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Quantification of 16 Metals in Fluids and Aerosols From Ultrasonic Pod-Style Cigarettes and Comparison to Electronic Cigarettes

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Background: Electronic cigarette (e-cigarette) fluids and aerosols contain metals, which can be detrimental to human health. Recently marketed ultrasonic cigarettes (u-cigarettes) claim to be less harmful than e-cigarettes, which use heating coils.

Objectives: We quantified chemical elements/metals in multiple flavors of SURGE u-cigarettes, JUUL e-cigarettes, and "Other Brands" of pod-style e-cigarettes.

Methods: Elements/metals were identified in atomizers of SURGE using a scanning electron microscope and energy-dispersive X-ray spectrometer. Quantitation of elements/metals in fluids and aerosols from SURGE, JUUL, and "Other Brands" was performed using inductively coupled plasma optical emission spectroscopy.

Results: U-cigarettes contained a sonicator, unlike e-cigarettes, which had heated coils. Sixteen elements were identified in at least one fluid or aerosol sample. Generally, u-cigarette fluids and aerosols had more elements/metals at higher concentrations than aerosols from fourth-generation e-cigarettes. Element concentrations generally increased in fluids after vaping. All products, including SURGE, had silicon in their fluids and aerosols. Nickel, which was present in low concentrations in all fluids except KWIT Stick (up to 66,050 $\mu g/mL$), transferred to the aerosols with low efficiency. SURGE, but not e-cigarettes, also had copper and zinc in their fluids, but little transferred to their aerosols. SURGE fluids and aerosols, unlike e-cigarettes, had relatively high concentrations of arsenic and selenium. Arsenic and selenium, which are on the US Food and Drug Administration list of "Harmful and Potentially Harmful Constituents," likely came from poor quality solvents used to produce the e-fluids in SURGE pods and possibly from the sonicator, which heats during use.

Discussion: SURGE u-cigarettes produce aerosols with metals equivalent to heated coil-style e-cigarettes and had high levels of arsenic and selenium, which are a health concern. Regulations limiting arsenic and selenium in these products are needed, and routine surveillance to identify rogue products, such as KWIT Stick, which have abnormally high levels of nickel or other metals, could protect human health. https://doi.org/10.1289/EHP15648

Introduction

Electronic cigarettes (e-cigarettes) have atomizers that heat e-liquids to generate an inhalable aerosol.[1–3] These atomizers contain metals and chemical elements that can transfer into e-liquids and aerosols[3–19] during storage and heating of the e-liquids.[9,11,14,20–28] Elements/metals in e-cigarette aerosols could potentially induce chronic diseases, such as pulmonary fibrosis, cardiovascular disease, chronic bronchitis, asthma, and pneumonitis.[29–31] Some, such as nickel, chromium, and lead, are carcinogens or potential carcinogens.[20,32–35]

E-cigarettes have evolved through at least four generations based on their design characteristics.[2,3,36,37] Most research has shown that the concentrations of elements/metals in e-cigarette aerosols vary among generations, device models, and sometimes even within duplicate samples of the same product.[6,10,11,13–15,17,23,29,38–40] These variabilities make it difficult to generalize about specific elements/metals in e-cigarette aerosols. As e-cigarettes evolved to the third generation (mods), their power output increased, resulting in increased metal emissions in their aerosols.[2,11,23,26,39] However, the now-popular fourth-generation e-cigarettes (pods) have reduced battery power, which is usually nonadjustable, suggesting their metal output is lower than that of second- (clearomizers) and third-generation (mod) devices. In recently introduced SURGE brand ultrasonic cigarettes (u-cigarettes), the heating coil is replaced with an ultrasonic nebulization system that aerosolizes a flavored fluid by vibrating at a rate of 3 million hits/s and produces a lower level of heat.[41] Although not yet studied, SURGE claims that their u-cigarettes deliver fewer harmful chemicals because aerosols are generated at lower heat than in traditional coil-based e-cigarettes.[41] However, a recent study showed high concentrations of flavor chemicals and aldehydes in SURGE fluids and aerosols.[42]

The fluids in pod-style e-cigarettes generally contain one or multiple acids, which form a salt with nicotine and lower the overall pH of the fluid and aerosol.[21,43–45] The addition of acid in pod-style e-cigarettes has been accompanied by increased concentrations of nicotine (e.g., 40–60 mg/mL).[45–48] Although adding acid to e-liquids makes their aerosols easier for novice users to inhale,[49–51] the low pH of fourth-generation e-liquids may also increase the release of metals from atomizer components, which could offset the benefit gained from their lower operating power.[21,52] SURGE u-cigarette fluids do not contain acids, suggesting their nicotine exists as a free-base ($\sim$13–19 mg/mL),[42] and they may be less likely to release metals from atomizer components. Although fourth-generation e-cigarettes, such as JUUL and PUFF, have been dominant in the e-cigarette market and are still available for purchase,[53–57] other brands, such as Suorin, VooPoo, and SMOK, have gained popularity.[58]

Our main objective was to compare element/metal concentrations in a pod-style u-cigarette (SURGE) and various e-cigarettes to determine whether the method of aerosol production (nebulization vs. heated coil) affects the occurrence and concentrations of metals in their aerosols. Eighteen different fluid flavors across SURGE u-cigarettes and multiple e-cigarette brands were

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evaluated (Table 1). Flavors included fruity, tobacco, mint/menthol, dessert, and "ice." Elements/metals were also compared in closed-system (prefilled) pod fluids and refill fluids used in open-system (refillable) pods. Finally, element/metal concentrations in fourth-generation e-cigarettes were compared to published data from previous generations (cig-a-likes, pens/tanks, and mods). The previous-generation products used for comparison were cig-a-likes/cartomizers [BluCig Plus, Mark Ten XL V2 Cigs (2017), Vuse Vibe], pens/tanks/clearomizers (Ego Protank, iTaste T3S, Ego Aspire), mods (Smok Alien, Nemesis Clone, iPV6X - Tsunami).[22]

Methods

Sample Acquisition and Storage

Rechargeable pod-style u-cigarettes and fourth-generation e-cigarettes were purchased online from the manufacturer or locally from reputable third-party vendors. Four flavors of SURGE (Shenzhen Innokin Technology Co. Ltd.) u-cigarettes were analyzed. Six brands of prefilled pods were evaluated: KWIT Stick (Aspire), Suorin Air (Shenzhen Blumark Technology Co., Ltd.), SMOK Infinix (Shenzhen Blumark Technology Co., Ltd.), JUUL (Pax Lab), KILO 1K (Kilo E-liquid Inc.), and PHIX (ECS Global LLC.). All eight flavor variants initially marketed by JUUL were included in the analysis.

Two salt-based nicotine refill fluids (Mynto Ice Mango from Drip Fire and Mango Bomb from VGOD Salt Nic Labs) were purchased and used in SMOK Infinix and Suorin Edge refillable pods. Three pods/devices of each brand were purchased at the same time to limit variations in purchase batch. All products were stored at room temperature and analyzed within a month.

Dissection, Scanning Electron Microscopy, and Elemental Analysis

All brands except SURGE have been previously analyzed using scanning electron microscopy (SEM) and energy-dispersive X-ray spectrometry (EDS).[3] In this study, SURGE flavored pods were emptied and carefully dissected to expose the atomizer/nebulizer components. Components were photographed using a Canon EOS Rebel SL2 and mounted on aluminum pin stubs covered with conductive carbon tape to prevent charging during SEM and elemental analysis.[4] Analyses were performed at the Central Facility for Advanced Microscopy and Microanalysis at the University of California, Riverside, using a Thermo Fisher Scientific Co. NovaNano-SEM 450 equipped with an Oxford Instruments energy EDS fitted with an X-Max50 50 mm^2 silicon drift detector (SDD) with an energy resolution of 126 eV at MnK-α.[11] A secondary electron mode with a dedicated detector at 15 kV was used to obtain SEM images. EDS spectra and elemental maps were acquired and processed with the Oxford Instruments AZtec Synergy (version 4) software package to reveal the distribution of elements within the sample area qualitatively. The system capabilities allow the identification and differentiation of element peaks with an atomic number of 5 or higher on the spectra. The detection limit for the EDS method is ~ 0.1 wt. %. An arbitrary threshold value of 5% weight was set to allow for ease and clarity of data analysis. Elements above the 5% threshold were denoted as "major." Those below the threshold were "minor." The elements were quantified by processing the acquired EDS spectra using the standard–less routine and Oxford Instruments factory-supplied table of elemental standards incorporated in the AZtec software.

Inductively Coupled Plasma Optical Emission Spectrometry Sample Preparation, Aerosol Production, and Capture Using an Impinger Method

All fluid and aerosol samples for elemental analysis were made using 2% nitric acid solutions prepared with Milli-Q System water (Millipore) at 18.2 mOhm of resistance. Nitric acid AR Select (ACS) for trace element analysis was purchased from Macron Chemicals (Avantor Performance Materials, Inc.). For fluid analysis of closed-system pods, 200 μL of e-fluid was removed from three unused pods and pooled (unvaped). Another 200 μL of e-fluid was collected from the same pods and pooled after vaping (vaped; see below). For refill fluids (Mynto Ice Mango and Mango Bomb) used with open-system pods, unvaped fluids were collected from the same bottle. A 1:10 dilution of each e-fluid/refill fluid was prepared with freshly made 2% nitric acid and stored at room temperature for 1–2 d before analysis.

Before aerosol production, impingers were washed and soaked in 2% nitric acid for at least 3–5 d to seal the glass and prevent the leaching of elements into the sample.[6,11,12] Because the devices performed differently, aerosols were generated at a 10–13 mL/sec airflow rate. To reduce the chance of "dry puffs," no more than three-quarters the e-fluid was vaped per pod. To saturate the wick for optimal performance before aerosol generation, each pod was primed by taking three puffs on a smoking machine custom built for our laboratory by technicians at the University of Kentucky (Lexington, Kentucky). The aerosols generated from the pods were bubbled through 30 mL of 2% nitric acid solution in two impingers connected in tandem.[48] The system was connected to a

Table 1. Comprehensive list of devices and fluid flavors used in this study.

Brand/manufacturer	Device type/system	Flavor category	Fluid flavor
SURGE	Closed	Mint/menthol	Green Mint
	Closed	Mint/menthol	Polar Mint
	Closed	Berry/Ice	Blueberry Ice
	Closed	Fruit/Ice	Watermelon Ice
JUUL	Closed	Fruit/Berry	Fruit Medley
	Closed	Fruit/Berry	Mango
	Closed	Mint/menthol	Classic Menthol
	Closed	Tobacco	Classic Tobacco
	Closed	Mint/menthol	Cool Mint
	Closed	Fruit/Berry	Cucumber
	Closed	Tobacco	Virginia Tobacco
	Closed	Dessert	Crème Brulee
Other Brands – PHIX	Closed	Fruit/Berry	Hard Strawberry
Other Brands – Kilo 1K	Closed	Fruit/Berry/Ice	Dewberry Fruit Ice
Other Brands – Suorin	Open	Mint/menthol/Fruit/Ice	Mynto Ice Mango (Dripfire Brand)
Other Brands – SMOK	Open	Mint/menthol/Fruit/Ice	Mynto Ice Mango (Dripfire Brand)
Other Brands – SMOK	Open	Fruit	Mango Bomb (VGOD Brand)
Other Brands – PHIX	Closed/open	Fruit	Mango Tango

Cole-Parmer Master-flex L/S peristaltic pump set to take a 4.3-s puff at 1 puff/min. For each product, 60 puffs were taken from three different pods, and all 180 puffs were collected in the same impinger. The aerosol collection was performed at room temperature in a biosafety cabinet, and room air control samples were collected similarly. Aerosol solutions and room air samples were produced in triplicates and stored at room temperature in 15-mL conical tubes presealed with 2% nitric acid.

The following elements were investigated: aluminum, arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, selenium, silicon, silver, tin, titanium, and zinc.

Quantification of Elements Using ICP-OES

The concentrations of elements/metals in the e-fluids and aerosols were analyzed using a PerkinElmer Optima 7300 DV inductively coupled plasma optical emission spectrometer (PerkinElmer). The inductively coupled plasma optical emission spectrometry (ICP-OES) was equipped with an autosampler, a PerkinElmer Nebulizer (N0777036 REV A, Cyclonic spray chamber Optima 5300DV, Quartz 7 mm baffle drain line) and a segmented array charge-coupled device (SCD) detector as previously described.[6,12] Daily calibration of the ICP-OES was done using PerkinElmer multielement calibration standards plus no. 2, no. 3, no. 4, and no. 5. Quality-control checks on calibration were then run using QCI-700A trace metal standard reference material by Ultra Scientific. Running conditions were plasma flow = 15 L/min, auxiliary flow 0.2 L/min, nebulizer flow of 0.75 L/min, radiofrequency power 1,450 W, sample flow rate = 0.80 mL/min, and a read delay time of 12 s. For an internal standard, yttrium (Y) at 2.5 ppm was run in line with the sample introduction into the nebulizer. Distilled deionized water with 1% nitric acid was run as the blank. Each sample was run in triplicate. When interference was observed for any element, additional peaks were monitored to identify the best wavelength for quantification. The concentrations of each element in the blank were subtracted from the measured concentrations in each sample. The limits of detection and quantification for each element are included in Table S1.

Device Design and Components of SURGE U-Cigarettes

SURGE u-cigarettes consist of a battery and a fluid reservoir (Figure 1A). The reservoir (1.8-mL capacity) has a mouthpiece (Figure 1A), a fluid guide, a bottom cover (Figure 1B), an air channel, a separator, and a seal assembly (Figure 1C). The air channel, which is plastic, is connected to the mouthpiece and runs through the reservoir to the fluid guide (Figure 1B,C). A flexible and elastic separator made of silicon or rubber sealed the fluid storage compartment. The separator only allowed the fluid to drain through a porous ceramic embedded in the separator onto a cotton material on the seal assembly (Figure 1C). The seal assembly is embedded in the bottom cover and tightly supported with push rods and jacks to seal the reservoir, preventing fluid spillage.

Data and Statistical Analyses

The formula limit of detection $(LOD)/\sqrt{2}$ or limit of quantification $(LOQ)/\sqrt{2}$ was used to impute values for concentrations of elements below the LOD or LOQ, respectively. Data processing was performed to subtract concentrations in control samples (2% nitric acid and room air) from experimental samples. The mean concentrations of all elements in the unvaped, vaped, and aerosol samples were compared. For the statistical analysis, the data were transformed using $Y = Log(Y)$ and subjected to a one-way analysis of variance (ANOVA) with Dunnett's post hoc test, or alternatively data was analyzed using an unpaired *t*-test. All statistical analysis was done using GraphPad Prism software (GraphPad, Inc.).

Results

Elemental Analysis and Mapping of SURGE U-Cigarette Components

Because, to our knowledge, u-cigarettes have not been studied previously, the elements/metals in the SURGE reservoir/nebulizer were first analyzed using SEM and EDS (Figure 1D–YY; Table S2; Figure S1). Examples of the major (carbon, oxygen, silicon, lead, nickel, and gold) and minor (sulfur and chromium) peaks are shown in the EDS spectra for the vaped wick and sonicator spring (Figure S2). Both cotton and ceramic wicks became discolored after vaping 60 puffs (Figure 1D vs. Figure 1J and Figure 1P vs. Figure 1V). Elements in cotton wicks were altered by vaping, with the most notable differences being an increase in silicon and appearance of oxygen (Figure 1D–O; Table S2; Figure S1). In vaped ceramic wicks, the most notable change was a visible increase in carbon (Figure 1P-AA; Table S2; Figure S1). The shell of the seal assembly was gold-plated nickel (Figure 1BB–EE; Table S2; Figure S1), whereas the top section that holds the wicks in place was lead and silicon (Figures 1FF–GG; Table S2; Figure S1). The spring component located within the seal assembly, which facilitates aerosol generation, was mainly nickel, gold, and iron with minor amounts of chromium (Figure 1HH–MM; Table S2; Figure S1; Figure S2). The bottom of the seal assembly, which is in contact with the battery, consisted of nickel, gold, phosphorus, and silicon (Figure 1NN–SS; Table S2; Figure S1; Figure S2). The sensor in the inner compartment of the bottom side of the seal assembly consisted of tin, silicon, and barium (Figure 1TT–YY; Table S2; Figure S1; Figure S2). The weight percentage of elements based on the EDS spectra for each component is shown in Table S2 and summarized in Figure 1ZZ, in which the dark gray and light gray squares signify major (>5%) and minor (<5%) thresholds, respectively. The EDS spectra of the cotton wick and sonicator spring is shown in Figure S2.

Device Characteristics and Fluid Flavors of SURGE U-Cigarettes and E-Cigarettes

The u-cigarette and e-cigarette pods used in the current study were either prefilled with e-liquid (closed system) or empty when purchased and filled with salt-based nicotine refill fluids (open system) before analysis (Table 2). E-liquid and battery capacities of the pods and devices ranged from 0.7 to 2 mL and 230 to 700 milliamperes/h, respectively (Table 2). Battery voltages were between 3.3–5 V, and wattages on the full charge were either not provided or between 7.5–16 W (Table 2). Information on the characteristics and specifications of the devices was obtained from the manufacturers' websites and online vape blogs and forums.

Concentration of Silicon in SURGE U-Cigarette and E-Cigarette Fluids and Aerosols

Silicon was a major element in some unvaped fluids, with concentrations varying between brands and among e-cigarette flavors (Figure 2A–C). Concentrations in unvaped SURGE fluids (3,782–6,077 μg/L) were similar among product flavors and were lower than in some JUUL flavors (e.g., Virginia Tobacco and Crème Brulee), which in some cases had concentrations >10,000 μg/L (range = 1,638–47,872 μg/L) (Figures 2A,B). Among "Other Brands," concentrations in unvaped fluids were higher in closed than in open systems, with most having concentrations below SURGE (i.e., <4,000 μg/L) (Figure 2C). Silicon was not detected in refill fluids used in the open-system pods,

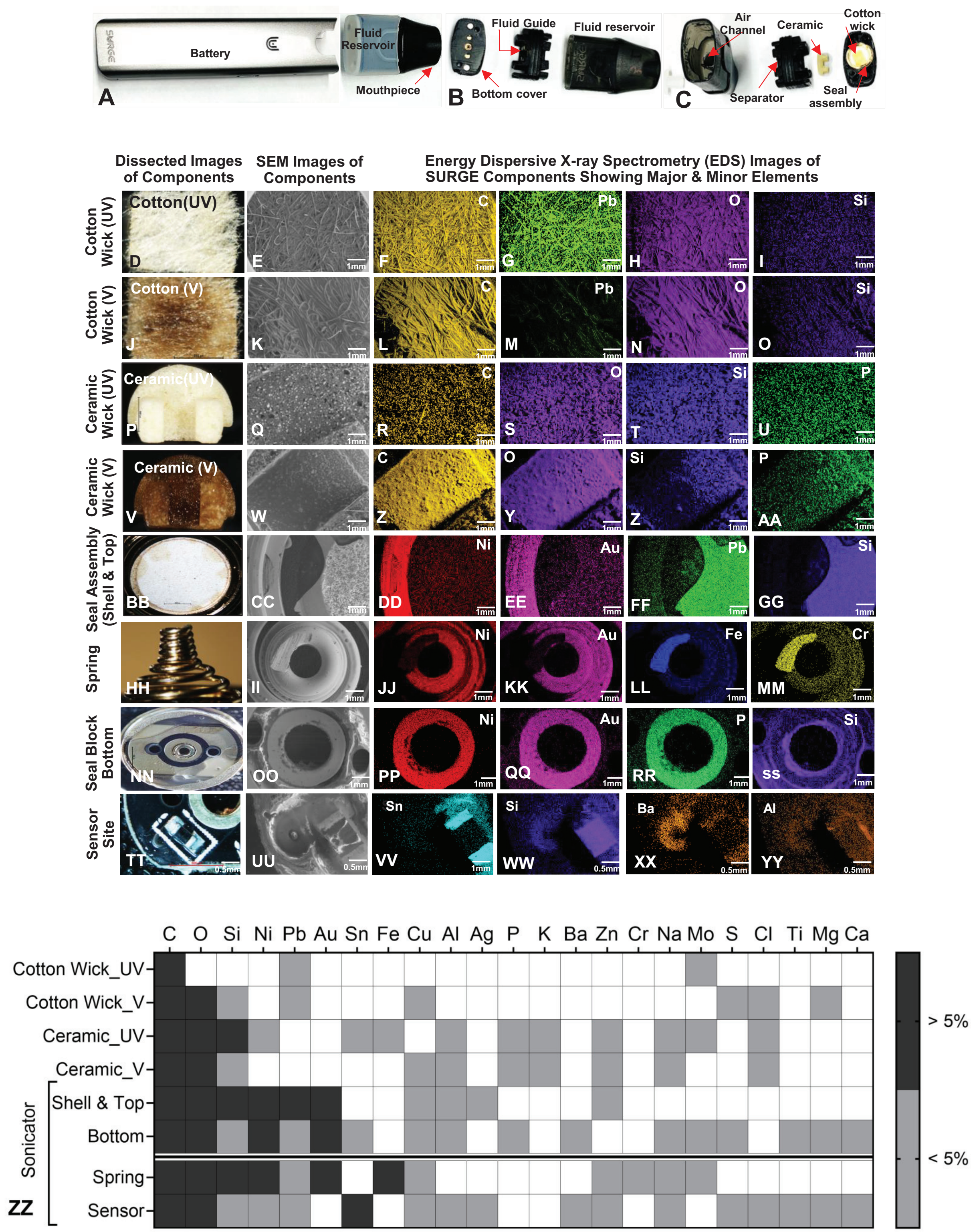

Figure 1. Device design and atomizer components of SURGE u-cigarettes. (A) Battery and fluid reservoir. (B,C) Dissections of the fluid reservoir and wicks. (D–YY) Digital, SEM, and EDS images of SURGE components. (D–I) Unvaped cotton wick. (J–O) Vaped cotton wick. (P–U) Unvaped ceramic wick. (V–AA) Vaped ceramic wick. (BB–GG) Sonicator shell and top (seal assembly). (HH–MM) spring embedded in the sonicator. (NN–SS) Sonicator bottom (seal block). (TT–YY) Chip/sensor. (ZZ) Heat map showing the elements mapped to the atomizer components. The weight percentage from which this heat map was generated and the complete elemental map to complement the data are in Table S2 and Figure S2. One sample was analyzed for each component. Note: Ag, silver; Al, aluminum; Au, gold; Ba, barium; Ca, calcium; Cl, chlorine; CO, carbon; Cr, chromium; Cu, copper; EDS, energy-dispersive X-ray spectrometry; Fe, iron; K, potassium; Mg, magnesium; Mo, molybdenum; Na, sodium; Ni, nickel; O, oxygen; P, phosphorus; Pb, lead; S, sulfur; SEM, scanning electron microscopy; Si, silicon; Sn, tin; Ti, titanium; Zn, zinc.

Table 2. Device characteristics obtained from manufacturer website or online sources.

Brand/manufacturer	SURGE[a]	JUUL[a]	PHIX[a]	Kilo 1K[a]	Suorin Edge	SMOK Infinix	KWIT Stick[a]
Pod system	Closed	Closed	Closed	Closed	Open	Open	Closed/open
E-liquid capacity (mL)	1.8	0.7	1.5	1.5	1.5	2.0	1.0
No. of puffs per cartridge	NA	200	400–450	NA	NA	NA	NA
Resistance (ohms)	NA	NA	1.4–1.5	1.8	1.4	1.4	1.0
Puff cutoff time (secs)	NA	NA	NA	NA	NA	NA	8
Activation method	Draw	Draw	Draw	Draw	Draw	Button	Draw
Battery type	Li-ion	Li-ion	NA	NA	NA	NA	NA
Battery (mAh)	700	200	280	350	230	250	230
Watt-hours (Wh)	0.7	0.7	NA	NA	NA	NA	NA
Voltage (volts)	5	3.7	3.7	NA	3.3–4.2	3.3–4.2	3.5–4.2
Watts on a full charge	7.5	8.5	NA	NA	10	10–16	NA

Note: NA, not applicable.
[a]Products with prefilled pods.

which were never in contact with the atomizer (Figure 2C, unvaped data). Except for the SMOK Infinix MB open-system pods and two JUUL flavors (Fruit Medley and Classic Tobacco), silicon concentrations were not significantly different in unvaped and vaped fluids (Figures 2B,C).

Concentrations of silicon in aerosol samples varied between SURGE and e-cigarettes, within JUUL flavors, and between open- and closed-system pods (Figure 2A–C). Concentrations in SURGE aerosols (459–2,975 μg/L) were within the range of four JUUL flavors (458–1,918 μg/L) but lower than silicon in the remaining JUUL flavors (2,690–22,800 μg/L) (Figures 2A,B). All but KILO 1K in the "Other Brands" aerosols had silicon concentrations (6,364–6,713 μg/L) within the range found for SURGE (Figures 2A,C). Silicon concentrations in closed-system pods from "Other Brands" (625–6,713 μg/L) were higher than the concentrations in open systems (Figure 2C).

For SURGE and JUUL pods, the percentage of silicon in the aerosol was $\sim 50\%$ of the concentration in the unvaped or vaped fluids. In contrast, the "Other Brands" aerosols produced with closed systems generally had concentrations similar to the unvaped and vaped fluids (Figure 2C). For open-system pods, concentrations of silicon increased in vaped fluids in comparison with unvaped, and the percentage of silicon in the aerosols was greater than that in the vaped fluid, with Mango Bomb showing the largest increase in the aerosol (Figure 2C).

Concentrations of Nickel in SURGE U-Cigarette and E-Cigarette Fluids and Aerosols

Nickel is of interest because of its known toxicity in humans.[33] Nickel was detected in all unvaped SURGE fluids (range = 6.3–43.0 μg/L) (Figure 3A). In contrast, nickel was detected in six of eight unvaped JUUL flavors and in five of seven of the "Other Brands," where it was generally <10 μg/L (Figures 3B,C), except for the closed-system JUUL-alike "JONES" and KWIT Stick [Mango Tango (MT)] pods, which had averages of 2,999 μg/L and 61,035 μg/L in their unvaped fluids, respectively (Figure 3C).

In three of four SURGE flavors, nickel concentration increased in fluids after vaping, but the increase was not significant (Figure 3A). However, in two of eight JUUL flavors, nickel was significantly higher in the fluid after vaping, whereas concentrations increased in three vaped fluids from "Other Brands" but was not statistically significant (Figure 3B,C).

Concentrations of nickel in aerosols were generally lower than in unvaped and vaped fluids, and the amounts in the aerosol were negligible in some products (Figure 3A–C). In general, the amount of nickel in aerosol in comparison with fluid was very low. In fact, nickel was detected in aerosols in only two of the SURGE flavors (Polar Mint and Blueberry Ice) (Figure 3A). Likewise, for JUUL, nickel was identified in the aerosol in five of eight flavors ranging from 0.6 μg/L in Virginia Tobacco to 6.8 μg/L in Fruit Medley (Figure 3B). In Fruit Medley, nickel was present at 0.57 μg/L in only one unvaped fluid but was quantified in all vaped fluids and aerosols (Figure 3B). In "Other Brands," closed systems generally had higher concentrations of nickel in their aerosols than open systems (Figure 3C). Moreover, aerosol concentration in two of the "Other Brands" products [SMOK Infinix Mango Bomb (MB) and JUUL-Jones Clear Mango (CM)] were similar to concentrations in the vaped fluids (Figure 3C). KWIT Stick aerosols had 940 μg/L of nickel, which is many times higher than its concentration in any other tested product (Figure 3C).

Concentration of Other Elements in SURGE U-Cigarettes and E-Cigarettes

The concentrations of the 14 other elements/metals (aluminum, arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, selenium, silver, tin, titanium, zinc) were totaled by simple addition (Figure 4). In unvaped fluids, total element/metal concentrations were higher in SURGE (1,265–2,492 μg/L) than in JUUL (54–234 μg/L) (Figure 4A,B). Except for KWIT Stick (4,078–5,703 μg/L), concentrations in "Other Brands" were similar to those in JUUL or slightly higher (16–598 μg/L) (Figure 4C). Total concentrations were generally higher in fluids after vaping, with a 13%–58% increase in SURGE, 2%–51% in JUUL (except Cool Mint), 9%–94% in open systems, and 6%–83% in closed-system pods (Figure 4A–C).

The concentration of the totaled elements in aerosols in comparison with the unvaped fluids varied between brands and among flavors of the same brand and was generally <100% (Figure 4A–C). Concentrations of total elements in SURGE aerosols in comparison with fluid were low and similar for all flavors, whereas concentrations in JUUL aerosols varied among flavors (Figure 4A,B). Among the "Other Brands," aerosol concentrations varied among device type, brands, and fluid flavors. In open-system pods that were filled with e-liquids before vaping, aerosol concentrations were higher for samples made with SMOK Infinix than Suorin Edge (Figure 2C). In closed systems, aerosol concentration were higher than or similar to SURGE (Figure 4C).

Individual Elements in SURGE U-Cigarettes, JUUL, and Other Brand E-Cigarettes

Individual elements/metals (not including silicon and nickel) were compared in the three product categories using heat maps in which concentrations below 100 μg/L were colored light blue, and elements that were >100 μg/L were colored according to the color scale to the right of each heat map in Figure 5. Several points are noteworthy. SURGE had more elements above 100 μg/L in the fluids and aerosols than either JUUL or "Other Brands" (Figure 5A–C).

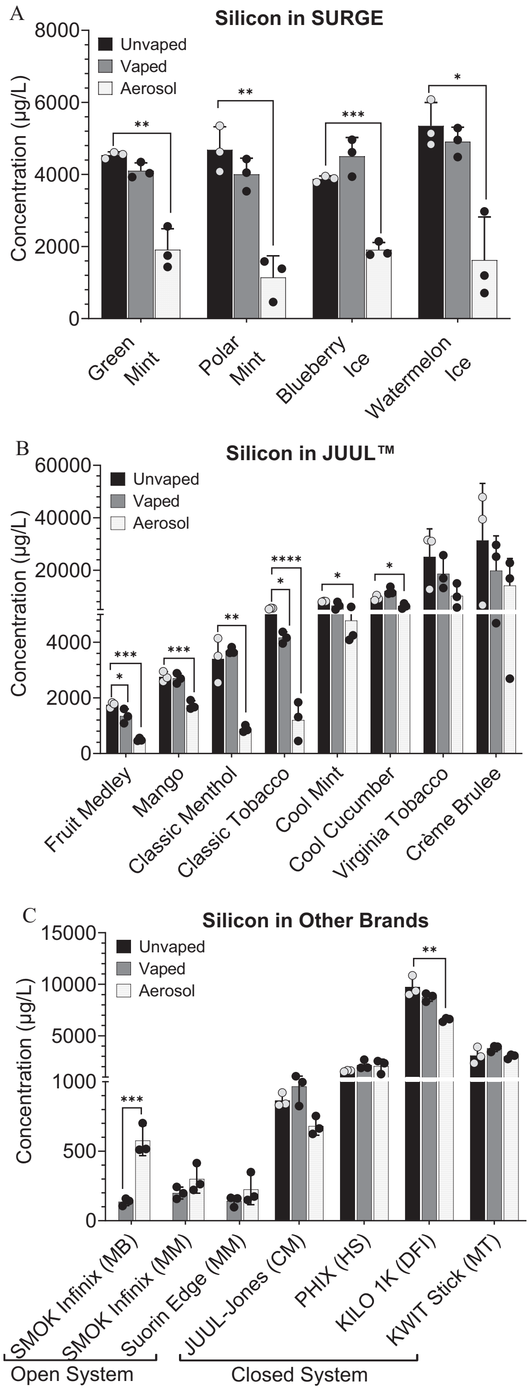

Figure 2. Concentration of silicon in fluids and aerosols of SURGE u-cigarettes and multiple e-cigarettes. Concentrations of elements were determined using ICP-OES. (A) Silicon in SURGE pods. (B) Silicon in JUUL pods. (C) Silicon in "Other Brands" pods with pod flavors indicated in parenthesis. The *x*-axis indicates u-cigarette and e-cigarette devices and flavors. The *y*-axis shows concentrations of elements in μg/L. Each bar is the mean ± SD of three independent pods/measurements. For comparisons of two groups, an unpaired *t*-test was used. When comparisons were done for three groups, a one-way ANOVA was used. Horizontal bars with overlying asterisks are comparisons between unvaped fluids and vaped fluids or unvaped fluids and aerosols where indicated. The mean ± range for each bar and the actual *p*-value for comparison are shown in Tables S3 and S6. Note: ANOVA, analysis of variance; CM, Clear Mango; DFI, Dewberry Fruit Ice; HS, Hard Strawberry; ICP-OES, inductively coupled plasma optical emission spectrometry; MB, Mango Bomb; MM, Mynto Ice Mango; MT, Mango Tango; SD, standard deviation. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; $^{****}p < 0.0001$.

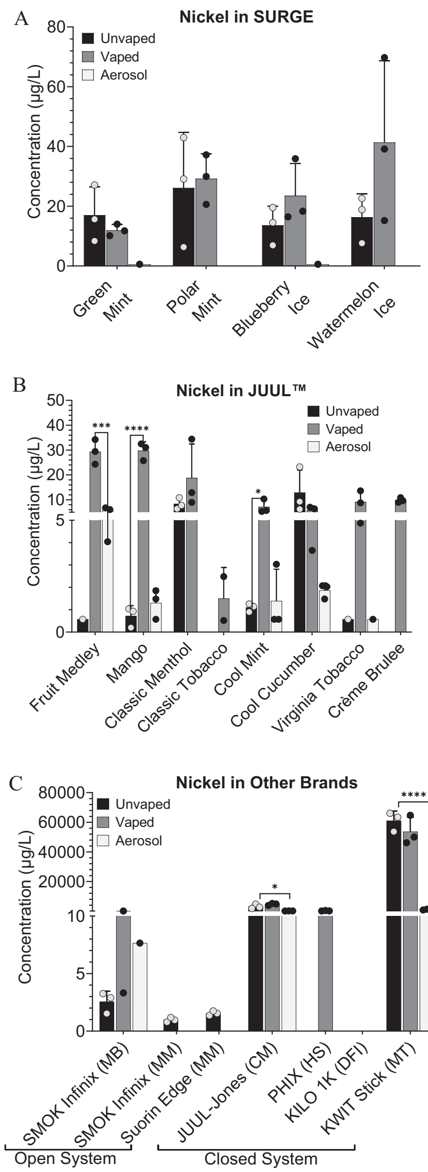

Figure 3. Concentration of nickel in fluids and aerosols of SURGE u-cigarette and multiple e-cigarettes. Concentrations of elements were determined using ICP-OES. (A) Nickel in SURGE pods. (B) Nickel in JUUL pods. (C) Nickel in "Other Brands" pods with pod flavors indicated in parenthesis. The *x*-axis indicates u-cigarette and e-cigarette devices and flavors. The *y*-axis shows concentrations of elements in μg/L. Each bar is the mean ± SD of three independent pods/measurements. For comparisons of two groups, an unpaired *t*-test was used. When comparisons were done for three groups, a one-way ANOVA was used. Horizontal bars with overlying asterisks are comparisons between unvaped fluids and vaped fluids or unvaped fluids and aerosols where indicated. The mean ± range for each bar and the actual *p*-value for comparison are shown in Table S4 and S6. Note: ANOVA, analysis of variance; CM, Clear Mango; DFI, Dewberry Fruit Ice; HS, Hard Strawberry; ICP-OES, inductively coupled plasma optical emission spectrometry; MB, Mango Bomb; MM, Mynto Ice Mango; MT, Mango Tango; SD, standard deviation. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; $^{****}p < 0.0001$.

The elemental composition of SURGE fluids and aerosols was similar for all four products (Figure 5A). In unvaped SURGE fluids, the elements that were highest in concentration included copper (range = 208–507 μg/L), zinc (range = 541–1,119 μg/L), arsenic (range = 413–819 μg/L), and selenium (range = 200–250 μg/L). In all but two cases, concentrations increased in SURGE fluids after vaping. Copper and zinc were usually present in SURGE aerosols,

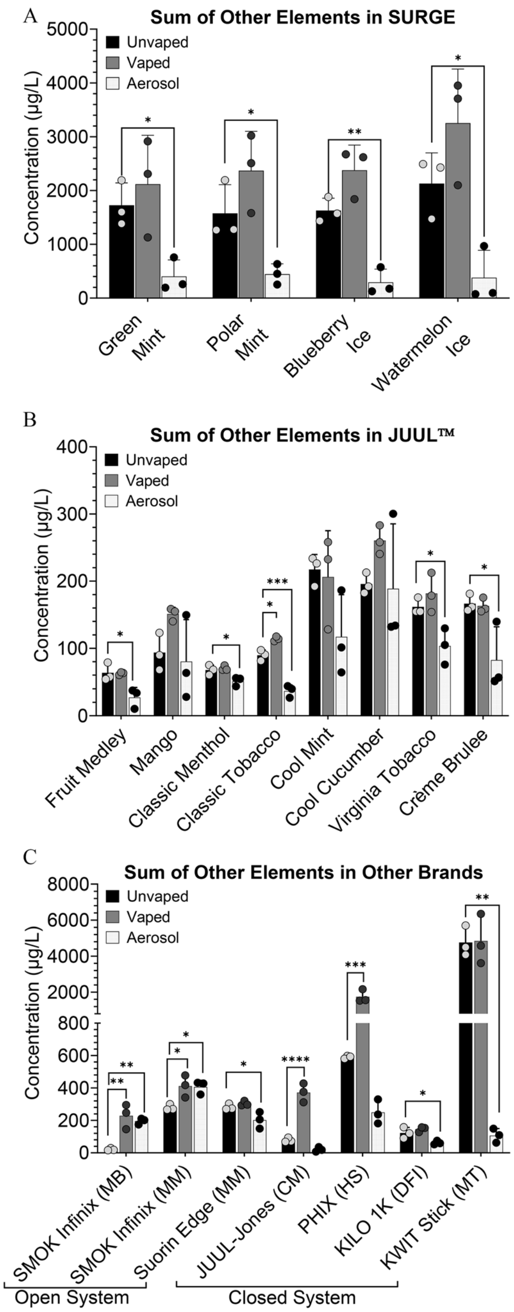

Figure 4. The sum of other elements in fluids and aerosols of SURGE u-cigarette and multiple e-cigarettes. Concentrations of elements were determined using ICP-OES. (A) The sum of other elements in SURGE pods. (B) The sum of other elements in JUUL pods. (C) The sum of other elements in "Other Brands" pods with pod flavors indicated in parenthesis. The *x*-axis indicates u-cigarette and e-cigarette devices and flavors. The *y*-axis shows concentrations of elements in µg/L. Each bar is the mean ± SD of three independent pods/measurements. For comparisons of two groups, an unpaired *t*-test was used. When comparisons were done for three groups, a one-way ANOVA was used. Horizontal bars with overlying asterisks are comparisons between unvaped fluids and vaped fluids or unvaped fluids and aerosols where indicated. The mean ± range for each bar and the actual *p*-value for comparisons are shown in Table S5 and S6. Note: ANOVA, analysis of variance; CM, Clear Mango; DFI, Dewberry Fruit Ice; HS, Hard Strawberry; ICP-OES, inductively coupled plasma optical emission spectrometry; MB, Mango Bomb; MM, Mynto Ice Mango; MT, Mango Tango; SD, standard deviation. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; $^{****}p < 0.0001$.

but in no case was their concentration >100 µg/L. In contrast, arsenic and selenium were measured in aerosols and, in all but one case, were concentrations >100 µg/L. Percentages in aerosols in comparison with fluids were generally low, even for elements that were high in concentration in the fluid (e.g., zinc was high in Blueberry Ice and Watermelon Ice products but were present in low concentration or not at all in the aerosols in both SURGE products).

In contrast to SURGE, element/metal concentrations in JUUL fluids and aerosols were all below 100 µg/L, except Cool Cucumber, which had >100 µg/L of selenium in its unvaped and vaped fluids (Figure 5B). Arsenic was detected in four JUUL aerosol samples at very low concentrations, and selenium was detected in only half the fluid and aerosol samples (Figure 5C). Although copper and zinc were both present in some JUUL samples, their concentrations, especially in aerosols, were very low (Figure 5A,B).

Like JUUL, "Other Brands" of e-cigarettes had relatively few samples with element/metal concentrations >100 µg/L (Figure 5C). KWIT was interesting in that it had high concentrations of copper and zinc in its fluids but relatively little in the aerosols. Arsenic was not detected in any "Other Brand" samples, whereas selenium was present above 100 µg/L in four of seven samples, with detection in the aerosol in all four.

The concentrations of individual elements/metals in the aerosols were statistically compared across groups (Figure 6A–D; Figure S3). For the statistical analyses, products that did not contain an element were excluded, and only groups with three or more samples were included. Twelve of the 16 elements/metals did not show statistical significances across groups (Figure S3). The concentrations of arsenic, selenium, and titanium were significantly higher in SURGE aerosols than in JUUL (Figure 6A–C). Nickel, which was unusually high in one "Other Brand" product (KWIT Stick), was significantly higher than in SURGE and JUUL aerosols (Figure 6D).

Comparisons between Fluids and Aerosols of Closed- and Open-System Pods

Chemical elements/metals in unvaped fluids, vaped fluids, and aerosols from three categories of cigarette products (u-cigarettes, open- and closed-system fourth-generation e-cigarettes) were compared (Figure 6E–G). The aerosols in each of the three categories contained silicon, selenium, aluminum, copper, zinc, tin, lead, iron, nickel, and titanium (Figure 6G). Aerosols from SURGE u-cigarettes and closed-system e-cigarettes additionally had silver, manganese, and cobalt (Figure 6G). The closed- and open-system e-cigarettes contained chromium, whereas only closed systems contained cadmium. In contrast, only u-cigarettes contained arsenic (Figure 6G). The changes in atomizer components as e-cigarettes evolved through four major generations[3] are compared with u-cigarette components in Figure 6H. Although the air tube and wicks have been preserved in all devices, only u-cigarettes contain a sonicator system in place of a heating coil (Figure 6H).

Comparison of Element Concentrations in Aerosols Across Generations of E-Cigarettes and SURGE U-Cigarettes

The concentrations of elements that are of greatest health concern were compared in the aerosols from first generation/cig-a-likes/cartomizers [BluCig Plus, Mark Ten XL, V2 Cigs (2017), Vuse Vibe], second-generation/pens/tanks/clearomizers (Ego Protank, iTaste T3S, Ego Aspire), third-generation/mods (Smok Alien, Nemesis Clone, iPV6X - Tsunami), and fourth-generation/pods (KWIT Stick, Suorin Air, SMOK Infinix, JUUL, KILO 1K, and PHIX) e-cigarettes and SURGE pod u-cigarettes (Table 3). Data from our lab were used for comparisons because the aerosols were all produced and analyzed in the same manner across generations.[11,22] All data were based on the collection of 180 continuous puffs. Values reported in Table 3 were the highest

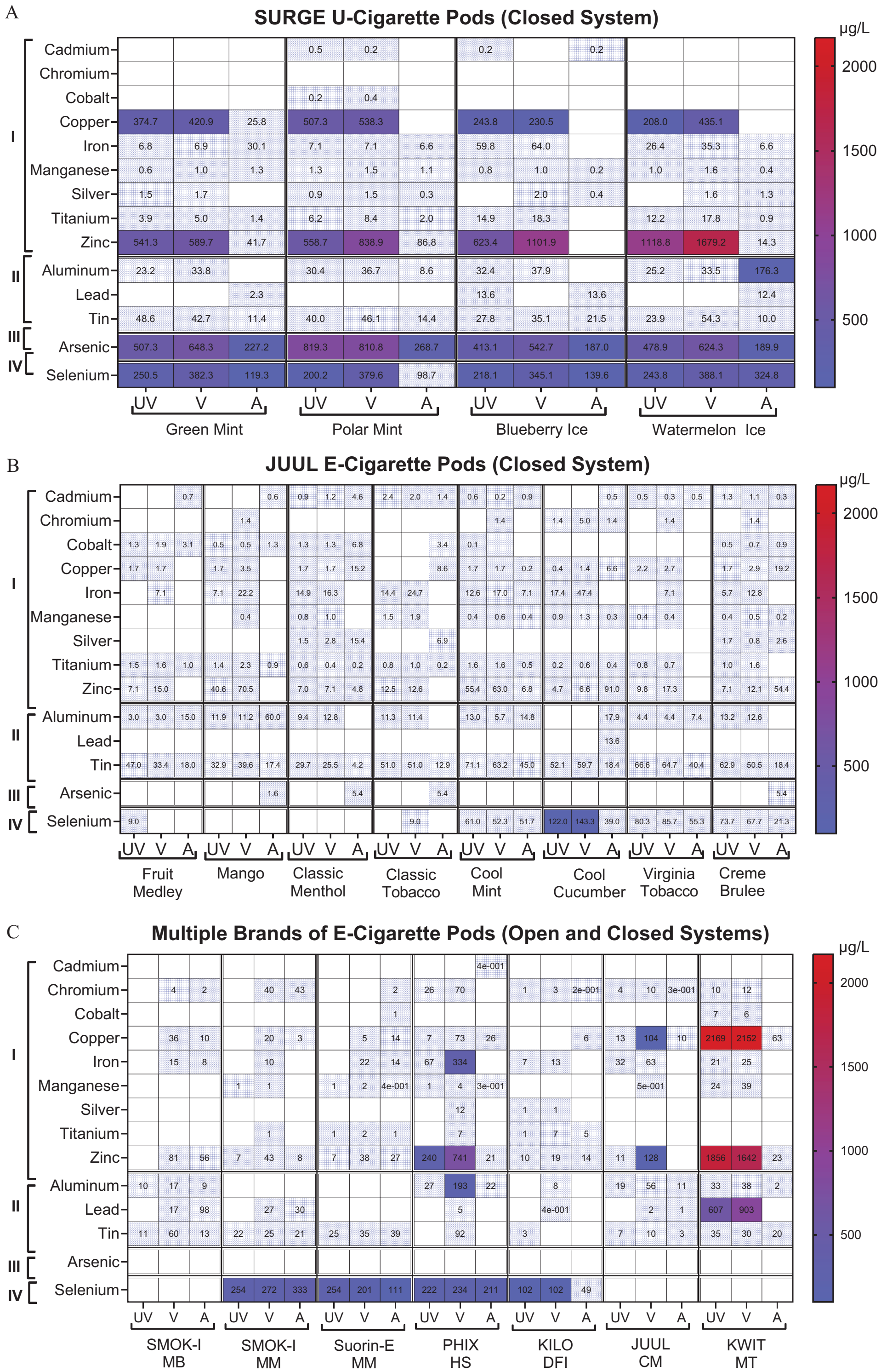

Figure 5. Concentrations of other individual elements in SURGE u-cigarettes and e-cigarettes measured using ICP-OES. (A) Four SURGE u-cigarette flavors. (B) Eight original JUUL flavors (C) Multiple flavors from open (SMOK Infinix and Suorin Edge) and closed (JONES, PHIX, Kilo 1K, and KWIT Stick) system pods. The *x*-axis on the heat map shows pods grouped by flavors: White squares represent elements not detected, and light blue squares represent concentrations below the threshold of 100 μg/L. Blue to red squares represent concentrations indicated on the color scale to the right. The *y*-axis indicates elements/metals grouped based on the periodic table. I: transition; II: post-transition (basic); III: semimetals; and IV: metalloid. Each point is the mean of three independent pods. Pod fluid flavors are indicated below the device names. The mean ± range for elements/metals in each sample type from each device are shown in Tables S7–S15. Note: A, aerosol; CM, Clear Mango; DFI, Dewberry Fruit Ice; HS, Hard Strawberry; ICP-OES, inductively coupled plasma optical emission spectrometry; MB, Mango Bomb; MM, Mynto Ice Mango; MT, Mango Tango; U, unvaped; V, vaped.

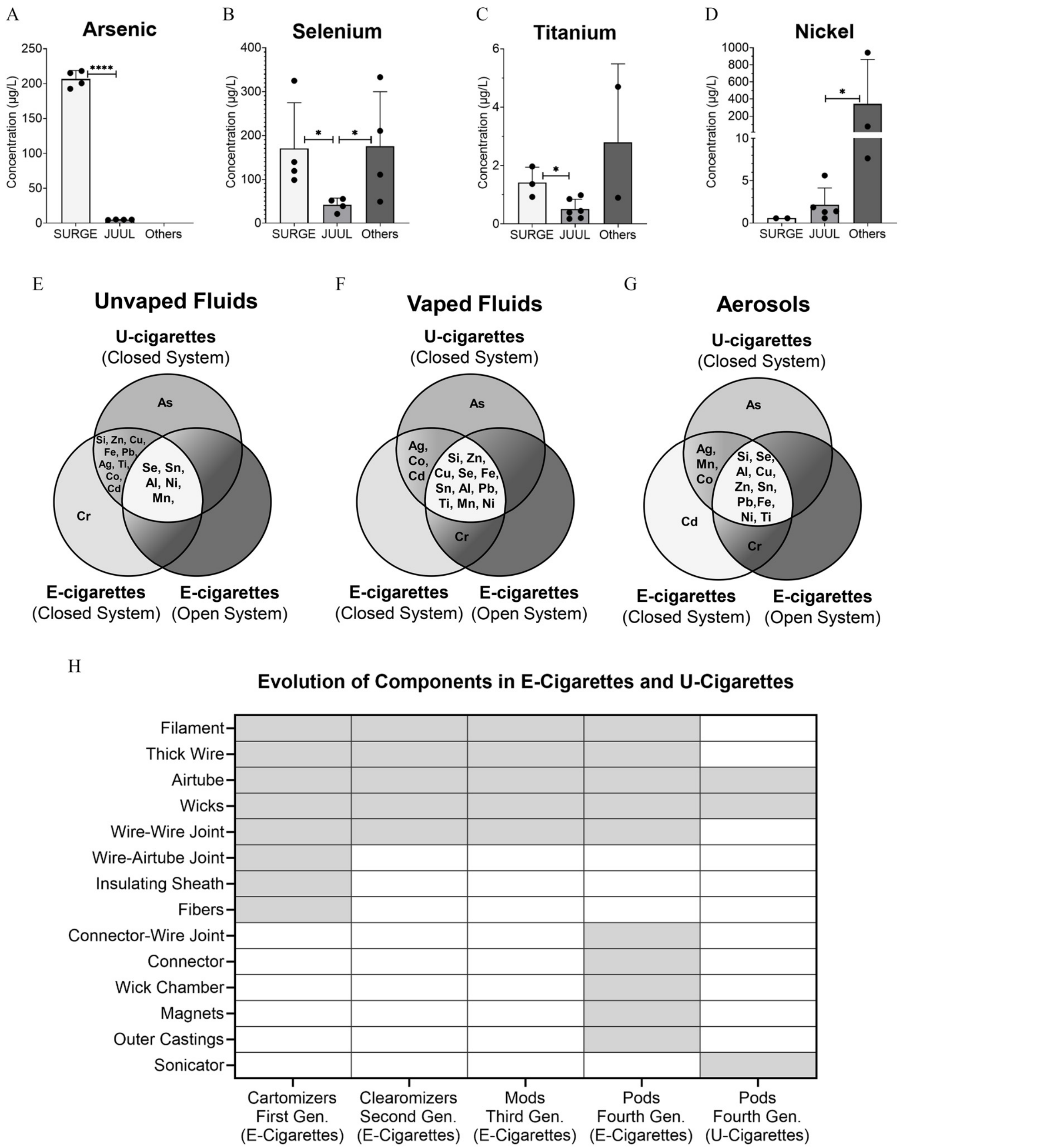

Figure 6. Comparison of elements/metals in aerosols and components of SURGE u-cigarettes and e-cigarettes. Concentrations of (A) arsenic, (B) selenium, (C) titanium, and (D) nickel in aerosols from three groups. The x-axis indicates the groups, and the y-axis shows concentrations of elements in μg/L. Each bar is the mean ± SD of samples in each group. For comparisons of two groups, an unpaired t-test was used. When comparisons were done for three groups, a one-way ANOVA was used. Significantly different groups are indicated by horizontal bars with overlying asterisks. Venn diagrams showing elements identified in (E) unvaped fluids, (F) vaped fluids, and (G) aerosols. (H) Components in multiple generations of e-cigarettes and u-cigarettes. Note: Ag, silver; Al, aluminum; ANOVA, analysis of variance; As, arsenic; Cd, cadmium; Co, cobalt; Cr, chromium; Cu, copper; Fe, iron; Mn, manganese; Ni, nickel; Pb, lead; Se, selenium; Si, silicon; Sn, tin; Ti, titanium; Zn, zinc. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; $^{****}p < 0.0001$.

concentrations in aerosols for each type of product and are organized from the highest to lowest based on the u-cigarette data.

Most elements (including silicon, selenium, arsenic, aluminum, and copper) were higher in concentration in aerosols from fourth-generation pods and/or from SURGE pods than from first to third generation cartomizers, clearomizers, and mods. Iron was highest in third-generation mod aerosols, and lead was highest in fourth-generation pods. Nickel was unusually high in fourth-generation e-cigarettes because of the rogue product from KWIT. Removal of KWIT from the "Other Brands" category drops the nickel in fourth-generation e-cigarettes to a maximum of about 79 μg/L in a JUUL-alike JONES Clear Mango pod, which is considerably lower than the third-generation mods. Chromium was highest in third- and fourth-generation mods and absent from SURGE pods, which do not have a nichrome filament. Several elements, including silicon, selenium, aluminum, copper, and lead, were present in SURGE and fourth-generation products at higher concentrations than previously reported in first-, second-, and third-generation e-cigarette aerosols prepared in the same way (Table 3).

Table 3. Highest concentrations of elements in e-cigarette and u-cigarette aerosols (μg/L).

Element	1st-generation e-cigarettes[a] (Cartomizers)	2nd-generation e-cigarettes[a] (Clearomizers)	3rd-generation e-cigarettes[a] (Mods)	4th-generation e-cigarettes (Pods)	SURGE u-cigarettes (Pods)
Silicon	1,408	578	186	14,104	1,914
Selenium	42	75	243	333	325
Arsenic	15	0	3	5	269
Aluminum	48	13	8	60	176
Copper	11	29	10	63	26
Iron	0	0	370	14	30
Lead	ND	0	32	98	14
Nickel	1	31	364	942	1
Chromium	0	0	32	43	ND

Note: ND, not detected.
[a]Previously reported data in Williams et al.[22]

Discussion

To our knowledge, this is the first study to analyze the elements/metals in a new ultrasonic cigarette product (SURGE) and compare SURGE data to popular closed- and open-system fourth-generation e-cigarettes, including JUUL. U-cigarettes are of interest because they generate less heat (120°–150°C) than heated coil-based e-cigarettes (200°–250°C) and purportedly produce less-toxic aerosols.[59] This logic notwithstanding, we did find elements/metals in SURGE fluids and aerosols, sometimes at higher concentrations than in JUUL and "Other Brands." In fact, nine elements/metals were found in all the aerosols of SURGE u-cigarettes; closed-system e-cigarettes, including JUUL; and open-system e-cigarettes; and five (arsenic, copper, selenium, nickel, and zinc) are on the ATSDR priority list of pollutants,[60] whereas three are on the US FDA list of "Harmful and Potentially Harmful Chemicals" (arsenic, nickel, and selenium).[61]

Silicon concentrations in fluids and aerosols were similar across SURGE, JUUL, and "Other Brands." Silicon can exist in several forms, such as crystalline or amorphous (ATSDR).[60] The form of silicon in e-cigarette aerosols is not commonly reported and was not determined in our study. However, the high concentrations of silicon in some e-cigarette aerosols and the potential silicon exposures received with chronic e-cigarette use emphasize the need for further studies on e-cigarette silicon and its effect on health.

Nickel was present at relatively low concentrations (except for KWIT Stick–MT), and its percentage in the aerosols in comparison with unvaped and vaped fluids was low. Unlike JUUL and "Other Brands," copper and zinc were in SURGE fluids before and after vaping but were not present in high amounts in aerosols. The concentrations of nickel in SURGE aerosols were uniform and quite low ($\sim 20\%$) in comparison with JUUL and most "Other Brands," perhaps because of the lower temperatures used to produce aerosols in SURGE. Although JUUL transfer efficiencies were sometimes higher than SURGE, the concentrations of metals in SURGE aerosols were often higher than in JUUL because of the higher element/metal concentrations in the SURGE fluids.

Of particular concern, SURGE fluids and aerosols had selenium (a metalloid) and arsenic (a heavy metal), which are both on the US FDA list of Harmful and Potentially Harmful Chemicals (HPHC)[61] and on the ATSDR priority list of pollutants.[60] Selenium is an essential element that is required for the synthesis of selenoproteins that control reactive oxygen species (ROS).[62] Insufficient production of selenoproteins leads to oxidative stress. However, the concentration of selenium tolerated by cells is very narrow. When selenium concentrations exceed the selenic range for normal homeostasis, ROS can be generated, which also results in oxidative stress.[63] Arsenic is a known toxicant and potential carcinogen.[64] Inhalation of arsenic produces cough and chest pains,[64] two frequently reported symptoms in e-cigarette users.[65,66] Arsenic and selenium were the most cytotoxic elements in e-cigarette fluids in the 3-(4,5-dimethylthiazol-2-yl)-2,5 diphenyl tetrazolium bromide (MTT) assay, which measured mitochondrial activity using human bronchial epithelial and pulmonary fibroblast cells.[22] The presence of selenium and arsenic in all SURGE fluids and aerosols raises serious concerns about the safety of SURGE.

The sources of elements/metals in SURGE fluids/aerosols are likely the atomizing unit and the fluid ingredients in SURGE pods. Based on the elemental analysis (SEM and EDS), SURGE atomizing units contained and could have contributed silicon, nickel, copper, zinc, lead, aluminum, and tin to SURGE fluids and aerosols. In support of this conclusion, SURGE, JUUL, and KILO 1K products with high concentrations of silicon (range = 1,088–47,872 μg/L) in their fluids had wicks containing silica,[3] whereas PHIX, KWIT Stick, Suorin, and SMOK products with cotton or cotton/ceramic wicks[3] had low concentrations of silicon (range = 98–3,988 μg/L). Although pods were handled carefully in the laboratory to prevent mechanical damage, accidental damage to silica wicks may have occurred in some pods before purchase, which could increase silicon in their fluid.

Nickel is a toxicant and potential carcinogen.[32,33] Its concentrations were relatively low in all tested products, except KWIT Stick MT flavor. Nickel was present in SURGE in the top and bottom seal assembly and spring, which could have been the source for the low levels of nickel found in SURGE fluids. Nickel was not identified at high levels or at all (in some cases) in the aerosols of SURGE and JUUL and is not likely to be a serious health threat for users of these brands. However, the concentration of nickel in a KWIT Stick (66,050 μg/L) was the highest we have seen in any product tested and may have leached from the nichrome filament or nickel in the air tube.[3] Even though it was detected in the aerosol at a low concentration, the aerosol concentrations of nickel in KWIT Stick (942 μg/L) were high due to its very high unvaped fluid concentration (average >61,000 μg/L). Chronic use of KWIT Stick could be a serious health threat, and users would not be aware of the high level of this toxicant and potential carcinogen in their products. KWIT Stick nickel content demonstrates a need for both regulation of nickel concentrations in cigarette products and surveillance to identify rogue products that exceed acceptable levels of nickel or other toxicants.

Pod fluid ingredients, specifically the solvents, are also a likely source of aluminum, silicon, selenium, and arsenic in SURGE, based on our earlier analysis of propylene glycol (PG) and glycerol (G).[22] Neither selenium nor arsenic was found in atomizer components of e-cigarettes or SURGE u-cigarettes, perhaps because their concentration in atomizers is below the LOD for SEM and EDS or because they are entrapped in plastic subcomponents that have not been previously investigated for elemental composition.[3,6,11] In our original study on fluids, selenium and sometimes arsenic were constituents of e-cigarette solvents, specifically PG and G.[22] In the current study, selenium and arsenic were in all unvaped fluids from SURGE products, and selenium, but not arsenic, was in about half of the fluids from JUUL and "Other Brands." Selenium concentrations in JUUL and "Other Brands" were similar to what we reported previously in solvents and refill fluids[22] and did not increase in vaped fluids. Although arsenic was not present in PG from multiple manufacturers, average concentrations in SURGE fluids (range = 413–819 μg/L) were 10–14 times higher than concentrations we reported previously for G and refill fluids.[22] Unlike our earlier studies on e-cigarettes,[22] this study found selenium and arsenic in SURGE products increased in fluids after vaping. These data support the conclusions that: *a*) the selenium and arsenic in the SURGE and e-cigarettes came mainly from the pod solvents; *b*) JUUL and "Other Brands" (in which arsenic was absent and selenium concentrations in unvaped fluids were low) may have used solvents of higher purity than SURGE; and *c*) in all SURGE aerosols except Polar Mint, the arsenic and selenium concentrations were above 100 μg/L. The increase in both elements in three of four vaped SURGE fluids could indicate that components in the SURGE atomizers released additional selenium and arsenic during vaping.

PG and G are manufactured from petroleum (G is also extracted from plants), which undergo extensive distillation to remove impurities, including arsenic and selenium.[67,68] PG and G are further processed by high vacuum distillation to achieve acceptable purity.[68] During distillation, arsenic copurifies with selenium. Unlike our earlier study in which arsenic was not always present,[22] all fluids from SURGE in this study had arsenic, and its concentrations in all SURGE were higher than we found previously. These data suggest that SURGE used low-grade solvents in their e-fluids, resulting in higher concentrations of selenium and arsenic than we found previously in e-cigarette fluids. In premarket evaluation of u- and e-cigarettes by the US FDA, the metal content of the fluids/aerosols should be considered, and both selenium and arsenic, which are components of the solvents, should be included in such evaluations. The safety of these products, in particular SURGE, could be improved by regulating the acceptable levels of arsenic and selenium in u-cigarette fluids and removing these elements from atomizer components. Concentrations of selenium have been reported to be elevated in the urine of e-cigarette users vs. nonsmoking controls and cigarette users.[69] Because selenium and arsenic concentrations in SURGE aerosols were higher than in previously examined fluids/aerosols,[22] it is likely the selenium and arsenic concentrations in the urine of SURGE users would exceed those in e-cigarette users.

Various methods have been used to evaluate metals in aerosols across multiple e-cigarette generations.[2–4,6,7,12–14,19,21–23,38,39,70–73] It is difficult to cross-compare metal concentrations in different studies due to the many variables in aerosol production (e.g., the e-cigarette products per se, topography, fluid composition, methods of aerosol collection and analysis, power settings, and flavor categories). Further confounding cross-comparisons, the units used to report concentration are highly variable and include as examples nanograms/puff, micrograms/puff, and ng/mg of fluid consumed.[14] In spite of these variables, a common theme across studies is that the concentrations of elements/metals in e-cigarette aerosols are variable among products.

In the Zhao review, which covered mainly cartomizers and tank-style e-cigarettes, the highest concentrations of nickel, chromium, and lead in aerosols were 0.43 μg/L, 0.1 μg/L, and 0.05 μg/L, respectively. In another study that focused on pod-style e-cigarettes,[39] the average concentrations of nickel (0.090 μg/L), chromium (0.002 μg/L), and lead (0.024 μg/L) were much lower than in the current study (4.67–104.08 μg/L). These elevated concentrations were attributed to variations in device design and heating coils, as well as manufacturing practices that vary among countries.

Previous studies and the current data have reported the presence of toxic metals and chemical elements in e-cigarette aerosols. The current study further shows for the first time (to our knowledge) that u-cigarettes have similar and, in some cases, higher concentrations of elements/metals in their fluids and aerosols than e-cigarettes. These data raise concerns about the health risks, such as cancer and neurotoxicity, that could result from long-term use of these products.

Conclusion

Newer technologies, such as u-cigarettes, do not necessarily eliminate or reduce exposures to hazardous elements/metals or their toxic effects, as shown by the data in this study. Elements/metals in u-cigarette aerosols were similar to those found in fourth-generation e-cigarettes. Moreover, SURGE u-cigarettes had higher concentrations of arsenic and selenium, both potential toxicants, than we have seen previously[22] in e-cigarette fluids and aerosols. Regulation of toxic elements/metals in u-cigarettes and e-cigarettes is needed, and surveillance to identify and remove rogue products such as KWIT Stick should be enacted to protect public health.

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