



Trends in environmental chemical concentrations in the Canadian population: Biomonitoring data from the Canadian Health Measures Survey 2007–2017

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ABSTRACT

Ten years of nationally representative biomonitoring data collected between 2007 and 2017 are available from the Canadian Health Measures Survey (CHMS). These data establish baseline environmental chemical concentrations in the general population. Here we sought to evaluate temporal trends in environmental chemical exposures in the Canadian population by quantifying changes in biomarker concentrations measured in the first five two-year cycles of the CHMS. We identified 39 chemicals that were measured in blood or urine in at least three cycles and had detection rates over 50% in the Canadian population. We calculated geometric mean concentrations for each cycle using the survey weights provided. We then conducted analyses of variance to test for linear trends over all cycles. We also calculated the percent difference in geometric means between the first and most recent cycle measured. Of the 39 chemicals examined, we found statistically significant trends across cycles for 21 chemicals. Trends were decreasing for 19 chemicals from diverse chemical groups, including metals and trace elements, phenols and parabens, organophosphate pesticides, per- and polyfluoroalkyl substances, and plasticizers. Significant reductions in chemical concentrations included di-2-ethylhexyl phthalate (DEHP; 75% decrease), perfluorooctane sulfate (PFOS; 61% decrease), perfluorooctanoic acid (PFOA; 58% decrease), dimethylphosphate (DMP; 40% decrease), lead (33% decrease), and bisphenol A (BPA; 32% decrease). Trends were increasing for two pyrethroid pesticide metabolites, including a 110% increase between 2007 and 2017 for 3-phenoxybenzoic acid (3-PBA). No significant trends were observed for the remaining 18 chemicals that included arsenic, mercury, fluoride, acrylamide, volatile organic compounds, and polycyclic aromatic hydrocarbons. National biomonitoring data indicate that concentrations, and therefore exposures, have decreased for many priority chemicals in the Canadian population. Concentrations for other chemical groups have not changed or have increased, although average concentrations remain below thresholds of concern derived from human exposure guidance values. Continued collection of national biomonitoring data is necessary to monitor trends in exposures over time.

1. Introduction

Human biomonitoring data are increasingly used to quantify environmental chemical exposures through the measurement of those chemicals, their metabolites, and related biomarkers in biological samples such as blood and urine (Haines et al. 2017). Over the past few decades, there has been a dramatic rise in the number of human biomonitoring programs and studies (Barnett-Itzhaki et al. 2018; Needham et al. 2007). Guidance outlining the best approaches for collecting, communicating, and interpreting biomonitoring information have made these data even more useful for risk assessors, risk managers, and policy

makers (LaKind et al. 2008, 2014, 2019). This is exemplified by the increasing use of human biomonitoring data for quantitative exposure estimates and risk evaluation in human health risk assessments (Barr and Angerer 2006; Fenske et al. 2005; Ganzleben et al. 2017; Louro et al. 2019; Zidek et al. 2016).

The National Biomonitoring Program of Health Canada is responsible for monitoring environmental chemical concentrations in a representative sample of the Canadian population. This information is collected in partnership with Statistics Canada through the Canadian Health Measures Survey (CHMS) (Statistics Canada 2020a). Biomonitoring data from the CHMS are used to determine baseline chemical

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concentrations in the Canadian population (Health Canada 2020). These can be compared with concentrations in vulnerable sub-populations in Canada measured as part of the First Nations Biomonitoring Initiative (Assembly of First Nations 2013) and the Maternal-Infant Research on Environmental Chemicals study (Arbuckle et al. 2013). They can also be compared with national biomonitoring program data from other countries, such as the U.S. National Health and Nutrition Examination Survey (NHANES), the German Environmental Survey, and the Korean National Environmental Health Survey (Khoury et al., 2018; LaKind et al., 2012, 2019; Pollock et al., 2021). Human biomonitoring data are used in human health risk assessments to inform quantitative exposure and risk characterization (Environment and Climate Change Canada and Health Canada 2012, 2016, 2020). Furthermore, some studies have used these data to examine the links among environmental exposures, determinants of exposure, and health outcomes (Eykelbosh et al. 2018).

With five cycles representing ten years (2007–2017) of CHMS data now available, additional uses of health and exposure indicators have been made possible. One such example is the recent use of national biomonitoring data in performance measurement evaluation reports for certain substances, such as lead (Government of Canada 2020a), mercury (Government of Canada 2020b), and di-2-ethylhexyl phthalate (DEHP) (Government of Canada 2020c). In these reports, chemical concentrations in Canadians are used as a key performance indicator for evaluating recent risk management actions intended to reduce exposures to those chemicals (Government of Canada 2020d). Changes in these concentrations over time can be used to demonstrate the effectiveness of public health measures or to identify priority substances for which further action may be needed.

Evaluating trends was a foundational premise for the establishment of Canada's National Biomonitoring Program and collection of biomonitoring data through the CHMS (Haines and Murray 2012). Here we sought to evaluate temporal trends in environmental chemical exposures in the Canadian population by quantifying changes in biomarker concentrations measured in the first five two-year cycles of the CHMS. We first identified chemicals suitable for trend analysis by establishing criteria based on the number of cycles in which they were measured and the detection rates in the population. We then conducted statistical tests with careful consideration to ensure that biomonitoring data were comparable across collection time points (LaKind et al. 2019; Pollock et al. 2021).

2. Material and methods

2.1. Biomonitoring component of the CHMS

The CHMS is a cross-sectional direct measures survey that collects information on the general health of Canadians including environmental chemical exposures. The survey is conducted by Statistics Canada in partnership with Health Canada and the Public Health Agency of Canada. Here we used data from cycle 1 (2007–2009), cycle 2 (2009–2011), cycle 3 (2012–2013), cycle 4 (2014–2015), and cycle 5 (2016–2017) of the CHMS. Detailed information about participant selection, questionnaire content, and sample collection are described elsewhere (Statistics Canada 2011, 2013, 2015, 2017, 2019a). Briefly, a stratified multistage sampling strategy was used to select approximately 5,600 to 6,400 participants aged 3 to 79 years (6 to 79 years in cycle 1) over each 2-year collection period that would produce estimates representative of the non-institutionalized Canadian population living off-reserve in the ten provinces. The number of collection sites differed across cycles, with a total of 15 sites in cycle 1, 18 sites in cycle 2, and 16 sites in each of cycles 3, 4, and 5. Participants completed an interview in their homes followed by a visit to a mobile examination centre where another interview was conducted, physical measurements were taken, and biological specimens were collected. Biological samples were aliquoted and shipped alongside quality control samples, such as field blanks and/or blind reference materials, to laboratories across Canada. Chemicals were

selected for measurement in each cycle through a stakeholder consultation process that sought input from federal and provincial governments, public health laboratories, industry groups, non-governmental organizations, and academic researchers (Haines et al. 2017). The analytical protocols and corresponding limits of detection (LODs) used by laboratories to measure chemicals in biological samples are described for each cycle in Health Canada's Reports on Human Biomonitoring of Environmental Chemicals in Canada (Health Canada 2010, 2013, 2015, 2017, 2019). Summary statistics of biomonitoring results are publicly available in these reports (Health Canada 2010, 2013, 2015, 2017, 2019) and can be accessed online through the Government of Canada's Open Data portal (Government of Canada 2020e). Full data can only be accessed through Statistics Canada's Research Data Centres (Statistics Canada 2020b). All components of the CHMS were approved by the Health Canada and Public Health Agency of Canada Research Ethics Board to ensure that ethical standards for human research were maintained (Statistics Canada 2019a).

2.2. Selection of chemicals for trend analysis

Chemicals were selected for trend analysis if they were measured at sufficient detection rates (>50%) in at least three of the five cycles of the CHMS. These criteria were chosen to focus on environmental chemicals with widespread exposure, to limit the impact of imputed data on statistical analyses, and to ensure trend outcomes are reliable across at least three collection time points. Although geometric means (GMs) are typically only calculated for chemicals with detection rates $\geq 60\%$, a detection rate of > 50% was selected to assess trends for chemicals for which detection rates were between 50% and 60% in one cycle (as was the case for mercury, triclosan, and o-xylene). Of the 199 chemical biomarkers measured in the first five cycles, 50 were selected for trend analysis based on these criteria. Of these 50 biomarkers, four were measured in five cycles, four were measured in four cycles, and the remaining 42 were measured in three cycles of the CHMS. Among the remaining 149 biomarkers not included in the present study, 122 were measured in only one or two cycles and 27 were measured in at least three cycles but had low detection rates. The 50 biomarkers selected for trend analysis represented 39 chemicals, as certain substances are commonly represented by multiple biomarkers or metabolites in biomonitoring studies and reports (Centers for Disease Control and Prevention 2021; Government of Canada 2020c; Willey et al. 2021). Concentrations of inorganic-related arsenic species were calculated and presented here as the sum of arsenite, arsenate, dimethylarsinic acid (DMA), and monomethylarsonic acid (MMA); DEHP was calculated as the sum of mono(2-ethylhexyl) phthalate (MEHP), mono(2-ethyl-5-hydroxyhexyl) phthalate (MEHHP), and mono(2-ethyl-5-oxohexyl) phthalate (MEOHP); fluorene was calculated as the sum of 2-, 3-, and 9-hydroxyfluorene; naphthalene was calculated as the sum of 1- and 2-hydroxynaphthalene; and phenanthrene was calculated as the sum of 1-, 2-, 3-, 4-, and 9-hydroxyphenanthrene. All individual biomarkers used to derive these composite measures had high detection rates (>90%), except for arsenite, arsenate, and MMA, which had low detection rates (<30%). For this reason, DMA was also considered separately for trend analysis given that it is the largest contributor to the summed concentrations of inorganic-related arsenic species. The 39 chemicals assessed for trends, as well as the biological matrix, age group, and cycles in which they were measured, are listed in Table 1.

2.3. Statistical analysis

Data analysis was performed in the R platform (R Core Team 2020) using the R survey package (Lumley 2020). Detection rates represent the unweighted percent of respondents measured at or above the LOD. All other analyses, including calculation of GMs, were conducted using the combined survey weights that correspond to the cycles measured for each chemical. Variance estimation and statistical testing were

Table 1

Overview of chemicals assessed for trends from Canadian Health Measures Survey cycles 1 (2007–2009), 2 (2009–2011), 3 (2012–2013), 4 (2014–2015), and/or 5 (2016–2017).

Number	Chemical	Matrix	Ages (years) ^a	Cycles
<i>Metals and trace elements</i>				
1	Inorganic arsenic ^b	Urine	3–79	2,3,4,5
2	Dimethylarsinic acid (DMA)	Urine	3–79	2,3,4,5
3	Mercury	Blood	6–79	1,2,3,4,5
4	Lead	Blood	6–79	1,2,3,4,5
5	Cadmium	Blood	6–79	1,2,3,4,5
6	Selenium	Blood	6–79	1,2,5
7	Fluoride	Urine	3–79	2,3,4
<i>Phenols and parabens</i>				
8	Bisphenol A (BPA)	Urine	6–79	1,2,3,4,5
9	Triclosan	Urine	3–79	2,3,4
10	Methyl paraben	Urine	3–79	3,4,5
11	Propyl paraben	Urine	3–79	3,4,5
<i>Acrylamide</i>				
12	Acrylamide hemoglobin adduct	Blood	3–79	3,4,5
13	Glycidamide hemoglobin adduct	Blood	3–79	3,4,5
<i>Per- and polyfluoroalkyl substances (PFAS)</i>				
14	Perfluorooctane sulfonate (PFOS)	Plasma	20–79	1,2,5
15	Perfluorooctanoic acid (PFOA)	Plasma	20–79	1,2,5
16	Perfluorohexane sulfonate (PFHxS)	Plasma	20–79	1,2,5
<i>Plasticizers</i>				
17	Di-2-ethylhexyl phthalate (DEHP) ^c	Urine	6–49	1,2,5
18	Mono-ethyl phthalate (MEP)	Urine	6–49	1,2,5
19	Mono- <i>n</i> -butyl phthalate (MnBP)	Urine	6–49	1,2,5
20	Mono-benzyl phthalate (MBzP)	Urine	6–49	1,2,5
21	Mono-3-carboxypropyl phthalate (MCPP)	Urine	6–49	1,2,5
<i>Polycyclic aromatic hydrocarbons (PAHs)</i>				
22	Fluorene ^d	Urine	3–79	2,3,4
23	Naphthalene ^e	Urine	3–79	2,3,4
24	Phenanthrene ^f	Urine	3–79	2,3,4
25	1-Hydroxypyrene	Urine	3–79	2,3,4
<i>Volatile organic compounds (VOCs)</i>				
26	Ethylbenzene	Blood	12–79	3,4,5
27	Styrene	Blood	12–79	3,4,5
28	Toluene	Blood	12–79	3,4,5
29	<i>m</i> -, <i>p</i> -Xylene	Blood	12–79	3,4,5
30	<i>o</i> -Xylene	Blood	12–79	3,4,5
31	Benzene	Blood	12–79	3,4,5
32	S-Phenylmercapturic acid (S-PMA)	Urine	3–79	2,3,4
33	<i>trans,trans</i> -Muconic acid (<i>t,t</i> -MA)	Urine	3–79	2,3,4
<i>Pesticides</i>				
34	3-Phenoxybenzoic acid (3-PBA)	Urine	6–79	1,2,5
35	<i>cis</i> -DCCA ^g	Urine	6–79	1,2,5
36	<i>trans</i> -DCCA ^g	Urine	6–79	1,2,5
37	Dimethylphosphate (DMP)	Urine	6–79	1,2,5
38	Dimethylthiophosphate (DMTP)	Urine	6–79	1,2,5
39	Diethylphosphate (DEP)	Urine	6–79	1,2,5

^a For the purposes of evaluating trends, a consistent age group was used for each chemical across all cycles.

^b Calculated as the sum of arsenite, arsenate, dimethylarsinic acid (DMA), and monomethylarsonic acid (MMA).

^c Calculated as the sum of mono(2-ethylhexyl) phthalate (MEHP), mono(2-ethyl-5-hydroxyhexyl) phthalate (MEHHP), and mono(2-ethyl-5-oxohexyl) phthalate (MEOHP).

^d Calculated as the sum of 2-, 3-, and 9-hydroxyfluorene.

^e Calculated as the sum of 1- and 2-hydroxynaphthalene.

^f Calculated as the sum of 1-, 2-, 3-, 4-, and 9-hydroxyphenanthrene.

^g DCCA, 3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropane carboxylic acid.

conducted via the balanced repeated replication technique using the combined bootstrap weights. Combined weights were calculated by dividing the survey and bootstrap weights for each cycle by the number of cycles combined, as recommended by Statistics Canada (Statistics Canada 2019b). Survey weights include adjustment for non-response (Statistics Canada 2019a) and respondents with no reported results for one or more chemicals are excluded from statistical analysis for those chemicals only.

Statistics Canada recommends imputing half the analytical LOD for non-detects (Statistics Canada 2019a). However, the LODs differed across cycles for most chemicals included in the present study. For consistency across cycles and to ensure meaningful trend analyses, chemical concentrations below the highest, most conservative LOD (LOD_c) were replaced with values equal to the LOD_c divided by two (LaKind et al. 2019; Pollock et al. 2021). For example, the LODs for perfluorooctanoic acid (PFOA) were 0.3, 0.1, and 0.066 µg/L in cycles 1, 2, and 5, respectively. The LOD_c for PFOA was therefore 0.3 µg/L; all non-detects across all cycles were replaced with half the LOD_c, 0.15 µg/L. Furthermore, all detects with reported concentrations < 0.3 µg/L in cycles 2 and 5 were substituted with 0.15 µg/L. Detection rates were calculated following the re-screening and imputation process using the LOD_c. For chemicals represented by multiple biomarkers, the individual biomarkers were summed following re-screening and imputation according to the LOD_c for each individual analyte. Detection rates were not calculated for chemicals represented by multiple biomarkers. To further improve comparability of data across cycles and facilitate trend analyses, the age group was standardized for each chemical. Since children aged 3 to 5 years were not sampled in cycle 1 (2007–2009) of the CHMS, trends for chemicals that included the first cycle were limited to participants aged 6 to 79 years. Additionally, in cycle 1, per- and polyfluoroalkyl substances (PFAS) were measured in adults aged 20 to 79 years and phthalates were measured in 6 to 49 year olds. Although these chemicals were measured in participants aged 3 to 79 years in more recent cycles, trend analyses were limited to the age group of participants sampled in cycle 1 to maximize the number of collection time-points included in the analysis.

For assessing trends, analysis of variance models included the natural log-transformed chemical concentration (continuous) as the dependent variable and cycle (categorical) as the predictor variable. Then a linear contrast of cycle was constructed and tested to determine if a statistically significant trend exists. This method of trend analysis is called polynomial orthogonal contrasts and is commonly discussed in textbooks on experimental design (e.g., chapter 5 in Keppel 1982). When chemicals were measured in non-adjacent cycles, such as in cycles 1, 2, and 5, the linear contrast terms were re-weighted to account for unequal spacing between cycles. For the purposes of depicting trends in figures and permitting comparisons among chemicals, the GM of each chemical was set to 1.0 for the first cycle measured; all other GMs and confidence intervals (CIs) were standardized to the GM of the first cycle measured. In addition to trend results across all cycles, the first cycle measured was also compared directly to the most recent cycle measured. For all chemicals, the comparison was made between the earliest available result from cycle 1, 2, or 3 and the latest available result from either cycle 4 or 5. ANOVA was used to test whether natural log-transformed chemical concentrations differed between the two cycles. Beta coefficients and associated CIs for the main effect of cycle were exponentiated to back-calculate the percent change (and associated CIs) in GMs between cycles. The degrees of freedom for each analysis varied based on the cycles being combined (ranging from 22 to 57). In each case, degrees of freedom were calculated as the difference between the number of collection sites (primary sampling units) and the number of regions sampled (strata); there were 11 degrees of freedom for each of cycles 1, 3, 4, and 5, and 13 degrees of freedom for cycle 2.

3. Results

3.1. Metals and trace elements

Seven metals and trace elements were assessed for trends in Canadians aged 3 or 6 to 79 years: inorganic arsenic, DMA, and fluoride in urine; and mercury, lead, cadmium, and selenium in blood. The percent differences between the first and most recent cycle measured are depicted in Fig. 1 and the trends across all cycles measured are shown in Fig. 2. Detailed information, such as detection rates and non-standardized GMs, is provided in Supplemental Table 1. Statistically significant decreasing trends were observed for lead, cadmium, and selenium ($p < 0.001$). In comparing the GMs between cycles 1 and 5, there was a 33% (26–39%) decline for lead, a 22% (13–30%) decline for cadmium, and a 16% (14–18%) decline for selenium. Concentrations of inorganic arsenic, DMA, mercury, and fluoride did not differ across cycles; no significant trend or percent difference was observed for these chemicals.

3.2. Phenols and parabens

Four phenols and parabens were assessed for trends in Canadians aged 3 or 6 to 79 years: bisphenol A (BPA), triclosan, methyl paraben, and propyl paraben in urine. The percent differences between the first and most recent cycle measured are depicted in Fig. 1 and the trends across all cycles measured are shown in Fig. 3. Detailed information is provided in Supplemental Table 2. Statistically significant decreasing trends were observed for BPA ($p < 0.001$), triclosan ($p = 0.004$), methyl paraben ($p = 0.017$), and propyl paraben ($p = 0.005$). In comparing GMs between cycles 1 and 5, there was a 32% (21–42%) decline for BPA. There was a 31% (12–45%) decline for triclosan between cycles 2 and 4, as well as a 32% (6.6–50%) decline for methyl paraben and a 36% (13–53%) decline for propyl paraben between cycles 3 and 5.

3.3. Acrylamide

Acrylamide hemoglobin adduct and glycidamide hemoglobin adduct in blood were assessed for trends as indicators of acrylamide exposures in Canadians aged 3 to 79 years. The percent differences between cycles

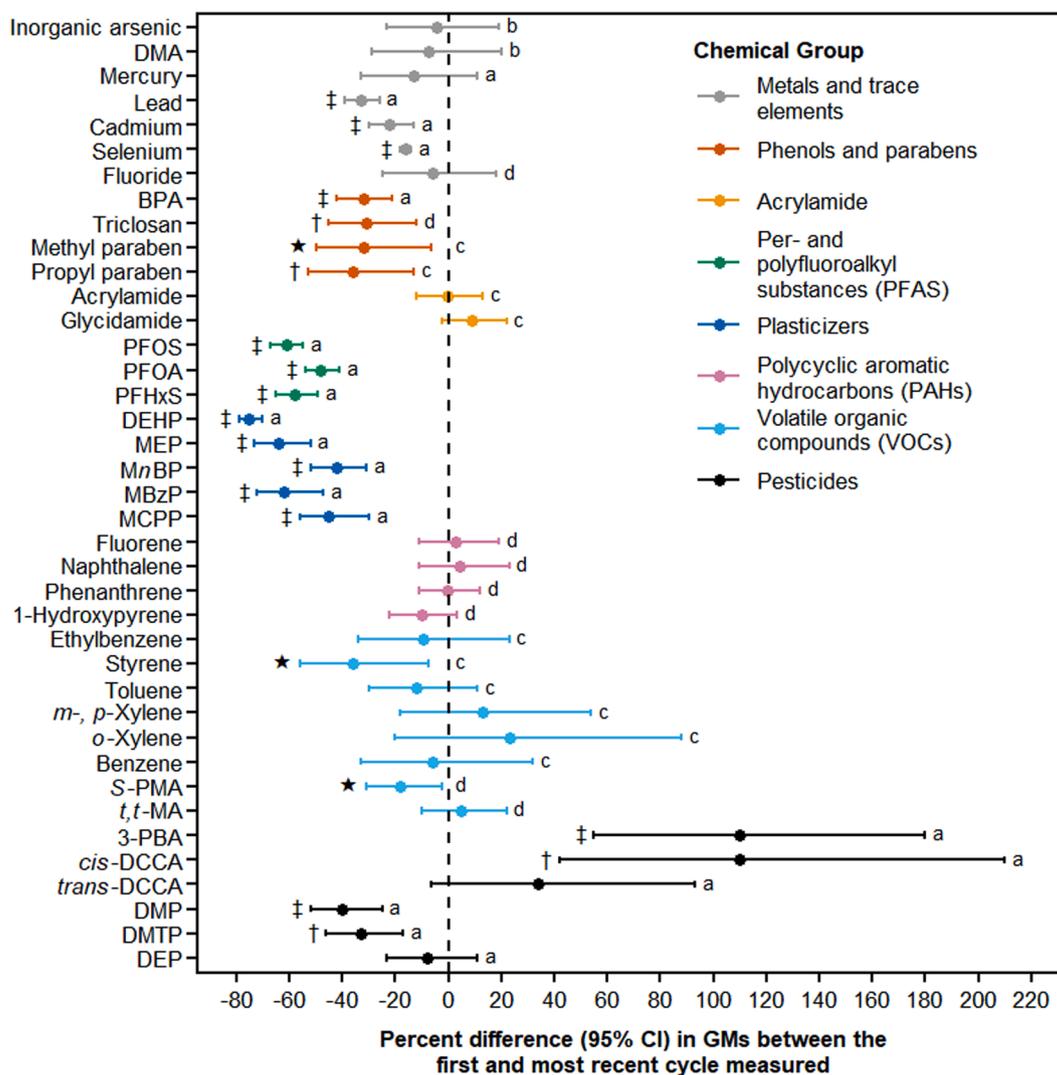


Fig. 1. Percent difference (95% CI) in geometric means between the first and most recent cycle measured for each chemical. Significant difference between the first and most recent cycle measured: ‡ $p < 0.001$, † $p < 0.01$, ★ $p < 0.05$. Comparisons were made between the following two cycles: a) 1 and 5, b) 2 and 5, c) 3 and 5, d) 2 and 4. DMA, dimethylarsinic acid; BPA, bisphenol A; PFOS, perfluorooctane sulfonate; PFOA, perfluorooctanoic acid; PFHxS, perfluorohexane sulfonate; DEHP, di-2-ethylhexyl phthalate; MEP, mono-ethyl phthalate; MnBP, mono-*n*-butyl phthalate; MBzP, mono-benzyl phthalate; MCPP, mono-3-carboxypropyl phthalate; S-PMA, S-phenylmercapturic acid; *t,t*-MA, *trans,trans*-muconic acid; 3-PBA, 3-phenoxybenzoic acid; DCCA, 3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropane carboxylic acid; DMP, dimethylphosphate; DMTP, dimethylthiophosphate; DEP, diethylphosphate; CI, confidence interval; GM, geometric mean.

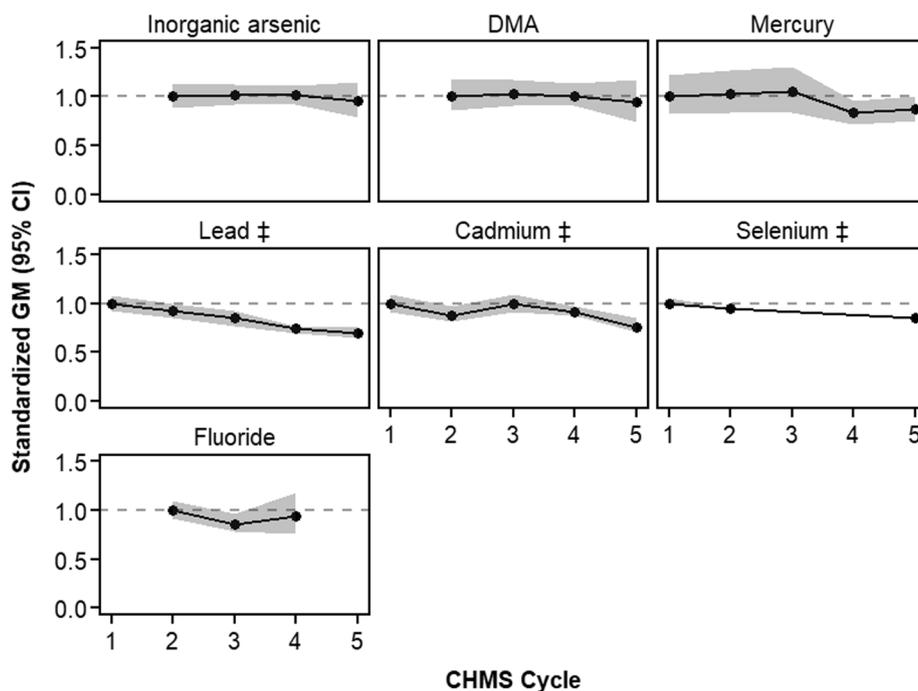


Fig. 2. Standardized GM (95% CI) of metals and trace elements. The GM of each chemical was set to 1.0 for the first cycle measured; all other GMs and CIs were standardized to the GM of the first cycle measured. Significant trend across all cycles measured: ‡ $p < 0.001$. GM, geometric mean; CI, confidence interval; DMA, dimethylarsinic acid.

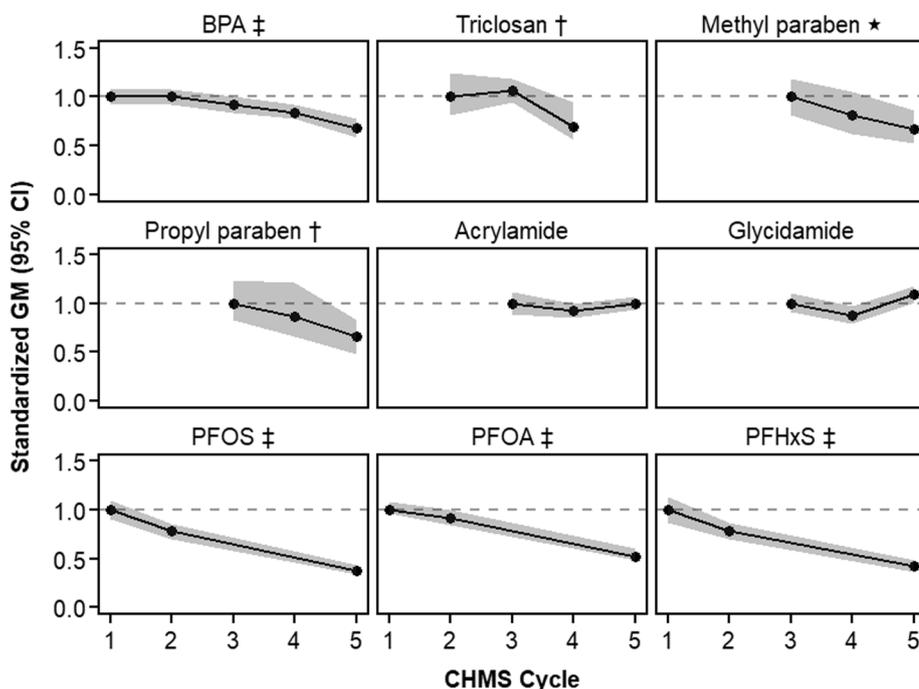


Fig. 3. Standardized GM (95% CI) of phenols and parabens, acrylamide, and per- and polyfluoroalkyl substances (PFAS). The GM of each chemical was set to 1.0 for the first cycle measured; all other GMs and CIs were standardized to the GM of the first cycle measured. Significant trend across all cycles measured: ‡ $p < 0.001$, † $p < 0.01$, ★ $p < 0.05$. GM, geometric mean; CI, confidence interval; BPA, bisphenol A; PFOS, perfluorooctane sulfonate; PFOA, perfluorooctanoic acid; PFHxS, perfluorohexane sulfonate.

3 and 5 are depicted in Fig. 1 and the trends across the three cycles measured are shown in Fig. 3. Detailed information is provided in Supplemental Table 3. Concentrations of acrylamide and glycidamide hemoglobin adducts did not differ across cycles; no significant trends or percent differences were observed.

3.4. Per- and polyfluoroalkyl substances (PFAS)

Three PFAS were assessed for trends in Canadians aged 20 to 79

years: perfluorooctane sulfonate (PFOS), PFOA, and perfluorohexane sulfonate (PFHxS) in blood plasma. The percent differences between cycles 1 and 5 are depicted in Fig. 1 and the trends across the three cycles measured are shown in Fig. 3. Detailed information is provided in Supplemental Table 4. Statistically significant decreasing trends were observed for all three chemicals ($p < 0.001$). In comparing GMs between cycles 1 and 5, there was a 61% (55–67%) decline for PFOS, a 48% (41–54%) decline for PFOA, and a 58% (49–65%) decline for PFHxS.

3.5. Plasticizers

Five phthalates were assessed for trends in Canadians aged 6 to 49 years: DEHP, mono-ethyl phthalate (MEP), mono-*n*-butyl phthalate (MnBP), mono-benzyl phthalate (MBzP), and mono-3-carboxypropyl phthalate (MCPP) in urine. The percent differences between cycles 1 and 5 are depicted in Fig. 1 and the trends across the three cycles measured are shown in Fig. 4. Detailed information is provided in Supplemental Table 5. Statistically significant decreasing trends were observed for all five chemicals ($p < 0.001$). In comparing GMs between cycles 1 and 5, there was a 75% (70–79%) decline for DEHP, a 64% (52–73%) decline for MEP, a 42% (31–52%) decline for MnBP, a 62% (47–72%) decline for MBzP, and a 45% (30–56%) decline for MCPP.

3.6. Polycyclic aromatic hydrocarbons (PAHs)

Four PAHs were assessed for trends in Canadians aged 3 to 79 years: fluorene, naphthalene, phenanthrene, and 1-hydroxypyrene in urine. The percent differences between cycles 2 and 4 are depicted in Fig. 1 and the trends across the three cycles measured are shown in Fig. 4. Detailed information is provided in Supplemental Table 6. Concentrations of all four PAHs did not differ across cycles; no significant trends or percent differences were observed.

3.7. Volatile organic compounds (VOCs)

Eight VOCs were assessed for trends in Canadians aged 3 or 12 to 79 years: ethylbenzene, styrene, toluene, *m*-, *p*-xylene, *o*-xylene, and benzene in blood, and *S*-phenylmercapturic acid (*S*-PMA) and *trans,trans*-muconic acid (*t,t*-MA) in urine. The percent differences between the first and most recent cycle measured are depicted in Fig. 1 and the trends across the three cycles measured are shown in Fig. 5. Detailed information is provided in Supplemental Table 7. Statistically significant decreasing trends were observed for styrene ($p = 0.018$) and *S*-PMA ($p = 0.026$). There was a 36% (7.3–56%) decline in the GMs of styrene between cycles 3 and 5 and an 18% (2.2–31%) decline for *S*-PMA between cycles 2 and 4. Concentrations of the remaining six VOCs (ethylbenzene, toluene, *m*-, *p*-xylene, *o*-xylene, benzene, and *t,t*-MA) did not differ across cycles; no significant trend or percent difference was

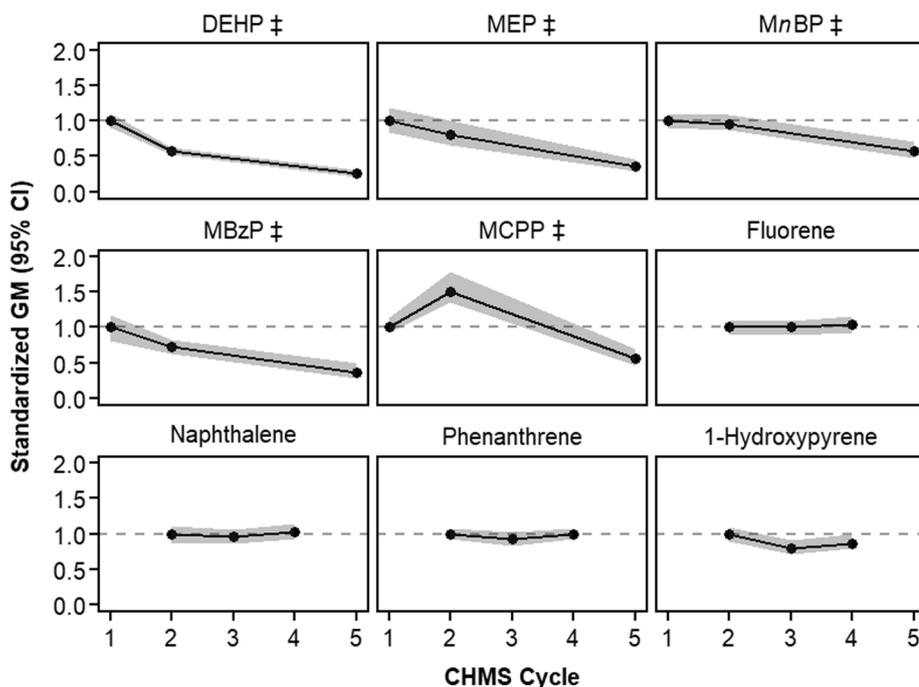


Fig. 4. Standardized GM (95% CI) of plasticizers and polycyclic aromatic hydrocarbons (PAHs). The GM of each chemical was set to 1.0 for the first cycle measured; all other GMs and CIs were standardized to the GM of the first cycle measured. Significant trend across all cycles measured: ‡ $p < 0.001$. GM, geometric mean; CI, confidence interval; DEHP, di-2-ethylhexyl phthalate; MEP, mono-ethyl phthalate; MnBP, mono-*n*-butyl phthalate; MBzP, mono-benzyl phthalate; MCPP, mono-3-carboxypropyl phthalate.

observed for these chemicals.

3.8. Pesticides

Three metabolites of pyrethroid pesticides [3-phenoxybenzoic acid (3-PBA), *cis*-3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropane carboxylic acid (*cis*-DCCA), and *trans*-DCCA] and three metabolites of organophosphate pesticides [dimethylphosphate (DMP), dimethylthiophosphate (DMTP), and diethylphosphate (DEP)] in urine were assessed for trends in Canadians aged 6 to 79 years. The percent differences between cycles 1 and 5 are depicted in Fig. 1 and the trends across the three cycles measured are shown in Fig. 6. Detailed information is provided in Supplemental Table 8. Statistically significant increasing trends were observed for 3-PBA ($p < 0.001$) and *cis*-DCCA ($p = 0.001$). In comparing GMs between cycles 1 and 5, there was a 110% (55–180%) increase for 3-PBA and a 110% (42–210%) increase for *cis*-DCCA. Concentrations of *trans*-DCCA did not differ across cycles; no significant trend or percent difference was observed. Significant decreasing trends were observed for DMP ($p < 0.001$) and DMTP ($p < 0.001$). There was a 40% (25–52%) decline for DMP and a 33% (17–46%) decline for DMTP between the GMs of cycles 1 and 5. No significant trend or percent difference was observed for DEP.

4. Discussion

In assessing temporal trends of national biomonitoring data over ten years of the CHMS (2007–2017), we found significant declining trends for 19 of 39 environmental chemicals that represent diverse chemical groups, including metals and trace elements, phenols and parabens, PFAS, plasticizers, organophosphate pesticides, and VOCs. In comparing GMs between the first and most recent cycle measured for these chemicals, reductions ranged from 16% to 75%. Most of these trends represented a substantial decrease in exposures in the Canadian population; the GMs for 16 of 19 chemicals declined by at least 30%. We also observed significant increasing trends for two metabolites of pyrethroid pesticides. No significant trends were found for the remaining 18 chemicals, which included arsenic, mercury, fluoride, acrylamide, PAHs, and VOCs; concentrations of these substances did not substantially change over time.

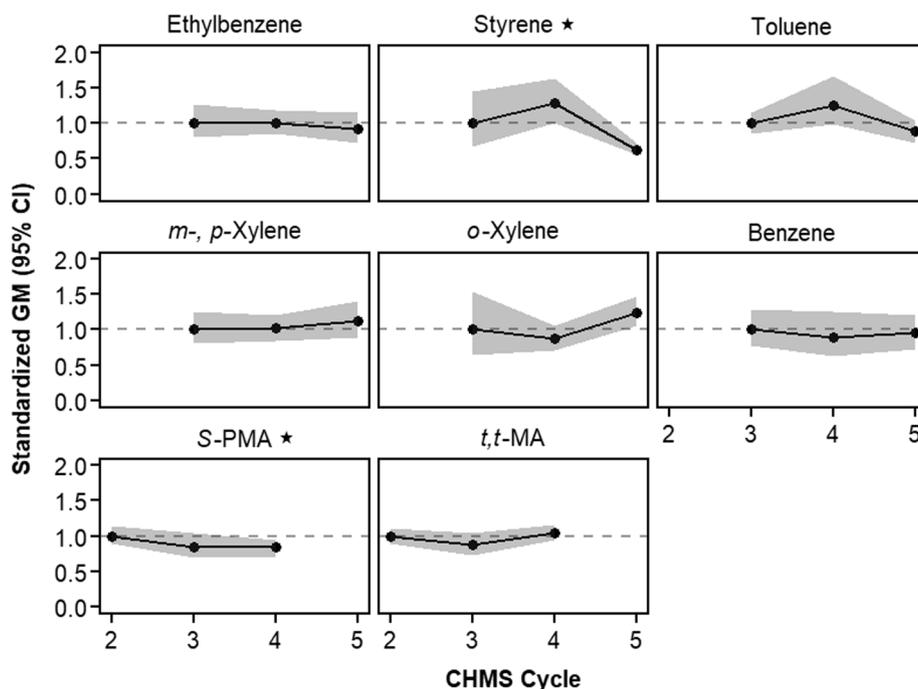


Fig. 5. Standardized GM (95% CI) of volatile organic compounds (VOCs). The GM of each chemical was set to 1.0 for the first cycle measured; all other GMs and CIs were standardized to the GM of the first cycle measured. Significant trend across all cycles measured: ★ $p < 0.05$. GM, geometric mean; CI, confidence interval; S-PMA, S-phenylmercapturic acid; *t,t*-MA, *trans,trans*-muconic acid.

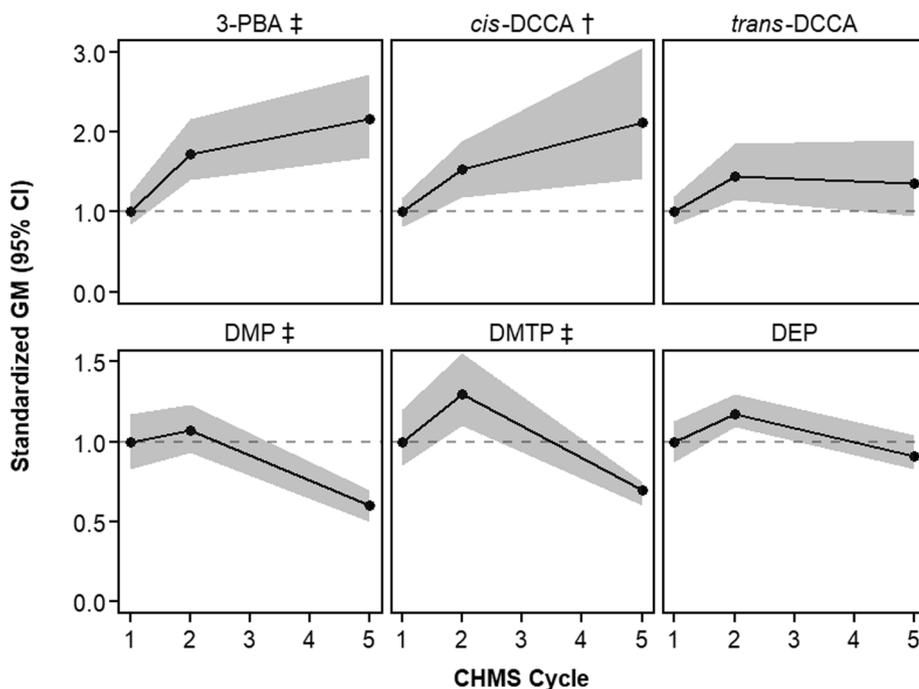


Fig. 6. Standardized GM (95% CI) of pyrethroid and organophosphate pesticides. The GM of each chemical was set to 1.0 for the first cycle measured; all other GMs and CIs were standardized to the GM of the first cycle measured. Significant trend across all cycles measured: ‡ $p < 0.001$, † $p < 0.01$. GM, geometric mean; CI, confidence interval; 3-PBA, 3-phenoxybenzoic acid; DCCA, 3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropane carboxylic acid; DMP, dimethylphosphate; DMTP, dimethylthiophosphate; DEP, diethylphosphate.

To the best of our knowledge, this is the first study to test and report detailed temporal trends of national biomonitoring data from the first five cycles of the CHMS. Exhaustive trend analysis of all measures in the CHMS, including nutritional, clinical, and chemical biomarkers, was conducted for cycles 1 to 4 (Chao et al. 2018); the study authors recently updated this trend analysis to include data from cycles 1 to 5 (Chao et al. 2020). Chao et al. (2020) provided valuable commentary on the opportunities and challenges in conducting trend analysis on national health survey data, including specific recommendations that can be

taken by survey administrators to facilitate trend analysis. However, results for only the ten substances with the greatest decreases and the ten substances with the greatest increases were reported in the study. Most of the increases and decreases reported were for chemicals measured in household indoor air over two cycles (2009–2013) of the CHMS.

Temporal trends have been extensively conducted for population biomonitoring data from other countries, such as the U.S., Germany, Belgium, and Korea. Using data from the U.S. NHANES, trends have been examined for various chemicals in the general population,

including BPA (Calafat et al. 2015; LaKind et al. 2019), triclosan (Han et al., 2016), phthalates (Calafat et al. 2015; Reyes and Price 2018), and PFAS (Dong et al. 2019). Temporal trends of NHANES data representing diverse chemical groups, including metals, phenols, PAHs, phthalates, and pesticides, were also assessed specifically in children (Hendryx and Luo 2018). The decreasing trends observed in this study were generally comparable with those observed in the U.S., presumably due to similarities in import, use, and, in some cases, regulation of these chemicals. Representative data from the German Environmental Survey (GerES) indicate similar decreasing trends between the German and Canadian populations for various substances, including lead (Becker et al. 2013; Lermen et al. 2021), phenols (Tschersich et al. 2021), PAHs (Murawski et al. 2020), and phthalate metabolites (Schwedler et al. 2020). Time trends of biomonitoring data from the Flemish Environment and Health Study (FLEHS) were also comparable to those observed for the Canadian population, with decreases observed for lead, cadmium, PFAS, and phthalates (Schoeters et al. 2017). Lead, cadmium, and mercury decreased in the Korean adult population between 2008 and 2011 (Seo et al. 2015). Blood metal concentrations were higher in the Korean population relative to the Canadian population, which may explain why a trend was observed for blood mercury in the Korean, but not Canadian, population.

Determining the underlying explanations for the observed temporal trends or the lack thereof for each chemical is a challenging endeavor and outside the scope of this study. Recent risk management actions intended to reduce environmental releases and human exposures appear to have contributed to the decline in lead (Government of Canada 2020a), mercury (Government of Canada 2020b), and DEHP concentrations (Government of Canada 2020c). Regulations pertaining to lead and mercury in Canada include those directed toward reducing industrial releases, as well as limits on the amount in some products available to consumers, certain foods, and drinking water (Government of Canada 2020a, 2020b). In Canada, DEHP is prohibited from use in cosmetics and regulations also limit the use of DEHP in products intended for children, such as soft vinyl toys and child-care articles (Government of Canada 2020c). In addition, the decreases observed for chemicals assessed here may generally be due to some combination of risk management actions, public health measures, voluntary industry initiatives, consumer awareness, and/or the use of replacement chemicals. Despite no trend being observed for several chemicals and an increasing trend observed for two metabolites of pyrethroid pesticides, average concentrations in the population remain below thresholds of concern (Faure et al. 2020), which are derived from exposure guidance values and often expressed as biomonitoring equivalents (Hays et al. 2007) or human biomonitoring (HBM) values (Schulz et al. 2011). However, concentrations of some chemicals in highly exposed individuals are above at least one threshold of concern. This was the case for cadmium, acrylamide, and benzene in smokers (which have significantly higher concentrations than non-smokers), as well as inorganic arsenic, PFOS, PFOA, 3-PBA, and fluoride at the 95th percentile in the general population (Faure et al. 2020). Furthermore, cancer risk of acrylamide and benzene in smokers, as well as inorganic arsenic in the general population, were above the range considered to be essentially negligible risk (Faure et al. 2020). However, caution must be exercised when interpreting elevated cancer risk given that there are uncertainties associated with cancer risk estimation, especially when extrapolating from the cancer slope factor to assess low concentrations in the population (Faure et al. 2020).

Although biomonitoring data from national health surveys are well suited to assess temporal trends of environmental chemical exposures in the population, there are some limitations when attempting to interpret the public health significance of these trends. One important limitation is the cross-sectional sampling design which, although suitable for quantifying temporal trends, does not capture repeated measures in each participant that could inform associations with health outcomes. Furthermore, the collection of spot urine and blood samples for chemical analyses does not permit estimation of total body burden that is

pertinent for establishing links with health outcomes. This is especially important for non-persistent chemicals with short half-lives, such as BPA (Völkel et al. 2002), triclosan (Sandborgh-Englund et al. 2006), phthalates (Shin et al. 2019), and parabens (Koch et al. 2004). Indeed, BPA, triclosan, and phthalates showed low to moderate reproducibility across repeated measures over time in pregnant women (Fisher et al. 2015; Weiss et al. 2015). In addition to these limitations, the use of national survey data may not permit evaluation of temporal trends for specific regions. In the case of CHMS, data from multiple cycles must be combined to produce reliable estimates that are representative of the populations in Ontario, Quebec, and the rest of Canada (Valcke et al., 2020). This process of combining data across cycles prevents the assessment of time trends in sub-regions of Canada. Nevertheless, biomonitoring data from the CHMS still provide an abundance of valuable information, and are the only data that can be used to explore temporal trends in a sample representative of the Canadian population.

5. Conclusions

Given the significant declining trends observed for many environmental chemicals in the first five cycles of the CHMS, it is critical to reassess and confirm these trends following the release of data from cycle 6 (2018–2019). Furthermore, continued collection of national biomonitoring data is necessary to establish temporal trends for emerging chemicals, such as bisphenol analogues (e.g., bisphenol S and bisphenol F) and novel plasticizers (e.g., 1,2-cyclohexane dicarboxylic acid diisononyl ester, commonly referred to as DINCH), which may be used as substitutes for similar chemicals with declining concentrations in the population. Future studies of biomonitoring data from the CHMS should consider using multiple cycles of data to ensure that findings, such as the links among chemical concentrations, determinants of exposure, and health outcomes, persist over time, especially in cases where a temporal trend is evident.

CRedit authorship contribution statement

Tyler Pollock: Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization. **Subramanian Karthikeyan:** Conceptualization, Methodology, Writing - review & editing. **Mike Walker:** Methodology, Formal analysis, Writing - review & editing. **Kate Werry:** Conceptualization, Methodology, Writing - review & editing. **Annie St-Amand:** Conceptualization, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2021.106678>.

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