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Seeing beyond the smoke: Selecting waterpipe wastewater chemicals for risk assessments

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A B S T R A C T

Background: Increasing use prevalence of waterpipe tobacco products raises concerns about environmental impacts from waterpipe waste disposal. The U.S. Food and Drug Administration (FDA) is required to assess the environmental impact of its tobacco regulatory actions per the National Environmental Policy Act. This study builds on FDA's efforts characterizing the aquatic toxicity of waterpipe wastewater chemicals.
Methods: We compiled a comprehensive list of waterpipe wastewater chemical concentrations from literature. We then selected chemicals for risk assessment by estimating persistence, bioaccumulation, and aquatic toxicity (PBT) characteristics (U.S. Environmental Protection Agency), and hazardous concentration values (concentration affecting specific proportion of species).
Results: Of 38 chemicals in waterpipe wastewater with concentration data, 20 are listed as harmful or potentially harmful constituents (HPHCs) in tobacco smoke and tobacco products by FDA, and 15 are hazardous waste per U. S. Environmental Protection Agency. Among metals, six (cadmium, chromium, lead, mercury, nickel and selenium) are included in both HPHC and hazardous waste lists and were selected for future risk assessments. Among non-metals, nicotine, and 4-methylnitrosamino-1-(3-pyridyl)− 1-butanone (NNK) were shortlisted, as they are classified as persistent and toxic. Further, N-nitrosonornicotine (NNN), with a low hazardous concentration value (HC_{50}; concentration affecting 50 % of aquatic species) for chronic aquatic toxicity, had high aquatic toxicity concern and is selected.
Conclusions: The presence of multiple hazardous compounds in waterpipe wastewater highlights the importance of awareness on the proper disposal of waterpipe wastewater in residential and retail settings. Future studies can build on the hazard characterization provided in this study through fate and transport modeling, exposure characterization and risk assessments of waterpipe wastewater chemicals.

1. Introduction

Waterpipe tobacco smoking has emerged as a global phenomenon with increasing use prevalence, raising concerns about the environmental impact from waterpipe waste disposal (Kassem et al., 2020; Maziak et al., 2015). Also known as hookah, narghile, shisha, arguile, hubble-bubble, or goza, a waterpipe consists of burning charcoal used to heat waterpipe tobacco placed in a bowl at the top of the apparatus. Smoke is produced and pulled through a vertical stem attached to a chamber filled with a liquid, typically water, before inhalation by the user. The wastewater is then discarded. Previous studies on environmental impacts of waterpipe tobacco use have largely focused on waterpipe tobacco smoke with limited attention on the environmental impacts of waterpipe waste and wastewater chemicals from the waterpipe smoking session.

The prevalence of waterpipe use is highest in Europe (8.4–11.5 %) and the Middle East (2.4–6.4 %), followed by the United States (see Fig. 2 in Bhatnagar et al. 2019). Evidence shows that rates of waterpipe tobacco smoking surpass cigarette smoking in some countries, and that online shopping searches for waterpipe related products increased 291 % between January 2004 and December 2013 (Bhatnagar et al., 2019). In the U.S., waterpipe tobacco smoking among youth has increased since 2009 along with the proliferation of waterpipe establishments around U. S. colleges (Kates et al., 2016; Cooper et al., 2019). For example, use prevalence in the U.S. doubled for both adults and young adults between 2009 and 2014 (Bhatnagar et al., 2019). U.S. imports of waterpipe

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tobacco simultaneously increased by 14 %, from 738 metric tons in 2012–841 metric tons in 2019, further highlighting the rise in use prevalence (USDA - FAS, 2019; Edwards et al., 2021). The upward trend in waterpipe tobacco smoking (see reviews in (Bhatnagar et al., 2019; Cooper et al., 2019) raises concerns about potential environmental impact from the disposal of waterpipe wastewater after each smoking session or end of business hours. Of particular concern is the opportunity for elevated and concentrated levels of hazardous waste frequently disposed of down the drain at waterpipe smoking establishments, especially as users may inhale 100–200 times the amount of smoke containing hazardous chemicals than from a single cigarette during a typical waterpipe smoking session (Husain et al., 2016; Centers for Disease Control and Prevention et al., 2021). Compounding this is the increased popularity of electronic-waterpipe (or e-hookah) use by youth, largely due to perceptions of lower overall health risks compared to combustible waterpipes (Rezk-Hanna et al., 2022).

In accordance with the National Environmental Policy Act (NEPA), the U.S. Food and Drug Administration (FDA) evaluates the environmental impact of its tobacco regulatory actions per rules described in 21 C.F.R § 25 (Environmental Impact Considerations, 2022). Environmental impact assessments address the environmental effects of manufacture, use and disposal of FDA-regulated tobacco products. Understanding the environmental impact of waterpipe wastewater on aquatic biota may be an important aspect of the disposal portion of the environmental assessment of waterpipe tobacco products.

Studies assessing residential waterpipe waste disposal habits report that about 90 % of waterpipe smokers discard all of the waterpipe wastewater down the drain (kitchen or bathroom sinks) post smoking (Kassem et al., 2020). As 90 % of waterpipe tobacco wastewater is disposed of into the municipal wastewater system, where it can reach aquatic systems, it raises environmental impact concerns (Kassem et al., 2020). Available evidence also indicates that waterpipe wastewater contains chemicals that may accumulate and persist in aquatic systems with potential negative impact on aquatic biota due to their aquatic toxicity potential. These include hazardous and toxic constituents, and environmental contaminants such as heavy metals, furanic compounds, carbonyls, and volatile organic compounds (VOCs) (Al-Kazwini et al., 2015; Schubert et al., 2012a, 2015, 2012b; Jafari et al., 2020) that may reach aquatic biota due to a lack of awareness of the need for proper disposal. Among the list of chemicals detected, those with the highest aquatic toxicity potential include acrolein, acrylonitrile, cadmium, lead, chromium, nickel, and cobalt (Edwards et al., 2021). Some of these chemicals are regulated under the U.S. Clean Water Act (CWA) (acrolein, acrylonitrile, cadmium, lead, chromium, and nickel) (US Environmental Protection Agency, 2015a) and as hazardous compounds under the U.S. Resource Conservation and Recovery Act (RCRA) (acrolein, cadmium, lead, chromium, and nickel) (Identification and Listing of Hazardous Waste, 2020), hence awareness of proper waterpipe wastewater disposal steps in both retail and residential settings is important (US Environmental Protection Agency, 1995a).

While these factors raise environmental impact concerns, available studies are limited to the identification of waterpipe wastewater chemicals and their aquatic toxicity characterization. Research efforts characterizing the hazard potential of the waterpipe wastewater chemicals or those prioritizing chemicals for risk assessments are currently not available. Of particular concern are hazardous chemicals that do not readily degrade in the environment, also known as PBT chemicals, that can accumulate in biota over time with increasing toxicological potential. These chemicals may pose a risk to human health and the environment because they can transfer across ecosystems and geographical boundaries, often making it difficult to predict long-term impact (Gramatica et al., 2015; Pizzo et al., 2016; Ruzzin, 2012). PBT assessments using computational tools such as Quantitative Structure Activity Relationship (QSAR) models are widely used by both European and U.S. regulatory agencies to perform preliminary screening for a variety of chemicals (Gramatica et al., 2015; Moermond et al., 2012; Muir and Howard, 2006). However, detailed information on the persistence and bioaccumulation of waterpipe wastewater chemicals is currently not available. Additionally, chemical concentrations are an important factor that can affect exposure and risk potential and are generally included in hazardous chemical screening studies (Arnot and Mackay, 2008). Again, a compilation of chemical concentrations in waterpipe wastewater and their hazards is not currently available. Therefore, the overall environmental impacts and ecological risks for waterpipe wastewater chemicals disposed of down the drain remain poorly understood. Characterizing and quantifying the chemical constituents and hazard potential of waterpipe wastewater aids in the development of strategies to reduce its environmental impact on aquatic systems.

This study aims to inform the environmental impact and risk assessments for waterpipe wastewater disposal. Specifically, this study provides a) a literature-based compilation of waterpipe wastewater chemicals and their concentrations, b) *in-silico* predictions of the environmental PBT persistence (P), bioaccumulation (B) and aquatic toxicity (T) of waterpipe wastewater chemicals, c) compilations of the hazardous concentration values (HC_{50}) for acute and chronic aquatic toxicity of these chemicals, d) hazard characterization and selection of waterpipe wastewater chemicals for risk assessments and e) discussion of relevant information on ecological and human health effects from exposures to the selected hazardous chemicals.

2. Methods

2.1. Study selection and compilation of waterpipe wastewater chemical concentrations

We conducted a literature search of six peer reviewed databases (PubMed, Embase, Web of Science, Academic Search Complete, SciFinder, and Google Scholar) using terms for articles that characterize and quantify waterpipe wastewater chemicals, as shown in Supplementary Figure S1. The search identified a total of 76 articles. After removing duplicates, the remaining 42 articles were further evaluated for scientific content and inclusion and exclusion criteria, and articles that did not quantify waterpipe wastewater chemicals were removed. Eleven articles were selected for full text review and those studies with small sample size, which can decrease statistical power, lack of methodological details and replicates, and where data did not support conclusions were excluded. Based on this, we selected four articles that reported chemical concentrations, for the screening-level hazard characterization and selection of waterpipe tobacco wastewater chemicals. In addition, we also included concentrations of waterpipe wastewater chemicals as provided by Edwards et al (Edwards et al., 2021). In all of the studies, samples were taken from the water in the bowls of a variety of waterpipes and chemical concentrations were calculated. The selected articles reported that sample preparation, analytical parameters, smoking methods, and method validation were performed according to international standards, such as Health Canada and German Industrial Norm.

A comprehensive list of waterpipe wastewater chemicals and their reported concentrations was compiled (Table 1). We confirmed the identity of the list of compiled chemicals and checked for consistency with other sources through U.S. Environmental Protection Agency's (EPA) CompTox Chemicals Dashboard (Williams et al., 2017; Lowe and Williams, 2021).

2.2. Hazard characterization and selection of waterpipe wastewater chemicals

We used EPA PBT assessment criteria to select non-metals for future risk assessment (US Environmental Protection Agency, 1999); PBT methods generally do not take into consideration various processes associated with the fate, bioavailability and toxicity of inorganic compounds and are therefore not applicable to metals and metalloids

(European Commission, 2003). We estimated the environmental persistence of the chemicals in water, soil, and sediment using predicted half-life periods from the BIOWIN™ program in the EPI Suite software (US Environmental Protection Agency, 2020). We classified chemicals as 'Not Persistent' or readily biodegradable if Biowin3 (ultimate survey model) estimate was $\geq$ 2.3 and Biowin5 (MITI linear model) estimate was $\geq$ 0.3. Chemicals were classified as 'Persistent' if any of these criteria were not met (US Environmental Protection Agency, 1999, 2020). For bioaccumulation predictions, we used fish bioaccumulation factor estimates (BAF; L/Kg wet-weight) generated with BCFBAF™ program in the Estimation Programs Interface (EPI) Suite software (US Environmental Protection Agency, 2020). We classified chemicals as 'Bioaccumulative' if the predicted BAF values were $\geq$ 1000 (US Environmental Protection Agency, 1999; Costanza et al., 2012). We used the fish *ChV* predictions for characterizing aquatic toxicity as part of the PBT assessments and classified chemicals with predicted $ChV < 10$ mg/L as 'Toxic' (US Environmental Protection Agency, 1999, 2020). Per the PBT screening assessment, we selected those classified as PBT, BT or PT from the total list of chemicals. Further, we collated available HC values (HC_{50}) for acute and chronic aquatic toxicity from the literature (Edwards et al., 2021; Venugopal et al., 2021; Posthuma et al., 2019). Metals and metalloids were selected for future risk assessment based on their inclusion in both the FDA harmful and potentially harmful constituents (HPHCs) in tobacco products and smoke (Harmful and Potentially Harmful Constituents in Tobacco Products and Tobacco Smoke, 2012) list and EPA hazardous constituents list (Identification and Listing of Hazardous Waste, 2020).

3. Results

Concentrations of 38 chemicals including 15 metals and metalloids found in waterpipe wastewater were recorded from literature (Table 1). Of the 38 chemicals, 20 are considered HPHCs per FDA's list, and 15 are hazardous constituents per EPA's list including two acute hazardous chemicals and six toxic chemicals (Table 1). Among metals, six (cadmium; 0.020–4.24 μg/L, chromium 2.72–33.17 μg/L, lead; 211.74–296.06 μg/L, mercury; 1.80 μg/L, nickel; 3.87–21.0 μg/L, selenium; 1.53 μg/L), in both the HPHC and hazardous waste lists were

Table 1
Chemical Constituents and Concentrations in Waterpipe Wastewater. Chemicals selected for detailed risk assessments are in bold.

CAS	Name	EPA Hazardous Waste	FDA HPHC *	Mean Concentration (μg/L) (SD)	Reference
16543-55-8	**NNK***	Listed	Yes	106.55 (165.38)	(Edwards et al., 2021)
98-00-0	2-Furanmethanol	Not listed	No	4547.20 (2329.251)	(Schubert et al., 2012a)
54-11-5	**Nicotine**	P075	Yes	1220.00 (1240)	(Edwards et al., 2021)
1192-62-7	Ethanone, 1-(2-furanyl)-	Not listed	No	346.13 (149.59)	(Schubert et al., 2012a)
107-13-1	Acrylonitrile	U009	Yes	0.84 (0.14)	(Edwards et al., 2021)
4170-30-3	Crotonaldehyde	U053	Yes	36.40 (18.34)	(Edwards et al., 2021)
98-01-1	2-Furancarboxaldehyde	Not listed	Yes	7250.67 (3533.795)	(Schubert et al., 2012a)
67-64-1	2-Propanone	Not listed	Yes	210.8**	(Schubert et al., 2012a)
50-00-0	Formaldehyde	U122	Yes	197.6**	(Schubert et al., 2012b)
				935.59 (402.67)	(Edwards et al., 2021)
123-72-8	Butanal	Not listed	Yes	63.6**	(Schubert et al., 2012b)
95-48-7	o-Cresol	Not listed	No	17.93 (6.00)	(Edwards et al., 2021)
120-80-9	Catechol	Not listed	Yes	143.91 (83.00)	(Edwards et al., 2021)
108-95-2	Phenol	U188	Yes	34.0	(Schubert et al., 2015)
				188.01 (63.90)	(Edwards et al., 2021)
107-02-8	Acrolein	P003	Yes	35.33**	(Schubert et al., 2012b)
				610.81 (249.39)	(Edwards et al., 2021)
75-07-0	Acetaldehyde	Yes	Yes	814.67**	(Schubert et al., 2012b)
				1950.84 (814.58)	(Edwards et al., 2021)
71-43-2	Benzene	U019	Yes	0.58 (0.06)	(Edwards et al., 2021)
90-05-1	Phenol, 2-methoxy-	Not listed	No	31.20	(Schubert et al., 2015)
123-38-6	Propanal	Not listed	No	22.36**	(Schubert et al., 2012b)
620-02-0	2-Furancarboxaldehyde, 5-methyl-	Not listed	No	958.93 (534.0187)	(Schubert et al., 2012a)
67-47-0	2-Furaldehyde, 5-hydroxymethyl-	Not listed	No	3817.33 (2722.331)	(Schubert et al., 2012a)
56-81-5	Glycerol	Not listed	Yes	253,530.00 (167,030)	(Edwards et al., 2021)
57-55-6	Propylene glycol	Not listed	Yes	82,860.00 (141,250)	(Edwards et al., 2021)
64091-91-4	**NNN***	Not listed	Yes	250.95 (262.80)	(Edwards et al., 2021)
7439-89-6	Iron	Not listed	No	335.12 (83.78)	(Jafari et al., 2020)
7440-66-6	Zinc	Not listed	No	361.46 (100.40)	(Jafari et al., 2020)
7440-02-0	**Nickel**	Listed	Yes	21.0 (11.5)	(Jafari et al., 2020)
				3.87 (4.11)	(Edwards et al., 2021)
7439-97-6	**Mercury**	U151	Yes	1.80 (1.13)	(Jafari et al., 2020)
7439-96-5	Manganese	Not listed	No	115.15 (42.64)	(Jafari et al., 2020)
7440-50-8	Copper	Not listed	No	182.70 (70.26)	(Jafari et al., 2020)
7440-31-5	Tin	Not listed	No	595.80 (175.23)	(Jafari et al., 2020)
7782-49-2	**Selenium**	Listed	Yes	1.53 (0.20)	(Edwards et al., 2021)
7440-48-4	Cobalt	Not listed	Yes	2.76 (1.10)	(Jafari et al., 2020)
				0.14 (0.12)	(Edwards et al., 2021)
7440-36-0	Antimony	Listed	No	53.01 (26.51)	(Jafari et al., 2020)
7429-90-5	Aluminum	Not listed	No	263.20 (71.13)	(Jafari et al., 2020)
7440-43-9	**Cadmium**	Listed	Yes	4.24 (2.12)	(Jafari et al., 2020)
				0.020 (0.014)	(Edwards et al., 2021)
7440-47-3	**Chromium**	Listed	Yes	33.17 (11.05)	(Jafari et al., 2020)
				2.72 (1.73)	(Edwards et al., 2021)
7439-98-7	Molybdenum	Not listed	No	50.18 (31.46)	(Jafari et al., 2020)
7439-92-1	**Lead**	Listed	Yes	296.06 (164.47)	(Jafari et al., 2020)
				211.74 (152.60)	(Edwards et al., 2021)

* HPHC – Harmful or potentially harmful constituents in tobacco products and smoke; NNK: 4-methylnitrosamino-1-(3-pyridyl)−1- butanone; NNN: N-nitrosonornicotine

** Converted to μg/L from μg/750 mL

selected for risk assessment. Among non-metals, nicotine; 1220 μg/L, 4-methylnitrosamino-1-(3-pyridyl)−1- butanone (NNK); 106.55 μg/L were selected, as they are classified as persistent and toxic (Table 1 in bold; Fig. 1; Fig. 2). Further, based on low HC_{50} value for chronic aquatic toxicity, which indicates high aquatic toxicity, N-nitrosonornicotine (NNN; 250.95 μg/L), was selected.

Additionally, seven chemicals (2-Furaldehyde, 5-hydroxymethyl-; formaldehyde; glycerol; ethanone, 1-(2-furanyl)-; catechol; 2-Propanone; Acetaldehyde; 2-Furanmethanol) were classified as “Not-PBT” (Fig. 1; Fig. 2). Of note, several potentially hazardous chemicals are found in relatively high concentrations in waterpipe wastewater (Table 1). These include acetaldehyde (1950.84 μg/L), aluminum (263.20 μg/L), and tin (595.80 μg/L). However, these chemicals were not selected for future risk assessment as our analysis indicates they may not be PBT.

Collectively, hazardous chemicals selected from our analysis can be candidates for future risk assessments to understand potential impacts of “down the drain” waterpipe wastewater disposal on human health and the environment, and these chemicals are further discussed below.

4. Discussion

Waterpipe tobacco use is increasing with little regulation or guidance for proper disposal of waterpipe wastewater. Evidence indicates that the majority of waterpipe wastewater is discarded down kitchen and bathroom sinks, and to a lesser extent disposed of in backyard soils (Kassem et al., 2020). However, the ecological effects of waterpipe wastewater chemicals disposed of down the drain remain poorly understood. We compiled a comprehensive list of waterpipe wastewater chemicals and their concentrations from the literature and selected the most hazardous of these chemicals for future risk assessments. This study is the first of its kind to characterize the hazards posed by waterpipe wastewater chemicals to aquatic systems and biota considering multiple criteria (PBT, HC_{50} and HPHC/Hazardous waste). Results from this study represent the hazard characterization portion of risk assessment to determine the ecological impact of waterpipe wastewater chemicals on aquatic biota.

This study advances FDA’s evaluation of the environmental impacts of tobacco products for NEPA, revealing that disposal of waterpipe wastewater “down the drain” by retail establishments and in residential settings may be an important source of toxicants that may affect aquatic biota. Our results also represent an important first step in understanding and determining the actual concentration of waterpipe wastewater chemicals disposed of down the drain and ultimately into aquatic environments. Results identified three tobacco-specific chemicals (nicotine, NNN, NNK), and six metals (cadmium, chromium, lead, mercury, nickel, selenium) on both the FDA HPHC and EPA hazardous constituents list, adding to the evidence that waterpipe wastewater contains contaminants that can bioaccumulate and persist in the environment if

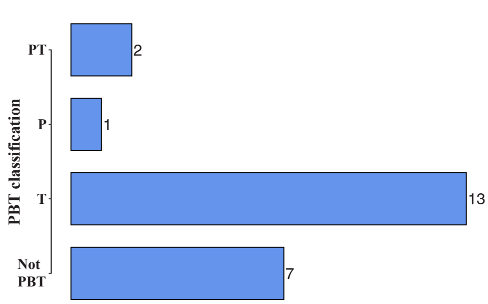

Fig. 1. Persistence, Bioaccumulation and Toxicity (PBT) Classification of Waterpipe Wastewater Chemicals. Chemicals reported from waterpipe wastewater were classified as persistent (P), bioaccumulative (B) or toxic to aquatic organisms (T).

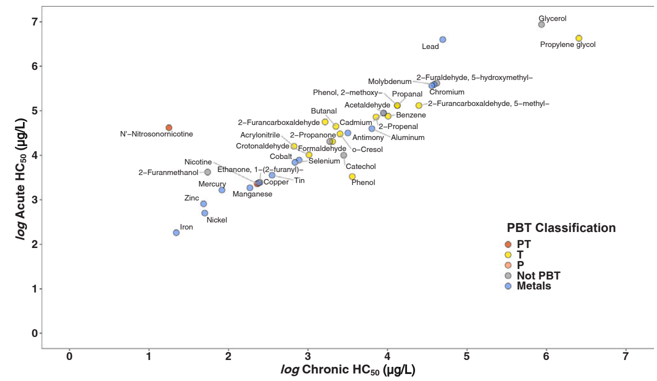

Fig. 2. Hazardous concentration values (HC_{50}) for acute and chronic aquatic toxicity, and the environmental persistence, bioaccumulation and aquatic toxicity classification of waterpipe tobacco wastewater chemicals. Chemicals classified as persistent (P), bioaccumulative (B), toxic for aquatic organisms (T) are depicted along with metals and metalloids.

introduced through public sewers or onsite drainage systems. Several chemicals in waterpipe wastewater are present at levels significantly higher than EPA’s recommended water quality criteria for aquatic biota (i.e., acrolein, aluminum, cadmium, lead, mercury NNK, NNN, nickel, tin, phenol, zinc) (US Environmental Protection Agency, 2015a). For instance, among chemicals selected for risk assessments, NNK (106.55 μg/L) and NNN (250.95 μg/L) are reported at levels high enough for potential aquatic and human toxicity to occur when these toxicants are disposed of down-the-drain. Several studies have demonstrated the adverse impacts of these chemicals on animals exposed through water exposures. Zebrafish embryos exposed to NNK (50–200 μM) had developmental defects (Merino et al., 2022), and rats exposed to NNN (0–500 ppm) for 3-weeks through drinking water developed reactive NNN metabolites in the lungs and the nasal cavity, leading to the formation of cancerous lesions (Zarth et al., 2016).

The source of metals detected in waterpipe wastewater is primarily from the waterpipe tobacco and to a lesser extent, from the waterpipe unit (Edwards et al., 2021). In the context of this study, high levels of cadmium, nickel and lead were reported in waterpipe wastewater. Lead is acutely toxic to fish through respiratory failure and neurotoxicity, respectively (Exley et al., 1991) and there are no safe levels for lead in drinking water (US Environmental Protection Agency, 2016). Nickel is a respiratory toxicant in aquatic species (rainbow trout) from acute exposures (Pane et al., 2003) and a recommended level of 100 μg/L is reported for drinking water (US Environmental Protection Agency, 1995b). Cadmium on the other hand, can readily bioaccumulate in high concentrations in aquatic animals, due to their feeding and metabolic processes. As well as impacting their physiology, cadmium contaminated aquatic animals, such as fish, can be part of the food chain and impact human health via dietary exposures (Han et al., 2020). As such, the reported Maximum Contaminant Level is 0.005 mg/L (US Environmental Protection Agency, 2015a) for cadmium in drinking water. While the level of mercury in waterpipe wastewater was lower than those metals mentioned above, it is worth noting that mercury can bioaccumulate in fish that are part of the food chain, which can lead to human mercury exposures through fish consumption. These factors raise concern in the context of ecological and human health effects, and water quality effects.

Although there are other chemicals in waterpipe wastewater in high concentrations, available information indicates they may not pose a risk to aquatic biota as indicated by lack of environmental persistence and bioaccumulation, or by high HC_{50} values (low aquatic toxicity). For example, formaldehyde rapidly hydrates to form glycol in water (Kehoe, 2005) and acetaldehyde undergoes biodegradation and volatilization (Canada Health, 2004). Similarly, crotonaldehyde readily volatilizes and importantly, does not enter the food chain (ATSDR, 2002), and acrolein is expected to be volatized from surface water (National Institutes of Health,). While tin and aluminum occur in high concentrations in waterpipe wastewater, they are not included in the HPHC or EPA hazardous waste lists. For these chemicals, fate and transport information suggest they may be of less concern for impacts on aquatic biota.

While this study raises environmental and water quality concerns regarding hazardous compounds and their concentrations in waterpipe wastewater, interpretation of our analysis should consider some limitations. The list of chemicals and concentrations information is limited by the overall small number of studies characterizing waterpipe wastewater chemicals and concentrations. This underscores the importance of research using both targeted and non-target chemical analyses to characterize the chemical compounds found in waterpipe wastewater. The chemical concentrations presented in Table 1 were measured in waterpipe wastewater bowls under standardized laboratory conditions. However, in real life scenarios the actual concentration of chemicals in waterpipe wastewater disposed of down the drain is dependent on multiple factors (duration of smoking session, volume of water used, frequency of waterbowl changes, i.e., refreshing the water, and amount of waterpipe tobacco used). Therefore, the actual concentration of chemicals reaching aquatic systems upon disposal varies and needs further consideration of publicly owned treatment works (POTWs) filtering capabilities, and chemical fate and transport properties. Also, the PBT method-based screening has limitations in the form of reduced consistency and arbitrary cut-off values in the binary scoring results (e.g., B or not-B). Further, data gaps and reliance on predictive models raise uncertainties, which are not directly addressed in the PBT-classification (Arnot and Mackay, 2008). These limitations notwithstanding, our study represents a robust and comprehensive hazard characterization and screening of waterpipe wastewater chemicals.

Beyond the hazard characterization of this study, our results may have regulatory implications for waterpipe establishments in the U.S, where they may be subject to requirements per the National Pretreatment Program under the CWA. Waterpipe wastewater contains chemicals listed on EPA's Toxic and Priority Pollutant Lists and regulated under the CWA (US Environmental Protection Agency, 2015a). Some hazardous waterpipe wastewater chemicals can pass through POTWs untreated due to variability in capacity and treatment techniques (Hargreaves et al., 2018). Toxic or hazardous waterpipe wastewater chemicals may also interfere with POTW functionality and cause unintended discharges of inadequately treated effluent into aquatic systems (US Environmental Protection Agency, 2015b). Consequently, depending on the amount of hazardous waste generated, waterpipe retail establishments may be subject to multiple steps involved in complying with regulations for hazardous wastes per RCRA, as well as notifying their POTW of hazardous waste discharges per 40 CFR § 403 regulations (US Environmental Protection Agency, 1995a, 2015b, 2015c). Local jurisdictions may consider these regulatory requirements as part of the permitting process for waterpipe retail establishments. Our analysis highlights the importance of increased awareness on the proper disposal of waterpipe wastewater in both residential and retail settings. Our selection of chemicals identified in waterpipe wastewater may be relevant for human health risk assessment through human water recreation activities, fish consumption and drinking water routes of exposure. Beyond NEPA, understanding the environmental impacts of waterpipe wastewater chemicals supports agency and worldwide One Health initiatives recognizing that the health of humans, animals and the environment are interlinked (US Food and Drug Administration, 2021; Destoumieux-Garzón et al., 2018).

Results from this screening-level hazard characterization, when combined with exposure concentration estimates from fate and transport models, will inform future risk assessments to determine the ecological impact of waterpipe wastewater chemicals. Further research to characterize exposure by modeling the fate and transport of these chemicals may help to assess potential ecological and human health risks of 'down-the-drain' waterpipe wastewater disposal.

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Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the Food and Drug Administration.

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. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.hazl.2022.100074.

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