals detected. Notably, no PFAS were detectable at the lowest temperature tested (400 °C), and overall removal of PPCPs exceeded 99.9%. Microplastic removal ranged from 91 to 97% depending on conditions. Additionally, the resulting biochar was rich in iron and phosphorus, making it a valuable fertilizer additive. The authors of the study indicated that a techno-economic analysis showed that pyrolysis could lead to significant cost savings, with revenue from biochar sales having the potential to offset the capital and operational costs of the drying and pyrolysis systems.

Vo et al. (2024) assessed treatment technologies for microplastics and organic contaminants in biosolids. Their multi-criteria analysis identified anaerobic digestion as the most established and practical approach, indicating that while thermal treatment shows potential, the application requires further advancements in infrastructure, regulatory frameworks, and public acceptance to become widely viable.

Recent studies have explored advanced oxidation treatment methods which are reportedly effective at degrading COECs including PPCPs and PFAS. Booton et al. (2024) indicate that chemical oxidation offers a promising alternative and eliminates persistent contaminants. Compared to biological systems, it is potentially simpler to operate and maintain, while requiring less space for efficient treatment. Key advantages of chemical oxidation are reported by the authors to include its ability to address COECs, its rapid start-up and shutdown capabilities, and its ability to avoid common challenges in biological treatment, such as toxic load management, biomass washout, sludge settling issues, and the complexities of sludge handling and disposal.

The recent research illustrates the potential for available technologies to destroy COECs, demonstrating that with further testing and implementation, that the risks association with the land application of biosolids could be greatly reduced.

4.2 Application Techniques and Site-Specific Application Considerations

Specific application techniques, such as injection, surface incorporation and amendment/mixing of biosolids to produce a biosolids growing media, have been demonstrated to reduce risks associated with biosolids land application. Injecting biosolids below the soil surface reduces bioaerosol dispersion, wind and water erosion, and prevents exposure to contaminants by reducing dust generation and the potential for surface contact. Injection also reduces adherence to plant tissues, and therefore exposures to livestock and wildlife. Similar results may be achieved by mixing biosolids into soil immediately after application (LRCS Land Resource Consulting Services, 2016).

BC ENV (2008), LRCS Land Resource Consulting Services (2016) and others have provided recommendations for reducing risks associated with the land application of biosolids. The recommendations include risk-based planning to reduce exposures, including avoiding sensitive ecosystems and proximity to water bodies, as well as areas with shallow groundwater where leaching of contaminants is more likely. Further, the use of personal protective equipment for workers, adhering to buffer zones required in the OMRR and avoiding application during heavy rainfall and snowmelt will further reduce exposures and the potential for contamination of groundwater and surface water. Implementing waiting periods between application and livestock (and wildlife) exposures is also recommended.

The amendment of biosolids with biochar or wood chips, as done in the CRD, has also been demonstrated to enhance the degradation and/or retention of leachable PPCPs (Pozzebon and Siefert, 2023).

5 Limitations of Extrapolating Lab-Based Testing to the Environment

The limitations in extrapolating lab-based toxicity testing results to real-world environmental scenarios are generally recognized and have been well documented by others (Cairns, 1983; Smith and Cairns, 1993; Hill et al., 1994). These limitations are exacerbated when considering the land application of biosolids owing to the large number of contaminants, including COECs, present in biosolids, and as the fate and toxicity of these contaminants which will vary depending on the mixture present and the application site characteristics. Controlled laboratory conditions cannot replicate the complex, variable nature of these environments.

The key limitations that arise during this extrapolation process include:

1. Laboratory tests are conducted under highly controlled conditions, which typically include simplified systems that do not reflect the complexity of the natural environment. Factors such as contaminant mixtures, environmental conditions (e.g., soil type, pH), and contaminant exposure pathways cannot be replicated in a lab setting.
2. Lab tests typical assess the effects of a single chemical or a small group of related chemicals. In the environment, specifically in the case of biosolids, organisms are exposed to complex mixtures with potential additive, synergistic, or antagonistic effects.
3. Lab studies typically expose test organisms to high concentrations of a single contaminant over short durations in confined spaces, with even chronic tests typically limited in duration. This does not reflect environmental exposures which often involve chronic exposures to low levels of contaminants over large areas. The effects of chronic, low dose exposures are typically underestimated in lab settings, leading to potential inaccuracies when predicting chronic toxicity in the natural environment.
4. In toxicity testing, exposures are usually simplified and typically limited to immersion in a contaminated medium or direct ingestion or inhalation. In natural environments contaminants exposure pathways are more complex and may include cross-media exposures, including food chain exposures. This oversimplification has the potential to underestimate exposures and associated effects.
5. Lab toxicity test methods have been developed for a limited number of species, focusing on model organisms that may not be representative species that are most sensitive to a specific contaminant. Further, lab tests may not include life stages (e.g., juveniles, larvae) most sensitive to the contaminants tested.
6. Laboratory organisms are often maintained in stable environments and lack the physiological adaptations that organisms may develop in response to natural stressors. Additionally, organisms may behave differently in the lab setting compared to in their natural environment, potentially influencing their exposure and response to contaminants.
7. In natural environments, interactions with abiotic factors (e.g., soil composition) and biotic factors (e.g., predation) may influence toxicity. These factors cannot be accounted for in a laboratory.

The above limitations of laboratory-based toxicity studies highlight the need for caution when extrapolating laboratory testing results to the environment. As noted, given the complex contaminant mixtures known to be present in biosolids, the likely potential for synergistic or additive effects, as well as the influence of the characteristics of the application area on fate and toxicity, the importance of field studies in the assessment of potential risks from the land application of biosolids cannot be understated. Field observations, together with laboratory toxicity testing, are essential to understanding risks. The collective results of both, once available, should be considered in the establishment of a risk-based, adaptive management strategy for the land application of biosolids.

6 Uncertainties in the Risks Associated with the Land Application of Biosolids

Numerous uncertainties exist in the assessment of risks associated with the land application of biosolids. Many of these uncertainties have been documented by others (McCarthy, 2015; Pozzebon and Siefert, 2023; Garcia-Santiago et al., 2020; Schoof and Houkal, 2005; LRCS, 2016), including those summarized below and discussed in previous sections of this report. The rapidly evolving science on COECs in biosolids and their fate and effects following land application, as well as the very recent government policies and regulations pertaining to COECs in biosolids in Canada and elsewhere (e.g., CFIA October 2024 limit for PFAS in biosolids; Government of Canada July 2024 draft report of PFAS; Government of Canada 2023 funding for research on microplastics), underscore that the science on COECs is "emerging".

Some of the key scientific gaps and uncertainties related to the land application of biosolids are summarized below:

1. Regulatory agencies have not derived limits for most COECs in biosolids, and further, given the paucity of toxicity (including ecotoxicity and specifically for wildlife at all trophic levels) and fate data for COECs, have not derived environmental quality standards. For the same reason, risk assessments evaluating the potential human health and environmental risks associated with exposures to COECs in biosolids, are limited and have generally focused on only a few of the more common COECs.

2. Due to advances in analytical chemistry methodologies, new COECs present in biosolids continue to be identified. The fate and effects of these contaminants are not well understood and thus, it is not possible to assess the potential for risks to human health and the environment.

3. Existing risk assessments and other evaluations of COECs in biosolids are focused on individual contaminants and are based on toxicity data from laboratory toxicity tests. These risk assessments do not consider that exposures to biosolids would result in the simultaneous exposure to numerous contaminants, and the potential for the contaminants to act additively or synergistically and thus are likely to have underestimated the potential for risks.

4. Similarly, the coexistence of numerous contaminants in biosolids may affect their fate, transport and distribution and therefore potential exposure pathways for human and ecological receptors. As an example, Wang and Good, (2024) identified that microplastics in biosolids can act as vectors for the long-range transport of PFAS. Field studies evaluated the influence of the contaminant mixtures present in biosolids on their environmental fate and transport are required to address this uncertainty.

5. The limited available toxicity data for most COECs is based on laboratory toxicity testing. The limitations and uncertainties associated with lab studies, and the need for field studies to be considered in the interpretation of risks, is highlighted in Section 5.

6. The long-term impacts of COECs in biosolids after land application, including their potential to accumulate overtime, leach into groundwater, enter the food chain, or impact human health or wildlife, are not fully understood. Further research in these areas is essential for the assessment and management of risks.

7. Efficient technologies for detecting and measuring COECs in biosolids and the environment are underdeveloped. Without reliable monitoring, it is challenging to assess or mitigate potential risks associated with contaminants in biosolids.

The rate at which our understanding of COECs in biosolids is advancing, with new data on the fate and effects of COECs being published continuously, underscores the importance an adaptive management framework for the land application of biosolids. . With time, it is anticipated that the uncertainties and data gaps identified here and elsewhere will be addressed, and thus regulators must keep pace with the evolving science and regularly weigh the risks and benefits of the practice in an informed and transparent manner.

7 Biosolid Land Application Bans

Several countries have restricted or banned the land application of biosolids due to concerns about environmental contamination, health risks, and public opposition primarily related to the presence of PFAS in biosolids, and their associated entry into the environment, specifically the human food chain.

In Canada, the land application of biosolids has been banned in specific regions due to environmental and public health concerns. In British Columbia, the Capital Regional District implemented a ban on the land application of biosolids in 2011. The ban was implemented due to concerns regarding COECs in biosolids, and to protect local drinking water sources, the environment, and public health. In March 2023, Quebec announced a temporary ban on the import and land application of biosolids originating from the United States due to concerns over PFAS contamination in imported biosolids. The province is working towards establishing standards for PFAS in biosolids to ensure environmental safety.

The following is a summary of the various countries that have banned or implemented strict regulations on the land application of biosolids.

7.1 United States of America

In the U.S.A., some states and municipalities have imposed restrictions or moratoriums on the land application of biosolids. In 2022, Maine became the first state to ban the land application of biosolids after it found PFAS had contaminated crops or water on over 50 farms throughout the state where sludge had been spread (Carey, 2023). Other states are starting to implement limits and bans. As of October 1, 2024, Connecticut prohibited the sale of PFAS-containing biosolids or wastewater sludge. Further, Michigan, New York, and Wisconsin have implemented interim strategies that limit the PFAS concentrations allowed in land-applied biosolids, and Colorado's interim strategy requires Source Control Programs to evaluate potential PFAS sources if concentrations in biosolids exceed a determined level.

Several more states have pending legislation that would enforce similar restrictions. As an example, Massachusetts is developing legislation that would set maximum levels for the amount of PFAS allowed in any fertilizer sold in the retail market, and proposed legislation in Oklahoma would require a warning label on any product derived from biosolids or sewage sludge.

7.2 Europe

In Europe, several countries have adopted a precautionary approach in banning the land application of biosolids, emphasizing soil and food safety. Switzerland has had a ban on agricultural use in place since 2006 with their current regulation requiring sewage sludge to be combusted, while the Netherlands has imposed stringent limits on several contaminants commonly identified in biosolids, resulting in very limited use. Due to concerns over COECs, including PFAS, pharmaceuticals and microplastics, Sweden, Germany and Austria (Vienna region) have banned the application of biosolids on agricultural land. The ban in Germany was implemented with the amendment of the German Sewage Sludge Ordinance in 2017, and by 2029 biosolids land application will be phased out. Germany is reportedly shifting towards incineration of sewage sludge and phosphorus recovery.

8 Discussion and Conclusion

In British Columbia, approximately 38,000 tonnes of biosolids are produced annually, with approximately 72% of biosolids and biosolids-derived products applied to land (BC ENV, 2019). As discussed throughout, while there are many benefits associated with the land application of biosolids, biosolids contain a complex mixture of contaminants, including COECs. Data on the fate and effects of these COECs is limited, and our understanding of the risks that these contaminants present to human health and the environment is rapidly evolving.

When weighed collectively, the available information on the land application of biosolids, including the information presented by others (e.g., Pozzebon and Siefert, 2023; LRCS Land Resource Consulting Service, 2016; McCarthy, 2015; BC ENV, 2024) and herein, supports the assessment of the practice in the context of the Precautionary Principle. The Precautionary Principle guides decision-makers to take action to protect the environment and public health in the face of environmental or health uncertainties (Goldstein, 2001).

Given the significant data gaps and uncertainties in the land application of biosolids, as well as the rapidly advancing science, previous studies that have concluded a low risk to human health and the environment must be interpreted in the context of the uncertainties. Risk assessments are conducted using the best scientific evidence available at the time of the assessment but must consider the unknowns in the overall interpretation of risks and in management decisions (Yoe, 2019, CSAP, 2016). Based on the data gaps and uncertainties summarized in Section 6, the uncertainty in the risk conclusions made to date, and specifically the potential for the assessments to have underestimated risks to human health and the environment, is categorized as moderate to high, and thus, is not supportive of a conclusion of low risk (CSAP, 2016). Rather, based on the uncertainties and the potential for the assessments to have underestimated risk, the risk conclusions are also uncertain, and cannot be further understood until the data gaps are resolved and the uncertainties are decreased.

In the context of biosolids from the CRD, with the data for PFAS and triclosan discussed herein, a review of the data indicates that the concentrations of the COECs are lower than measured in other Canadian biosolids. As noted, the comparison of the low concentrations of COECs with existing toxicity data suggests that the COECs in CRD biosolids represent a negligible to low risk to human health and the environment. Despite this, given the uncertainties discussed in Section 6, the uncertainty in this conclusion is moderate to high and should be reviewed regularly as the science on biosolids evolves.

Oberg and Mason-Renton (2018) examined how uncertainties and gaps in scientific knowledge were addressed and communicated in British Columbia, compared to Sweden, during their jurisdictional review of regulations on the land application of biosolids. The study highlighted how the jurisdictions had approached the uncertainty in the land application of biosolids differently; with BC taking the position that the absence of evidence of risk implies the practice is safe. Sweden, however, prioritized a precautionary approach, operating under the assumption that the absence of evidence or risk is not equivalent to evidence of absence (Oberg and Mason-Renton, 2018).Given the benefits of the land application of biosolids, the Canada-wide approach (CCME, 2012) encouraging the beneficial use of biosolids versus disposal, and as the scientific evidence available to date suggests that the land application of biosolids represents a negligible to low risk, Sweden's approach is likely overly restrictive.

Applying the Precautionary Principle aligns with using an adaptive management framework for the land application of biosolids. As noted, with time, it is anticipated that the uncertainties and data gaps identified in this report and elsewhere will be addressed, and thus regulators must keep pace with the evolving science and regularly weigh the risks and benefits of the practice in an informed and transparent manner. In the interim actions such as source control to limit the introduction of COECs to WWTPs, adopting advanced treatment technologies as they become available, careful site selection through the application of risk-based principles, and ongoing monitoring to minimize risks, are essential for the protection of human health and the environment. Such strategies are increasingly emphasized in regulatory guidelines around the globe to ensure biosolids use does not compromise human health and the environment. This approach addresses both the potential risks and the benefits of nutrient recycling while minimizing ecological and human health hazards (Schoof & Houkal, 2005; Gianico et al., 2021).

9 Limitations

This report has been prepared and the work referred to in this report has been undertaken by Dr. Chris Kennedy for the Capital Regional District (CRD). Dr. Chris Kennedy makes no representation or warranty to any other person with regard to this report and the work referred to in this report and he accepts no duty of care to any other person or any liability or responsibility whatsoever for any losses, expenses, damages, fines, penalties or other harm that may be suffered or incurred by any other person as a result of the use of, reliance on, any decision made or any action taken based on this report or the work referred to in this report.

This report has been prepared based on the CRD Terms of Reference and the literature identified during the review. Dr. Chris Kennedy expresses no warranty with respect to the accuracy of the data reported in the literature.

The evaluation and conclusions reported herein do not preclude the identification of additional literature pertinent to the contaminants discussed in this report. If new literature/studies become available, modifications to the findings, conclusions and recommendations in this report may be necessary.

Where information obtained from reference sources is included in the report, no attempt to verify the reference material was made. Dr. Chris Kennedy expresses no warranty with respect to the toxicity data presented in various references or the validity of the toxicity studies on which it was based. Scientific models employed in the evaluations were selected based on accepted scientific methodologies and practices in common use at the time and are subject to the uncertainties on which they are based.

Nothing in this report is intended to constitute or provide a legal opinion. Dr. Chris Kennedy makes no representation as to the requirements of or compliance with environmental laws, rules, regulations or policies established by federal, provincial or local government bodies. Revisions to the regulatory guidelines and standards referred to in this report may be expected over time, especially considering the evolving nature of the science for many of the contaminants evaluated. As a result, modifications to the findings, conclusions and recommendations in this report may be necessary.

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