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Are we using more sugar substitutes? Wastewater analysis reveals differences and rising trends in artificial sweetener usage in Swedish urban catchments

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ABSTRACT

The market for artificial sweeteners as substitutes for conventional sugar (sucrose) is growing, despite potential health risks associated with their intake. Estimating population usage of artificial sweeteners is therefore crucial, and wastewater analysis can serve as a complement to existing methods. This study evaluated spatial and temporal usage of artificial sweeteners in five Swedish communities based on wastewater analysis. We further compared their levels measured in wastewater with the restrictions during the COVID-19 pandemic in Sweden and assessed health risks to the Swedish population. Influent wastewater samples ($n = 194$) collected in March 2019-February 2022 from communities in central and southern Sweden were analyzed for acesulfame, saccharin, and sucralose using liquid-chromatography coupled with tandem mass spectrometry. Spatial differences in loads for individual artificial sweetener were observed, with sucralose being higher in Kalmar (southern Sweden), and acesulfame and saccharin in Enköping and Östhammar (central Sweden). Based on sucrose equivalent doses, all communities showed a consistent prevalence pattern of sucralose > acesulfame > saccharin. Four communities with relatively short monitoring periods showed no apparent temporal changes in usage, but the four-year monitoring in Uppsala revealed a significant ($p < 0.05$) annual increase of ~19 % for sucralose, ~9 % for acesulfame and ~8 % for saccharin. This trend showed no instant or delayed effects from COVID-19 restrictions, reflecting positively on the studied population which retained similar exposure to the artificial sweeteners despite potential pandemic stresses. Among the three artificial sweeteners, only acesulfame's levels were at the lower end of the health-related threshold for consumption of artificially sweetened beverages; yet, all were far below the acceptable daily intake, indicating no appreciable health risks. Our study provided valuable, pilot insights into the spatio-temporal usage of artificial sweeteners in Sweden and their associated health risks. This shows the usefulness of wastewater analysis for public health authorities wishing to assess future relevant interventions.

1. Introduction

Excessive sugar intake is a dietary contributor to overweight and obesity, and poses a major problem for local governments and health sectors worldwide (Flieh et al., 2020; Turck et al., 2022). Artificial sweeteners are significantly sweeter than conventional sugar (sucrose), but have no calories. Thus, the popularity of artificial sweeteners on the global food market, as substitutes for sugar, has increased in recent years (Sylvetsky and Rother, 2016). Certain artificial sweeteners are approved by the European Chemical Agency as food additives in processed products such as canned and bottled fruits, jams, candy, desserts, and beverages, and are often found in low-energy products (e.g., diet sodas)

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The use of artificial sweeteners is controversial, due to concerns about carcinogenicity (Landrigan and Straif, 2021) and the potential for promoting obesity and type II diabetes (Rios-Leyvraz and Montez, 2022). Monitoring the usage of artificial sweeteners in populations is therefore crucial, but is challenging. To date, monitoring has mainly been based on infrequent self-reported population surveys, and on manufacturing and household sales data (Sylvetsky and Rother, 2016). However, these methods can lead to under- or over-estimation, due to, for example, unconscious consumption of artificial sweeteners by survey participants, missing or inaccessible manufacturing data, and sales data not necessarily correlating to actual intake of artificial sweeteners (Sylvetsky and Rother, 2016).

Wastewater-based epidemiology (WBE) has been shown to be a useful approach for evaluating exposure and usage of different substances (Choi et al., 2018; Gracia-Lor et al., 2020) with results that can reveal, for example, population lifestyle (Gracia-Lor et al., 2020), stress levels (Choi et al., 2020a), and health status (Kasprzyk-Hordern et al., 2023; Ahmed et al., 2020; Lundy et al., 2021). Levels of artificial sweeteners in influent wastewater and their related environmental fate were previously studied, for example, in Switzerland (Buerge et al., 2009), Germany (Scheurer et al., 2011), the US (Subedi & Kannan, 2014), Vietnam (Nguyen et al., 2018) and Australia (Li et al., 2020). Temporal trends in population usage of artificial sweeteners were estimated for the first time by Li et al. (2021), in which seasonal changes and increasing trends in artificial sweetener consumption were identified in an Australian catchment. In Sweden, WBE has not been applied to evaluate population usage of artificial sweeteners, but illicit drugs (Haalck et al., 2021) and also recently SARS-CoV-2 RNA (Isaksson et al., 2022; Perez-Zabaleta et al., 2023; Saguti et al., 2021).

During the COVID-19 pandemic, several WBE studies were performed to reveal behavioral changes regarding e.g., illicit drug use, alcohol consumption, and pharmaceutical use across several European countries (Boogaerts et al., 2022; Estévez-Danta et al., 2022; Galani et al., 2021; Reinstadler et al., 2021). Changes in artificial sweetener usage in relation to the pandemic were reported in a previous study from Greece, in which higher artificial sweetener loads were observed during lock-down as compared to pre-covid conditions in a wide-scope target and suspect screening (Alygizakis et al., 2021). Additionally, survey-based studies have shown that COVID-19 restrictions negatively influenced people's mental health and caused behavioral changes in terms of physical exercise, social interactions, and eating habits (Bemanian et al., 2020; Bracale and Vaccaro, 2020). In particular, people consumed greater quantities of food than usual during lockdown periods and more often chose to eat 'comfort foods' (e.g., sodas, pastries, desserts) (Bracale and Vaccaro, 2020; Janssen et al., 2021).

The aim of the present study was to evaluate usage of the artificial sweeteners, acesulfame, sucralose, and saccharin in different Swedish local populations and over time, based on analysis of influent wastewater. The specific objectives were to: (a) determine the usage across five communities in Sweden; (b) investigate whether the implementation and lifting of COVID-19 restrictions influenced the artificial sweetener loads over time, and consequently whether changes in population exposure to the artificial sweeteners were induced by the pandemic; and (c) evaluate whether the consumption levels calculated from wastewater analysis pose health risks to the studied population.

2. Materials and methods

2.1. Chemicals and reagents

Reference native standards (acesulfame, saccharin and sucralose) and isotopically-labelled internal standards (IS; acesulfame-D_4, Hydrochlorothiazide-$^{13}C_6$ and sucralose-D_6) were purchased from Sigma-Aldrich, Alsachim, and TRC, as neat powders, and dissolved in methanol to obtain a stock solution (1000 μg mL^{-1}). A working solution (10 μg mL^{-1}) was also prepared in methanol for each of the native compounds and isotopically-labelled compounds. All stock and working solutions were stored at −20 °C. Methanol solvent and acetic acid (>99 %) of LC-grade were purchased from Merck and Sigma-Aldrich. MilliQ water (LC-PAK) was generated in our laboratory, in a Milli-Q® IQ-7000 purification system with 0.22 μm filters, Millipak Express membrane, and an LC-PAK polishing unit (Merk Millipore, Billercia, MA, USA).

2.2. Wastewater collection

Samples of influent wastewater were taken at the major wastewater treatment plants (WWTP) of five Swedish communities (Östhammar, Knivsta, Enköping, Kalmar, Uppsala) with varying population sizes (Table 1). All samples (Table S1 and Fig. S1) were collected using a flow-dependent sampling method. In Östhammar, Knivsta, Enköping, and Kalmar, one 24-h composite sample was taken per week. In Uppsala, seven 24-h composite samples were combined according to the daily flow rate into one weekly composite sample. Östhammar was the smallest community, with a population of 4500, and a total of 31 influent wastewater samples was collected from its WWTP, covering 27 weeks in 2021 plus another four weeks in 2022. Knivsta has a population size of 11 000 inhabitants and 10 samples were taken from its WWTP, all in 2021. Enköping has a population of 30 000 inhabitants and a total of 32 samples was collected at its WWTP, covering 24 weeks in 2021 and eight weeks in 2022. Kalmar (population 66 000) was the second largest community included in the study, and 16 wastewater samples covering eight weeks in 2021 and eight weeks in 2022 were taken at its WWTP. The largest community included in the study was Uppsala, with 200 000 inhabitants (in 2022; Table S2) and 91 available wastewater samples, covering almost two years.

In total, 180 weekly wastewater samples were analyzed, plus an additional 14 daily composite samples taken in Uppsala during spring and autumn 2019 (Haalck et al., 2021) to assess the pre-Covid situation and reveal any change in usage. All samples were transported to our laboratory within two hours after collection and stored at −20 °C, except for those from Kalmar which were delivered within two days in low-temperature transport, due to geographical constraints. Stability of acesulfame, sucralose and saccharin was previously studied and considered high in gravity sewer reactors, rising main sewer reactors and biofilm free conditions (Choi et al., 2020b, Li et al., 2020).

2.3. Sample preparation and analysis

Wastewater samples were defrosted, vortexed, and centrifuged at

Table 1
Sampling locations, population size, sampling times, and number of samples analyzed. The sampling period is visualized in Fig. S1.

Location	Population[a]	Time (year/week number)	Number of Samples
Östhammar	4 500	2021/14–2021/25; 2021/36–2021/51; 2022/05–2022/08	31
Knivsta	11 000	2021/14–2021/16; 2021/18–2021/20; 2021/22–2021/24; 2021/26	10
Enköping	30 000	2021/19; 2021/22–2021/24; 2021/26; 2021/28; 2021/32–2022/08	32
Kalmar	66 000	2021/44–2021/48; 2021/50–2021/52; 2022/01–2022/08	16
Uppsala	191 000 –200 000[b]	2020/13–2022/08 2019/11; 2019/42	91 14 Total: 194

[a] Székely et al. (2021).
[b] See Table S2 for population size in 2019–2022.

9500 rpm for 10 min. Each sample (160 μL) was spiked with IS (20 μL of 100 ng mL^{-1}) and methanol (20 μL). Together with nine calibration standards (0–250 ng mL^{-1} with IS 10 ng mL^{-1} each), the target compounds in the samples were analyzed by direct injection onto a system of ultra-high performance liquid chromatograph (HPLC) coupled with tandem mass spectrometry (MS/MS) (ExionLC™ SCIEX® 3500 Triple Quad™). Data acquisition was performed using multiple reaction monitoring (MRM) in negative ionization mode (Table S3). Mobile phase A (0.1 % acetic acid in MilliQ water) and mobile phase B (0.1 % acetic acid in methanol) were used for a run of 15.5 min at 0.5 mL min^{-1} in a gradient of: 0.5 min, 10 % B (convex gradient, −3); 2 min, 20 % B; 7 min, 75 % B (convex gradient, −4); 9–12 min, 100 % B; 12.1–15.5 min, 10 % B. The injection volume was 20 μL. Chemical separation was performed on a Phenomenex® Kinetex® Biphenyl Column (100x2.1 mm, 2.6 μm) at 40 °C oven temperature. Both acesulfame and acesulfame-D_4 showed a retention time at 1.25 min, saccharin at 2.53 min, hydrochlorothiazide-$^{13}C_6$ at 2.80 min, and both sucralose and sucralose-D_6 at 3.20 min. Quantifications take into account the correction of responses between native and IS compounds, in which acesulfame is coupled with acesulfame-D_4, saccharin with hydrochlorothiazide-$^{13}C_6$, and sucralose with sucralose-D_6. Method detection limit (MDL) and method quantification limit (MQL) were determined using wastewater samples at low levels, showing a signal-to-noise ratio of 3 and 10, respectively. MQL was estimated at 0.5 μg L^{-1} for acesulfame and saccharin and at 2 μg L^{-1} for sucralose.

2.4. Quality assurance and quality control

MilliQ water blank samples were included in each sample preparation batch to monitor potential contamination. Duplicate or native-spiked samples were also prepared every 20th wastewater samples. For the native-spiked samples, a wastewater sample (160 μL) was spiked with IS (20 μL of 100 ng mL^{-1}) and native standard (20 μL of 100 ng mL^{-1}). A side-spike standard, prepared with MilliQ water (160 μL) spiked with IS standards (20 μL of 100 ng mL^{-1}) and native standards (20 μL of 100 ng mL^{-1}), was also included to evaluate any inter-day variation in spiking of each sample preparation batch. Side-spike standards and calibration standards were injected at least three times during sample analysis. MilliQ water blank samples showed no contamination with the target compounds during sample preparation and analysis. Recovery was calculated by comparing the difference between native-spiked samples and the corresponding non-spiked samples to the mean of the side-spike standards. The average recovery rate was 104 % for acesulfame, 102 % for sucralose, and 124 % for saccharin. Within-day precision was determined as relative standard deviation (RSD%) of duplicate samples, and was on average 2.9 % for acesulfame, 3.3 % for sucralose, and 3.9 % for saccharin. Between-day variation (RSD%) in sample preparation and analysis was determined using the side-spike standards across three days, and was 4.7 % for acesulfame, 6.1 % for sucralose, and 4.1 % for saccharin. Based on repeated analysis of a 10 ng mL^{-1} standard solution (n = 5), within-run instrumental variation (RSD %) was 0.54 % for acesulfame, 2.8 % for sucralose, and 17 % for saccharin. Linearity (r^2) over the nine-point calibration range with at least three time-analyses was 0.999 for acesulfame, 0.998 for sucralose, and 0.999 for saccharin.

2.5. Data calculations

Daily mass load per 1000 people (g day^{-1} 1000 people^{-1}) was calculated by multiplying concentrations (g L^{-1}) by daily wastewater flow (L day^{-1}), and then normalization to the population size:

$$Daily\ mass\ load\ \left(g\ day^{-1}\ 1000\ people^{-1}\right) = \frac{Concentration\ \left(g\ L^{-1}\right)\ \times\ Flow\ rate\ \left(L\ day^{-1}\right)}{Population\ Size\ (in\ a\ thousand)} \quad (1)$$

Following consumption or exposure, acesulfame, saccharin, and sucralose, are mainly (~99 %) excreted as parent compounds, without being metabolized to other forms (Magnuson et al., 2016), and therefore, they are not a source of energy when consumed. Their influent mass loads could reflect usage of these chemicals in the catchments represented by the wastewater samples (Li et al., 2020). Nevertheless, direct disposal of these chemicals to sewer network, e.g., from household sinks, cannot be excluded. In the Uppsala catchment, population data for each year from 2019 to 2022 (Table 1, Table S2) were provided by the local WWTP and used to calculate population-normalized figures. Details about the concentrations, flow rates and populations are provided in the Supporting Information (Tables S1, S2 and S4.1–S4.5).

Artificial sweeteners are significantly sweeter than conventional sugar (sucrose), but vary in their intensity. Acesulfame and saccharin are 200- and 300-times sweetener than sucrose, respectively (Luo et al., 2019). Sucralose is the sweetest of the three compounds studied, with an intensity 600-times higher than sucrose. To account for these varying sweetness levels, sucrose equivalent dose (SED) was calculated (Eq. (2)), as proposed in previous studies (Li et al., 2020, 2021):

$$SED\ \left(kg\ day^{-1}\ 1000\ people^{-1}\right) = Per\ capita\ mass\ load\ \left(g\ day^{-1}\ 1000\ people^{-1}\right) \times Sweetening\ intensity \quad (2)$$

2.6. Trend and statistical analyses

A regression model was used to investigate trends in usage of acesulfame, saccharin, and sucralose in Uppsala from 2019 to 2022. The usage variables were log-transformed prior to analysis, leading to an estimate of the percentage increase per year for each artificial sweetener. Usage patterns during the COVID-19 pandemic were evaluated using a generalized additive mixed model (GAMM) (Hastie and Tibshirani, 1986). The artificial sweetener mass loads were modelled as a smooth function over time, and the time points of start and end of COVID-19 restrictions were included as factors to evaluate whether their implementation or removal had an effect on the artificial sweetener loads. The model accounted for an instant effect, but also for a delayed effect at 1 week, 2 weeks, and 4 weeks. The time series structure of the data was accounted for by an autoregressive error term. An one-way ANOVA model with subsequent Tukey post hoc tests was performed to assess the significance for the spatial differences in levels of acesulfame, saccharin, and sucralose across the five locations, the seasonal variations in the Uppsala catchment, and also the spring measurements. Statistical tests were performed using R Studio Version 2023.03.1 (RStudio, Inc.). All results were considered significant at $p < 0.05$.

3. Results and discussion

3.1. Occurrence of artificial sweeteners in wastewater

Acesulfame, sucralose, and saccharin were detected in 100 % of the samples across all five communities over the whole study period (Table 2). The average concentration of acesulfame was measured at 35.4–52.5 μg/L, saccharin at 17.1–21.3 μg/L and sucralose at 15.7–25.2 μg/L (Table 2 and Tables S4.1–S4.5), with the average mass load of

Table 2
Concentrations (μg L^{-1}) and mass loads (g day^{-1} 1000 people^{-1}) across the locations and studied period via wastewater analysis. See Table S4.1–4.5 for concentration data points.

		Concentration (μg L^{-1})			Mass Load (g day^{-1} 1000 people^{-1})		
		Acesulfame	Saccharin	Sucralose	Acesulfame	Saccharin	Sucralose
Östhammar	Mean	35.4	17.1	15.7	13.0	6.16	5.85
	Median	34.0	17.5	14.9	13.3	6.35	5.87
	Range	19.1–55.5	7.9–30.2	7.8–28.4	8.20–16.8	4.23–7.20	3.05–8.16
Knivsta	Mean	52.5	17.9	24.6	12.7	4.32	6.01
	Median	54.7	17.7	24.5	13.0	4.25	6.23
	Range	39.9–64.3	14.5–22.2	18.2–30.7	8.93–14.0	3.75–4.96	3.78–7.48
Enköping	Mean	51.6	19.3	22.9	14.7	5.50	6.56
	Median	52.3	19.6	23.8	14.6	5.56	6.38
	Range	21.2–74.8	5.96–33.8	9.50–31.0	6.11–20.0	1.72–7.66	2.73–9.70
Kalmar	Mean	41.5	17.5	22.5	13.1	5.59	7.09
	Median	42.1	18.1	22.2	12.9	5.45	6.98
	Range	29.7–56.6	13.0–22.5	15.9–33.1	10.8–16.2	4.20–6.55	5.99–8.73
Uppsala	Mean	52.5	21.3	25.2	12.9	5.26	6.20
	Median	52.9	22.0	25.2	12.9	5.35	6.12
	Range	24.8–70.1	11.1–28.6	9.60–38.9	10.1–16.5	3.69–6.47	3.91–8.85

12.7–14.7 g day^{-1} 1000 people^{-1} for acesulfame, 4.32–6.16 g day^{-1} 1000 people^{-1} for saccharin and 5.85–7.09 g day^{-1} 1000 people^{-1} for sucralose (Table 2). Considering all the five studied locations (population-weighted), acesulfame showed the highest average mass load, 13.3 g day^{-1} 1000 people^{-1} (median: 13.1 g day^{-1} 1000 people^{-1}; range: 6.11–20.0 g day^{-1} 1000 people^{-1}), followed by sucralose with 6.27 g day^{-1} 1000 people^{-1} (6.22 g day^{-1} 1000 people^{-1}; 2.73–9.70 g day^{-1} 1000 people^{-1}) and saccharin with 5.43 g day^{-1} 1000 people^{-1} (5.45 g day^{-1} 1000 people^{-1}; 1.72–7.66 g day^{-1} 1000 people^{-1}). Average daily combined load of the three artificial sweeteners across the five communities was 7.55 kg day^{-1}. More than half of this load consisted of acesulfame at 4.01 kg/day, while saccharin and sucralose accounted for 1.64 kg day^{-1} and 1.90 kg day^{-1}, respectively.

Recent comparable studies on artificial sweeteners in Swedish influent wastewater are not available. Sucralose has been detected in Stockholm at levels of 0.8–2.1 g day^{-1} 1000 people^{-1} in previous studies (Lange et al., 2012; Swedish Environmental Research Institute, 2008). A recent study in Australia revealed a very similar mass load pattern in 2016 as that observed in the present study: acesulfame was present in the highest average mass loads (6.9 g day^{-1} 1000 people^{-1}), followed by sucralose (3.7 g day^{-1} 1000 people^{-1}) and then saccharin (2.0 g day^{-1} 1000 people^{-1}) (Li et al., 2020).

3.2. Community-wide usage of artificial sweeteners

The sampling opportunities were not consistent across the studied catchments. However, during a 12-week period (Fig. S1), sampling occurred simultaneously in Uppsala, Kalmar, Enköping and Östhammar, allowing a spatial comparison of the artificial sweetener usage (Table 3). The four communities revealed a similar pattern in the loads of the three artificial sweeteners (acesulfame > saccharin ≈ sucralose). Acesulfame showed very similar average usage at all locations, ranging between 12.9 and 13.8 g day^{-1} 1000 people^{-1} in Kalmar and Enköping, respectively, without significant difference observed between locations. Similarly, there was no significant spatial difference in the average use of saccharin, which ranged between 5.45 g day^{-1} 1000 people^{-1} in Enköping and 6.21 g day^{-1} 1000 people^{-1} in Östhammar. Sucralose usage was significantly higher ($p < 0.05$) in Kalmar, at 6.99 g day^{-1} 1000 people^{-1}, compared to the lowest usage in Östhammar, at 5.53 g day^{-1} 1000 people^{-1}.

Table 3
Mass loads (g day^{-1} 1000 people^{-1}) of artificial sweeteners across the four studied catchments over the same sampling period for 12 weeks (see Fig. S1 for the overlapping period).

		Mass Load (g day^{-1} 1000 people^{-1})		
		Acesulfame	Saccharin	Sucralose
Östhammar	Mean (median)	13.0 (13.3)	6.21 (6.54)	5.54 (4.95)
(n = 12)	Range	8.4–15.0	4.34–7.10	3.37–7.99
Enköping	Mean (median)	13.8 (14.0)	5.45 (5.48)	6.03 (6.01)
(n = 12)	Range	6.1–16.6	1.72–7.66	2.73–7.66
Kalmar	Mean (median)	12.9 (12.9)	5.48 (5.45)	6.99 (6.90)
(n = 11)	Range	11.8–14.0	5.06–6.28	6.19–8.64
Uppsala	Mean (median)	12.9 (12.5)	5.63 (5.75)	6.65 (6.92)
(n = 12)	Range	11.0–15.4	4.73–6.33	5.18–7.93

The results suggest a general acceptance of using artificial sweeteners in all communities studied, as part of a health-conscious lifestyle with lower sugar intake. Interestingly, the highest mass load of acesulfame, saccharin, and sucralose were observed at different locations (Enköping, Östhammar and Kalmar, respectively), rather than one location showing consistently highest use of all sweeteners. Depending on their properties, artificial sweeteners are used in different kinds of products. For instance, sucralose has high stability at different temperatures and pH levels, and thus it is used in a variety of products, such as beverages but also protein powders and bars (Spencer et al., 2016). The occurrence of a particular artificial sweetener in wastewater therefore varies depending on the specific sweetener-containing products consumed in a community. This can be influenced by the demographics of the local population, geographical location, and access to different products containing artificial sweeteners. Given that estimating population-wide usage of artificial sweeteners remains challenging with traditional methods, this study applied wastewater analysis to provide new insights into potential spatial differences in exposure to artificial sweeteners among the Swedish population. These findings will benefit from further studies on a larger number of communities across Sweden, from southern to central and northern regions, in the future. Spatial differences have also been reported for Australian communities, with e.g., the highest loads of acesulfame and sucralose observed in the communities from Tasmania and Northern Territory and the highest loads of saccharin observed in the communities from Victoria and Northern Territory (Li et al., 2020).

3.3. Usage of artificial sweeteners over time

Use of artificial sweeteners in the five communities was monitored over a certain period that ranged in length from a total of 11 weeks to 91 weeks. No particular temporal trends in sweetener use were observed for Knivsta and Kalmar across 10 weeks and 16 weeks of monitoring, respectively (Fig. S2). Similarly, no considerable changes over time were detected even with a longer monitoring period, i.e., 31 weeks for the populations of Östhammar and 32 weeks for Enköping (Fig. S2). Further investigations with greater numbers of samples taken over a longer monitoring period are needed to better detect trends in usage of artificial sweeteners in these communities.

For Uppsala, trends in usage of the three artificial sweeteners were evaluated over a 91-week period (1.75 years) (Fig. 1). With the linear regression model considering all data points (Fig. 1a), the yearly increase in usage was estimated to be ~19 % for sucralose ($r^2 = 0.357$, $p < 0.05$), ~9 % for acesulfame ($r^2 = 0.247$, $p < 0.05$), and ~8 % for saccharin ($r^2 = 0.149$, $p < 0.05$) over the monitoring years. The low r^2-values obtained is to some extent caused by seasonal variations (Fig. S3) in the use of these artificial sweeteners, which leads to high variation around the regression lines. Acesulfame showed slight seasonal differences, with elevated levels during autumn compared to the other seasons and significantly higher when compared to summer ($p < 0.05$). Sucralose showed a similar pattern, with a significant increase in levels during autumn compared to summer and winter ($p < 0.05$). For saccharin, the seasonal pattern is more prominent with significantly lower levels during summer compared to all the other seasons ($p < 0.05$). Understanding seasonal patterns remains challenging as variations in population over the seasons could influence the estimation of population-weighted usage of the artificial sweeteners, for instance, certain residents including university students would typically leave for summer vacations especially in July in Sweden, leading to a brief, temporary change in the local population. Seasonal variations in artificial sweeteners usage were also previously observed in an Australian community (~110 000 inhabitants), with higher levels in summer (Li et al., 2021). To eliminate potential seasonal effects on changes in usage in the local population, only spring samples, i.e., March 2019 (n = 7), March 2020 (n = 3), March 2021 (n = 3), and February 2022 (n = 3), were compared (Fig. 1b). Still, a clear increasing trend was observed over the four years represented by these samples, from total SED of 5.61 kg day^{-1} 1000 people^{-1} in spring 2019 to 8.50 kg day^{-1} 1000 people^{-1} in spring 2022. Sucralose showed the highest increase in SED, with the average value almost doubling, from 2.37 to 4.31 kg day^{-1} 1000 people^{-1}, between spring 2019 and spring 2022 ($p < 0.05$). Significant changes ($p < 0.05$) in sucralose use was already observed in 2021 compared to 2019, and again between 2020 and 2022. A smaller increase was seen for acesulfame, with a change in SED from 1.93 to 2.62 kg day^{-1} 1000 people^{-1} between spring 2019 and spring 2022 ($p < 0.05$). Similar to sucralose, significant changes in acesulfame use were also noticed between 2019 and 2021 ($p < 0.05$). Saccharin increased from 1.30 to 1.57 kg day^{-1} 1000 people^{-1} between spring 2019 and spring 2022, which was however not significant. There is a limitation of wastewater analysis in which it cannot distinguish whether this increase is due to an increase in usage/exposure per person, an increase in the number of people using/being exposed to artificial sweeteners, and/or an increase in the content per product, with the same number of users.

With SED (Fig. 1), the usage pattern (sucralose > acesulfame > saccharin) in this study was the same as that identified in the Australia communities (Li et al., 2020, 2021). Increasing trends in usage of some artificial sweeteners have also been detected in the Australian population through wastewater analysis (Li et al., 2021). Our Swedish study communities showed an approximately two-fold greater increase (~19 % increase) in sucralose loads over four years than an Australian community (~10 % increase) over seven years (2012–2018). For acesulfame, an increasing trend was found in our study communities, while no distinct trend was seen in the Australian community. For saccharin, the annual increase for our Swedish communities (~8 %) was similar in the Australian community (~6 %) (Li et al., 2021).

To assess whether the increasing trend in wastewater levels of the three artificial sweeteners in our study is independent of an increase in the population of Uppsala over time, data on population registration from the Swedish Tax Agency and data on wastewater inflow rates at the WWTP in Uppsala during the study period were evaluated. The variability of the registration numbers at the Swedish Tax Agency was about 2 % (coefficient of variation, CV%) from 2019 to 2022 (Statistiska centralbyrån, 2021), while the variability of the wastewater flow rate was about 11 % (CV%) (Table S1). These are smaller than the variability in the concentrations of the artificial sweeteners (CV%: 18 % for sucralose, 15 % for acesulfame, 23 % for saccharin) over the whole monitoring period, indicating that population growth is unlikely to have been the main driving factor for the observed increase in usage.

Increasing artificial sweetener usage in general is evident in the growing global market for artificial sweeteners, with a 5.1 % increase between 2008 and 2015 (Sylvetsky and Rother, 2016). Health issues with obesity and the public health recommendation on lower intake of added sugar have increased the demand for non-caloric sweeteners

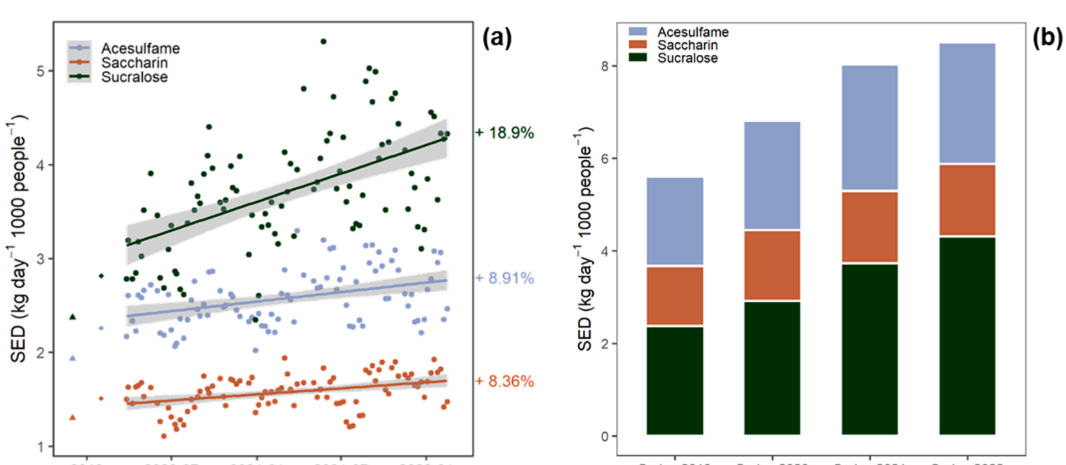

Fig. 1. Time trend in artificial sweetener usage in Uppsala: (a) SED of all data points over time (year-month) in a linear regression model with 95 % confidence level interval and annual percentage increase; and (b) sucrose equivalent doses (SED) in spring 2019–2022. In the sub-figure (a), the weekly averages of the 2019 samples are presented as triangle symbols for week 11 and diamond symbols for week 42; please note a temporal discontinuity between the 2019 and 2020 data points along the x-axis due to a gap between the different sample collection periods across these years.

(Sylvetsky and Rother, 2016). In Sweden, the highest quantity of sugar is consumed through sugar-sweetened soft drinks (Livsmedelsverket, 2022). One of the main strategies for decreasing sugar intake through soft drinks is replacement of sugar with artificial sweeteners (Warshaw and Edelman, 2021). Sales of artificially sweetened soft drinks have increased by 200 % in the past decade in Sweden, and the market share of these products compared to sugary soft drinks increased from 20 % in 2012 to almost 50 % in 2021 (Sveriges Bryggerier, 2022).

3.4. Usage patterns over the COVID-19 waves

The Swedish strategy of preventing the spread of COVID-19 was very consistent and the recommendation to work from home was in place for 1.5 years (Fig. 2). It was issued for the first time in March 2020 and remained in place until the end of September 2021, when all recommendations concerning the spread of COVID-19 were lifted for the first time. They were re-introduced at the beginning of December 2021 and lifted again at the beginning of February 2022 (Ludvigsson, 2022). The effect of these pandemic-related restrictions on the usage patterns of artificial sweeteners was evaluated in this study using a GAMM. The model showed no significant ($p < 0.05$) correlation between implementation or removal of COVID-19 restrictions in Uppsala and the artificial sweetener levels detected in wastewater (Fig. 2). Furthermore, there was no instant effect or delayed effect after 1, 2, and 4 weeks. During the critical period of the pandemic, changes in lifestyle associated with usage of artificial sweeteners appeared dissimilar to those reported for other substances. Previous WBE studies have revealed changes such as higher alcohol consumption during lock-down periods and lower illicit drug use due to restricted access over the pandemic (Estévez-Danta et al., 2022; Reinstadler et al., 2021; Galani et al., 2021), as well as higher artificial sweetener loads during lock-down (Alygizakis et al., 2021). In countries with strict COVID-19 restrictions (e.g., curfew, lockdown), the impact of the pandemic on eating habits has been studied using survey-based methods. Respondents reported temporarily altering their food consumption when spending much time at home (Janssen et al., 2021). Our wastewater analyses did not reveal a clear change in exposure to the three artificial sweeteners in relation to COVID-19 restrictions in Sweden, at least not for food or beverages that contain the three artificial sweeteners studied. This may be due to the more consistent, but less stringent, restrictions in Sweden, which were mostly based on recommendations and civic responsibility, rather than mandatory lockdown. In fact, certain aspects of daily life, such as physical exercise and other recreational activities, were not limited in Sweden, while keeping social contact at a minimum. Our results reflect positively on the Swedish population in the studied catchments, as it appeared to retain similar exposure to the artificial sweeteners under the stress of the pandemic, albeit with annual increases in their usage.

3.5. Comparison with health-related thresholds

We evaluate for the first time whether the average usage of acesulfame, saccharin, and sucralose as reflected by wastewater loads poses a health risk to the Swedish population, by comparing the levels measured in wastewater with the acceptable daily intake (ADI, mg kg body weight^{-1} day^{-1}) values defined by the European Union (EU) (European Commission, 2021) and World Health Organization (WHO) (Rios-Leyvraz and Montez, 2022) (Table 4). To enable comparison with the wastewater data (mg day^{-1} person^{-1}), the ADI values were converted by multiplying them by the average body weight of a Swedish male (84 kg) and female (68 kg) (Statistiska Centralbyrån (SCB), 2018). The per capita mass loads of the three artificial sweeteners measured in wastewater were only around 0.5 % (sucralose), 1.4 % (saccharin) and 2 % (acesulfame) of the ADI set by the EU and the WHO, indicating that there is no appreciable health risk to the study communities from use of these artificial sweeteners at these calculated intake levels. Considering that intake of artificially sweetened beverages has been linked to health concerns at levels far below the ADIs of artificial sweeteners (Zhang et al., 2021) and that artificially sweetened beverages are the primary source of artificial sweeteners, it is relevant to evaluate how the estimated population intake based on wastewater analysis compares to thresholds of artificially sweetened beverages. A recent study reported that consumption of more than 1.5 servings (where one serving is equivalent to 355 mL) of artificially sweetened beverages per person and day could be associated with adverse health effects, i.e., higher risks of

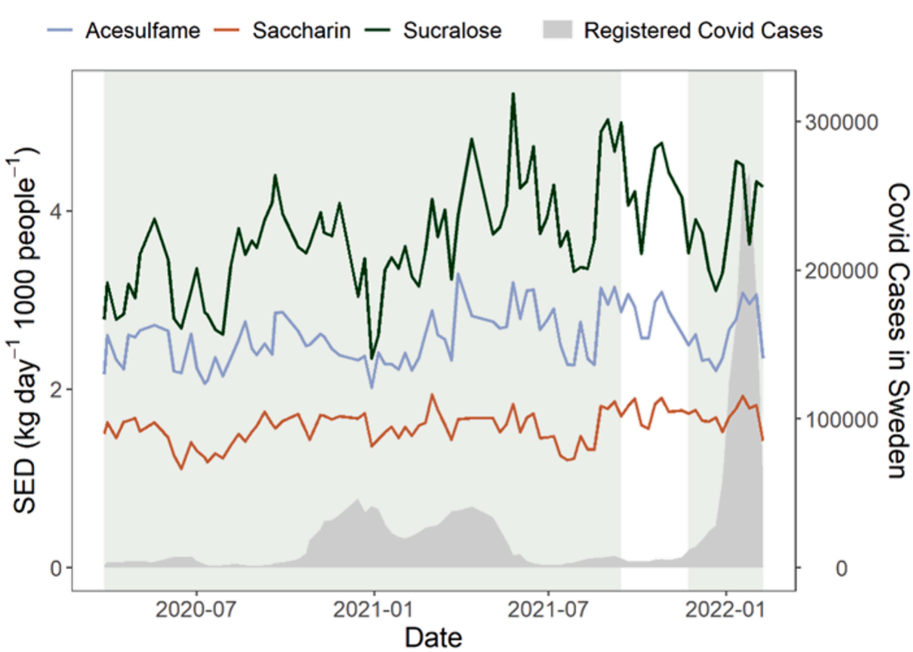

Fig. 2. Artificial sweetener sucrose equivalent doses (SED) in wastewater during the COVID-19 waves in Sweden 2020–2022 compared with the number of officially recorded cases reported by the Public Health Agency of Sweden (year-month). The light green area indicates when the recommendation to work from home was in place, the white area indicates when this recommendation was lifted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Acceptable daily intake (ADI) values (mg per kg bodyweight per day) for different artificial sweeteners proposed by the European Union (EU) and World Health Organization (WHO) compared with wastewater mass loads (average) across the communities in this study.

	ADI ($mg\ kg^{-1}\ day^{-1}$)	ADI Male ($mg\ day^{-1}\ person^{-1}$)	ADI Female ($mg\ day^{-1}\ person^{-1}$)	Östhammar	Knivsta	Enköping	Kalmar	Uppsala
				$mg\ day^{-1}\ person^{-1}$				
Acesulfame	9*; 15^	756*; 1260^	612*; 1020^	13.0	12.7	14.7	13.1	12.9
Saccharin	5*,^	420	343	6.16	4.32	5.50	5.59	5.26
Sucralose	15*,^	1260	1020	5.85	6.01	6.56	7.09	6.20

* EU guideline; ^WHO guideline.

all-cause mortality and cardiovascular disease mortality (Zhang et al., 2021). Although the types of artificial sweeteners used in artificially sweetened beverages are shown on the label of commercial products, the amounts added are not usually stated. Thus, there is a lack of information on how many grams of acesulfame, saccharin, and sucralose are present in one standard can (330 mL) of artificially sweetened beverage in Sweden. A recent study analyzed a range of the most commonly consumed soft drinks in Portugal (colas, juice drinks, iced teas, and lemon-flavored drinks, $n = 68$) for a few artificial sweeteners (Silva et al., 2021), and found that acesulfame was present in a median concentration range of 23–94 mg L^{-1}, saccharin in a median concentration of 16 mg L^{-1}, and sucralose in a median concentration range of 17–45 mg L^{-1}. The suggested usage of no more than 1.5 servings of artificially sweetened beverages per person per day would then be equivalent to no more than 12.2–50.1 mg day^{-1} $person^{-1}$ for acesulfame, 8.5 mg day^{-1} $person^{-1}$ for saccharin, and 9.1–24.0 mg day^{-1} $person^{-1}$ for sucralose. These values are at the lower end of the average per capita mass loads detected in wastewater for acesulfame, but are above those for saccharin and sucralose (Table 4). Potential risks of adverse health effects in the local populations still cannot be ruled out, because the data cited do not necessarily represent other kinds of artificially sweetened products and because there could be differences in preferences for sweetness intensities between European countries. It should also be noted that our assessment is conducted at the whole population level, and that differences in individual consumption rates are possible.

4. Conclusions

This study used wastewater data to evaluate the usage of acesulfame, sucralose, and saccharin in five Swedish communities. The study communities had a similar mass load pattern (acesulfame $>$ saccharin $\approx$ sucralose) of the artificial sweeteners, but showed differences in the exposure to specific artificial sweeteners, with the highest mass load ($p < 0.05$) for sucralose found in a community (Kalmar) from southern Sweden and the highest for acesulfame and saccharin in communities from central Sweden (Enköping, Östhammar). The longest period of monitoring data, for Uppsala, revealed a clear rising trend in the use of the three artificial sweeteners, albeit some seasonal variations identified, with an annual increase of ~8 %–19 % over a 4-year time period. This temporal trend was not influenced by COVID-19 restrictions in terms of instant or delayed effects, meaning that the local populations did not substantially change their exposure to these artificial sweeteners under the pandemic restrictions. Measured levels of the artificial sweeteners in wastewater were far below ADI values set by the EU and WHO, as well as below thresholds for consumption of artificially sweetened beverages, except for acesulfame which had levels at the lower end of the latter. This indicates that, in general, there is no appreciable health risk to the Swedish population from the use of these artificial sweeteners. This work confirmed that, with systematic sample collection, wastewater analysis is a useful complementary approach to population surveys and manufacturing or household sales data for public health authorities in assessing and understanding population consumption of artificial sweeteners.

CRediT authorship contribution statement

Inga Haalck: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **Anna Székely:** Writing – review & editing, Resources, Investigation. **Stina Ramne:** Writing – review & editing. **Emily Sonestedt:** Writing – review & editing. **Claudia von Brömssen:** Writing – review & editing, Methodology, Formal analysis. **Elin Eriksson:** Writing – review & editing, Supervision, Resources. **Foon Yin Lai:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.108814.

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