Sample preparation methods for elemental analysis in electronic cigarette aerosols: a critical review

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ABSTRACT

In the last decade, e-cigarettes have been marketed as a less harmful alternative to classical tobacco smoking and are currently being used by millions of people. An e-cigarette consists of an e-liquid and a heating device, generating an aerosol that the user can inhale. Recently, several studies have shown that metals and metalloids (=elementals), including As, Cd, Cr, and Pb, known carcinogens, were present in these aerosols. To ensure the accuracy of dose-toxicity estimations, it is essential to have access to reliable and reproducible methods for estimating the dose in question. Although more standardization methodologies were introduced in the analysis of elementals from aerosols, a huge divergence in sample preparation can be found in the literature. This work aimed to provide an overview of the scientific literature. Therefore, a literature search was conducted in September 2024, that followed the PRISMA guidelines. A total of 51 articles were selected for analysis and large variability in the sample preparation, specifically variations in aerosol generation characteristics and collection techniques could be observed. Despite the widespread use of methods as filters and impingers, many studies failed to validate critical steps such as aerosol recovery, blank corrections, and the extent of matrix effects. Therefore, further standardization of methodologies is urgently needed to improve the reliability of metal quantification in e-cigarette aerosols, which could potentially enhance regulatory frameworks and facilitate the routine analysis of e-cigarette emissions.

KEYWORDS: Chemical analysis; metals; metalloids; e-cigarettes; vaping; trace element; emission

1. INTRODUCTION

According to the World Health Organization (WHO), tobacco kills up to half of its users, accounting for more than 8 million deaths annually (1). Even though the dangers of cigarettes have been known for many years and a lot of effort has been made to reduce tobacco smoking, there is still much work to be done. In the last decade, e-cigarettes have been marketed as a less harmful alternative and potential smoking cessation aid. In contrast to burning tobacco leaves, an e-liquid is heated up, comprising propylene glycol (PG), glycerin (G), occasionally water, organic solvents such as ethanol (2) (3), and flavorings (4). The vapors condense with the cold air that is drawn into the e-cigarette device to form aerosols which are then inhaled. These smoking alternatives became quite fashionable as a study estimated that already in 2020, there were approximately 68 million e-cigarette users worldwide (5). This scale of popularity comes with an important societal health risk due to the inhalation of constituents with an unknown toxicological profile. For example, in 2017 a study identified 15 586 unique flavors in e-liquids (6). Although most ingredients are Generally Recognized as Safe , this does not translate into (long-term) safety after inhalation (7). In addition, unwanted side-products may be created during the heating process (8),(9). Moreover, previous studies have shown that metals and metalloids are present in the aerosols and this may lead to elevated metal levels in biological samples (10). Elements that were found in e-cigarette aerosols, such as As, Cd, Cr, and Pb, are classified as human carcinogens by the U.S. Environmental Protection Agency and the International Agency for Research on Cancer. They are also known to cause multiple organ damage at low levels of exposure (11). It has been demonstrated in several cases that these substances are predominantly released from the heating element, also referred to as an "atomizer" or "heating coil", which evaporates the e-liquid. This element acts as an electrical resistor that generates heat when an electric current is passed through it, eventually reaching hundreds of degrees Celsius (12). Several mechanisms are proposed for how the elements are

removed from the heating element. Some researchers mention that metals may be released from the heating element due to bubble bursting or the vaporization of metal−organic compounds (13). Others suggest that metals can evaporate, condense, and then coagulate into nanoparticle clusters (14). This mechanism is similar to the "hot wire generator", a technique for producing metallic nanoparticles using electrically heated wires. In this technique, a resistively heated wire is used to evaporate the material to the gas phase. The gas vapors subsequently condense to form nanoparticle aerosols (15). In e-cigarettes, metallic nanoparticles tend to be < 100 nm, which further supports their incidental formation (16). Metal(loid)s may also dissolve in situations where e-liquids have favorable conditions to allow this, such as certain pH values (17). Nicotine salts at high concentrations of 40 mg/ml showed an increase in Cr and Ni transfer (18). Moreover, it was demonstrated that the presence of nicotine lactate resulted in significantly greater Cr and Ni leaching compared to devices that contained nicotine benzoate or nicotine levulinate. This finding may be attributed to the differing complexion properties of the acids involved (19). When comparing elemental concentrations in a fresh e-liquid, post-vaping e-liquid, and aerosol, there is a common phenomenon of higher metal(loid) concentrations in the tank than aerosol concentrations, leading to speculation that elements are first transferred from the heating coil to the e-liquid in the tank and later to the aerosol (20),(21). However, not all studies show this trend. For example in another study, the concentrations of metals were compared in the bottled e-liquid, the tank, and the aerosols to better understand the transfer of metal(loid)s. Ni, Cu, and Cr concentrations were greater in the aerosol than in the e-liquid after puffing, which could indicate that elements are also transferred directly from the coil into the aerosol (22). It is important to recognize that the composition of the elements present is highly device-specific and is related to the metals found in the aerosols, which has been verified by comparative studies analyzing both the internal composition of the device and the resulting aerosols (23),(24). A less important (22),(25), but still a possible source of

metal(loid)s are the e-liquid ingredients themselves. Elements were previously found in PG, G (26) nicotine, and flavorings (27) that were used by an e-liquid manufacturer.

To perform risk assessment studies on the impact of these metal(loid) nanoparticles in e-cigarette aerosols on human health, the dose-response relationship is a key parameter. To determine these doses, various research groups have already performed several quantification studies of these elements in e-liquids and aerosols, resulting in rough estimates of what metal concentrations can be expected in aerosols. Because the methods used to prepare these samples vary widely among researchers, an effort was made to provide an overview of previously used sample preparation methodologies. This work both highlights the lack of consistency, and sometimes lack of information to ensure reproducibility and validation in different steps of the sample preparation process, and provides a structured summary of the existing methods that have been used. Such a structure can serve as a basis for the development of new methods, but more importantly, it can facilitate the achievement of standardized methods.

2. METHODOLOGY

2.1.Statement on the terminology metals, metalloids, and/or elementals

Metals tend to be characterized based on material properties such as high thermal and electrical conductivity, metallic luster, malleability, ductility, and ability to form cations and basic oxides (28). The distinction between metals and nonmetals is not always easy to make, consequently materials with properties in between are called metalloids or semimetals (29),(30), (31). Therefore it was chosen to include reports on both metals and metalloids, termed elementals, in this study as both might have toxicological implications(32).

2.2. Article search and selection

Articles were searched in PubMed, Scopus, and Embase in September 2024. The following terms were used: 'electronic nicotine delivery systems' OR 'e-cigarette' OR 'e-cigarette' OR 'electronic cigarette' OR 'e-cig' OR 'e-cig' AND 'aerosol' OR 'aerosols' OR 'emission' OR 'emissions' OR 'vapor' OR 'vapors' AND 'ICP' OR 'metal' OR 'metals' OR 'trace element' OR 'trace elements' OR 'heavy metals' OR 'heavy metal' OR 'metalloids' OR 'inorganic' OR 'arsenic' OR 'iron' OR 'chromium' OR 'nickel' OR 'copper' OR 'lead'. No additional filters were set due to a lack of studies. To be included in the screening, the full text had to be publicly available. After removing duplicates, article titles and abstracts were screened for relevance to the research question. Articles were included if it was clearly stated that metals and/or metalloids were quantified in e-cigarette aerosols. Studies on secondary aerosols were excluded due to the different nature of aerosol collection.

A total of 1125 articles were found to match the keywords. After removing the duplicates, 612 articles were screened by reviewing the titles and abstracts. Of the remaining 54 publications, four were excluded because they were not in English. One additional publication was found to be relevant from the citations of the included papers and was also included. Finally, a total of

51 articles were included in the review. Figure 1 shows the PRISMA diagram illustrating the steps involved in the selection process.

3. RESULTS & DISCUSSION

The first part describes the different steps or modules in the experimental setup for the analysis of elementals in aerosol (see Figure 2). First, the different aerosol generation techniques are described, followed by an overview of the different aerosol collection techniques, and finally, the methodologies used to analyze the elementals are also mentioned**.** The second part then focuses on a critical analysis of the described methodologies.

3.1. E-cigarette aerosol generation techniques

The aerosols were usually generated using an e-cigarette device coupled to a device that generates airflow and controls the puffing topography (Table 1). All studies utilized an e-cigarette device to generate the aerosols, with one exception (33), where e-liquids were evaporated by a distillation pump set up in the presence of the heating element. The device type was usually disclosed in various levels of detail, ranging from only mentioning the generation to mentioning the device type, brand, and model name. One author mentioned using a 5th-generation device, describing it as a rechargeable pod (34). Further device details such as the power settings and especially the coil properties were often left out and are therefore not shown. To generate airflow and to activate the e-cigarette, commercial smoking machines were used in 19 cases. One research group utilized a syringe to draw the aerosols from the e-cigarette device (35). The most popular way to eject the aerosols from the e-cigarette device was the use of (self-built) setups involving pumps. The pump was usually connected in series with the e-cigarette and the aerosol collection medium was located between both elements. In several cases, no additional info was given on how the airflow was monitored or calibrated, which was occasionally done by placing a flow meter and flow control valve in the setup (22),(36). Some also implemented a HEPA filter to prevent aerosols from reaching the pump (22). Liu et al.

developed a button-activation system in which the firing button of the e-cigarette is pushed repeatedly, in combination with a peristaltic pump to generate the aerosols (37). Jeon et al. utilized a pneumatic actuator to set the puffing parameters and to operate their commercially purchased vaping machine (38). Goniewicz *et al*. (39) and Prokopowicz *et al*. (40) utilized the "Palaczbot", a more advanced device developed by the Technical University of Lodz, which is a single-port piston-containing device that can generate various puffing protocols controlled by computer software (41). Another well-engineered device was the one utilized by Zhao et al. (42), called an "E-cig-EGS system" that was previously developed (43). The research group of Williams et al. (23,44,45) utilized a device that encompassed a previously designed "puffer box", a device that is utilized to choose puffing parameters, connected with a peristaltic pump. Between both elements, there were two T-connections, in which the one closest to the puffer box made a connection with the e-cigarette, and the other one with a manometer. The latter was used to monitor the vacuum levels during the vaping experiments (46). Calibration of the puff volumes was done, if mentioned, with a soap bubble meter (40).

Puff topography data was generally well reported compared to other parameters. There were wide variations in these values, especially in the number of puffs (see table 1).

3.2. E-cigarette aerosol collection techniques

Various methods were used to collect e-cigarette aerosols for quantitative elemental analysis and are summarized in Figure 2. The total number of methods used exceeds the number of collected articles because some publications discuss multiple aerosol collection methods. These were discussed separately in this work to obtain more valuable information. 20 articles used a method involving impingers and related setups, i.e., any method in which aerosols are collected in a liquid. 11 articles discussed a method using filters, 9 articles used tubing, 8 used a series of pipette tips and tubing, and 3 used electrostatic precipitation. One article did not fit

into any of these groups (47). Three articles did not report an aerosol collection method (48) (49) (50).

3.2.1. Aerosol collection in impingers and related setups

20 of the 51 articles used impingers to collect e-cigarette aerosols, making it the most commonly used technique for the purpose of elemental quantification (Table 2). A single impinger was used in seven cases (22,33),,(53,54),(55) and two impingers in series were used in eight cases (26),(39,45,56–58),(59),(60). From the latter group, one setup involved a combination of an impinger and a waste impinger without any solvent, in which only the first impinger was utilized to process the sample (57). One research group did not provide any details concerning the collection vessel (61). Five studies utilized round bottom flasks (23,40),(45)-(44) instead of impingers in which three studies from the same research group coated the recipient with parafilm to prevent the escape of aerosols and adding a small glass capillary as exhaust (45)-(44). Round bottom flasks were always immersed in an ice-bath except once (44), and four studies utilizing impingers decided to use an ice-bath approach (22,39),(56),(59). Details on the ice bath characteristics were seldom disclosed but were, if reported, made using ice/water (22) or dry ice/acetone (39). The volumetric dimensions were sparingly disclosed but ranged from 25 ml (56) to 125 ml (54) (55) per impinger and 500 ml (45)-(44) and 1000 ml (40) per round bottom flask. Midget impingers were only used in duplicate, with one exception in which the impinger was immersed in an ice/water bath. All reported recipients were made of glass and precautions to prevent metals leaching from the glass involved pre-treatment with either an aqueous nitric acid solution (22) or a mixture of nitric acid and hydrochloric acid in water (45). Another research group rinsed with water prior to acid treatment (52). Impinger extraction solvent volumes varied between 5 ml (52) and 50 ml (39). The major extraction solvent was a diluted nitric acid solution, with concentrations

between 1% (52) and 10% (40). One research group collected the aerosols in deionized water, and after the sample collection, nitric acid was added to obtain a 2% nitric acid solution (55). Mixtures of nitric acid and hydrochloric acid were also utilized for extraction (45),(62),(56),(59). Furthermore, organic solvents such as acetone (56),(59), methanol and hexane (56) were also implemented in methods. Experiments with a 10% hydrogen peroxide solution as impinger solvent were done as well (56). Acidified $KMnO_4$ was utilized as impinger solvent for the analysis of Hg, hydroxylamine was added to quench excess $KMnO_4$ after digestion (51). After aerosol collection, the samples were treated in various ways. Many methods involved direct storage of samples in (acid pre-washed) recipients without disclosing the implementation of a digestion step (26),(45),(62),(52). Few performed a digestion step but barely provide details on the duration and temperature gradient. In some cases, an internal standard was added (39),(57),(53). Organic solvents were removed by evaporation prior to digestion (56),(59). Two articles described multiple sampling processing methods due to using multiple impinger solutions in one method (56),(59). One article combined the extracts from aerosols collected in a tubing and impinger, which were both connected in one setup with the rationale of also collecting gaseous metals (51). For the same reason, another research group connected an impinger with an electrostatic precipitator (53).

3.2.2. Aerosol collection on filters

11 of the 51 articles utilized a filter to collect the e-cigarette aerosols (Table 3). The filter materials utilized were polytetrafluoroethylene (PTFE) (13,35,42,63), glass fiber (4,64,65), quartz (66,67), mixed cellulose ester (36) and methyl cellulose (68). Details on the pore diameter and filter diameter were not always disclosed. Three articles performed particle size selection by connecting PTFE filters with a Micro-Orifice Uniform Deposit Impactor (35,63) and a compact cascade impactor (42). In one method, as shown in Figure S1 of the article in

question, an aerosol collector tank containing a liquid was installed in series behind the filter for reasons that remain unclear (64). Two methods involved a pre-cleaning step of the filter prior to sampling to decrease metal contamination by leaching in concentrated nitric acid overnight (13) or by utilizing a 1% nitric oxide solution (67). Samples were immediately digested using a mixture of nitric acid and hydrofluoric acid (63), a mixture of nitric acid and hydrogen peroxide (67) or concentrated nitric acid (13,36,66) at various heating protocols. In other cases, a certain volume of the collected aerosol was taken (64) and/or the whole filter (4) was added to an aqueous acidified extraction solution. One research group compared various aerosol extraction methods from aerosols collected on Cambridge filter pads: rotary shaking, ultrasonication, and digestion (65). An additional method included a "solubilization" step, but no further details were provided (42).

3.2.3. Aerosol collection by condensation in tubing

Nine of the 51 articles utilized a tubing system in which the e-cigarette aerosols condensed on the inner wall (Table 4). This is an approach first published by Halstead et al. in 2019 as part of the research group of Pappas at the Centers for Disease Control and Prevention for the purpose of elemental analysis in e-cigarettes (69). Further contributions have been published involving metal analysis in e-cigarette aerosols utilizing this method, or a variant based on the original work (19,70–72). Fluoropolymer tubing, more specifically fluorinated ethylene propylene (FEP) tubing, was usually used in these methods except for one case where ethylene propylene (EP) tubing was used (51). The internal volume of the tubing varied between 64.1 ml (72) and 113 ml (69). Measures to avoid elemental contamination from the tubing involved using an acid solution (71),(69), sonication with an acid solution followed by rinsing and sonication with distilled water (38) and rinsing with acetone followed by acid solution (72). Some researchers utilized Tygon tubing as connecting tube that was acid cleaned as well (72).

To avoid aerosol exposure to the pump, one method involved connecting a PTFE-filter at the end of the setup (72). Some research groups submerged the tubing in an ice bath (56,59). After condensation of the samples within the tube, extraction was done using various methods, involving capping of the tubing followed by sonication in 75% methanol solution (38), rinsing with diethylene glycol monoethyl ether (DEGMEE) followed by acid solution (72), rinsing with acetone (56,59), ultrapure water (70), acid solution (69) and methanol (51). After extraction, organic extracts were evaporated followed by adding a diluted nitric acid solution (38) or digestion (56). In one case, the diluted acid solution was mixed with a diethylene glycol monoethyl ether extract. The latter solvent was chosen due to its high purity, miscibility with water and hydrophobic properties (72). Aqueous extracts were typically diluted to the desired final acid concentration (56,69).

3.2.4. More described methods to collect aerosols

Eight out of 51 articles utilized a system consisting of multiple cut pipette tips connected with short pieces of tubing, with a centrifuge tube at the end (20,21,34,37) (73–76), a method published by the working group of Olmedo et al. in 2016 (77). In contrast to previous methods, the pump is now located in series between the e-cigarette and the aerosol collection zone. All published articles using this method, referred to Olmedo's work in their method section, in which four out eight articles were in collaboration with this very researcher. These researchers additionally collected condensed aerosols from the e-cigarette mouthpiece (20,21,73,76). In several cases, the system was flicked followed by reconnecting with the pump to gather the rest of the remaining droplets (74,76). Generally, a low amount of sample was taken with a pipette tip and dissolved in a diluted acid solution (21), ultrapure water (20) or diluted nitric acid/methanol/Triton-X mixture (76). Some researchers added an internal standard to the samples (21),(76).

Three out of 51 articles utilized an electrostatic precipitator to collect e-cigarette aerosols. One group utilized acid-washed quartz tubes (78) and the others utilized glass tubes (79),(53) as collection medium. Extraction solutions were in two cases methanol and were either directly digested (78) or first evaporated prior to digestion (79). In the other case, a 5% nitric acid solution was utilized, followed by adding an internal standard (53). As mentioned before, two of the articles placed an impinger in the setup to collect "gaseous phase metals" (79),(53).

Finally, one research group published a method involving a centrifuge tube that was cut at the bottom and packed at the bottom with silica wool. After aerosol disposition, the sample was spun down into a microcentrifuge tube for further processing (47).

3.3 Analysis of the elementals

Inductively coupled plasma mass spectrometry (ICP-MS) was used 37 times among the collected articles for the elemental analysis. Seven research groups utilized Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) and four utilized Atomic Absorption Spectroscopy (AAS) (22),(40),(68), in which one group used AAS only for Hg analysis and ICP-MS for other elements (51). Other methods were Energy Dispersive X-ray Fluorescence (EDXRF) Spectroscopy (50) and Total Reflection X-ray Fluorescence Spectroscopy (TXRF) (33). Two research groups did not mention any method (49,73).

3.4. Critical analysis of the described experimental setups

To the best of our knowledge, this is the first review to summarize the known methods for collecting e-cigarette aerosols for the quantification of metals and metalloids. Although some trends can be observed among the different methods, it is clear that there is a great variety in each step of the sample preparation among the analyzed articles. The exception is the collection

methods of e-cigarette aerosols in tubing and in the pipette tips-tubing system, as most articles were produced by or in collaboration with the developers of the original method (69,77).

Puffing parameters were generally well reported. This is particularly important because higher temperatures, which can be achieved by longer puff duration (80), higher power output (64) or lower flow rate (62), have shown to directly increase metal release from the heating element (64). The power output is associated with the observation that device types, such as mod-type devices, release a greater number of elements than pod-type devices (13). The XP D 90-300-2 AFNOR guidelines recommend that the highest power level recommended by the manufacturer should be utilized. In the absence of a specified value, the largest possible value is selected (81). As evidenced in Table 1, a substantial number of researchers have selected the puffing parameters outlined in the CORESTA Recommended Method N° 81 (55 ml puff volume, 3 seconds puff duration, and 30 seconds of rest between the puffs) (82). It is noteworthy, however, that a large number of researchers have opted for alternative parameters, which is acceptable due to the heterogenous nature of puffing topography amongst vapers. Choosing an accurate topography is challenging because it depends on factors such as user-experience (83,84) and psychological effects such as compensation behavior for lower e-liquid nicotine concentrations (85). Despite not always being representable for real-life usage, the previously recommended parameters by CORESTA can be useful for comparison purposes between different items. The number of puffs was the most variable parameter amongst the collected articles. It is important to emphasize that some of the outlying values belong to studies investigating the effect of puff parameters on elemental concentrations in aerosols (13,42,45,62) and are not intended to represent human behavior. Several of the selected articles performed toxicity studies (26,47,58,68,70), which would require more realistic puffing parameters. Analytically speaking, a high puff number is advantageous for the quantification

of metal(loid)s, given the low concentrations of these elements present in e-cigarette aerosols and the potential for contamination during the sampling process.

Various aerosol collection methods were shown to be capable of collecting most of the aerosols produced (72), (37), (65), (53). It is important to note that elemental specific recoveries can vary depending on the method used. For example, Williams et al. found that the use of a cold trap resulted in significantly higher total elemental recoveries compared to impingers at room temperature (45). On the other hand, the use of FEP tubing immersed in an ice bath coupled to an impinger was found to provide similar elemental recoveries when using a two-impinger setup to collect oil-based e-cigarette aerosols (59). This suggests that each method may be viable, but also that collection conditions may need to be optimized depending on the characteristics of the sample.

Despite this, there is a clear preference for using impinger-like systems (Table 2, to collect e-cigarette aerosols for elemental analysis, which is an obvious choice due to its long history of use for air sampling (86). Impingers are also quite customizable, which allows for method optimization by using different sizes and shapes (87), extraction solvent characteristics, and temperatures. Also, the XP D 90-300-2 AFNOR guidelines recommend using impingers, more specifically two 250 ml glass impingers in series. They briefly mention that quartz filters, electrostatic and cryogenic traps can also be used (81). For the solvent, they propose utilizing a 5% nitric acid solution when sampling. One research group compared the extractability of metals from e-cigarette aerosol samples when using 5% nitric acid compared to 10%. Although they state that using a 5% had favorable results, no statistical significance test was demonstrated (57). Some researchers also added hydrochloric acid, which is known to have additional metal complexing properties (19). One researcher added $KMnO_4$ for Hg analysis (51), which was possibly done to promote the increase of Hg removal efficiency (88). Importantly, trapping the aerosols in a nitric acid solution is not always an ideal choice. Firstly,

organic solvents such as methanol and acetone have the advantage of being easily removed by evaporation, allowing further concentration of the sample, which is very useful due to the generally low levels of elements present in e-cigarette emissions. In addition, one research group found that oil-based e-liquids can clog the frits in the impinger. Organic solvents not only solved this problem, but also improved the sensitivity of the method, especially acetone. However, an aqueous impinger solvent was still considered necessary for Hg collection (56). A major concern in elemental analysis is the use of glass impingers, as it has been shown that elements tend to release from the glass surface (45). Despite this, all articles using impinger-like systems preferred impingers or round-bottomed flasks made from glass, while only three researchers took precleaning measures to avoid potential contamination (22,45,52). In addition, blank preparation to correct metal backgrounds was not always performed. Since plastic is known to be less contaminating than glass (89), impingers made of nitric acid resistant materials such as PTFE and perfluoroalkoxy (PFA) may be a viable way to reduce metal backgrounds. However, none of the research groups employed such materials for elemental analysis in e-cigarettes. One researcher used three interconnected PFA midget impingers for the collection of cigarette smoke and elemental analysis of it (90), which could be potentially used for collecting e-cigarette aerosols.

Filters were the second most utilized method for the collection of e-cigarette aerosols. These filters were typically composed of quartz, PTFE, and cellulose derivatives (Table 3), which are generally recognized to exhibit low metal backgrounds (91). For the same reason as with impingers, researchers argue that glass filters are not suitable for metal analysis (69). Despite this, two research groups chose to utilize glass syringe filters (4,64) and one research group chose Cambridge filters (65), which are typically made from glass. Filters are a particularly convenient way to collect aerosols and cigarette smoke, and are vastly used to collect particular matter from and e-cigarettes (92). It is important to note that filters may be limited in their

ability to quantify the elements present in e-cigarette aerosols. This is because a sufficient quantity of aerosols must be sampled to ensure that the sensitivity of the method is adequate. However, this conflicts with the fact that filters may saturate, which would result in a decreased flow rate (13). While the majority of articles reported puff numbers below 45 per filter, three research groups have documented higher values [4,64,] (66). None of these research groups shared validation tests to ensure a constant airflow and aerosol mass transfer over time. A number of articles have been published using FEP tubing (Table 4). In this setup, the aerosols flow through the tube where most of them condense on the inner wall. The condensed aerosols are then removed from the walls with for example organic solvents (38,56) and acid solutions (71). Although not relevant to the scope of this study, it is noteworthy to add that that rinsing with ultrapure water was done to prevent dissolution of the metallic nanoparticles themselves (16,70), or alternatively, the aerosols were collected on a PTFE filter instead in tubing (93). This enabled the possibility of studying the metallic nanoparticles. A key benefit of utilizing FEP tubing is the elimination of glass contact, generally low metal background along with excellent acid resistance, which permits thorough cleaning prior to aerosol collection. The reduced expense of these materials in comparison to PTFE or PFA impingers is another advantage. In addition, similar to impingers, this method allows for high sample enrichment, which is not possible with all filter types. Conversely, due to its unconventional nature, this methodology may prove challenging for laboratory personnel to become proficient in, particularly when utilizing tubing lengths of several meters long. For a comprehensive overview of the method development, readers are encouraged to consult the work of Halstead et al. (69).

Olmedo's group developed a method using an alternating series of pipette tips connected to small tubes that collect the aerosols directly into a small storage container (77). Aerosols are subject to impaction and deposit on the inner walls. However, efficient deposition requires "*the*

sequence of tubing sections to be curved in a polygon-like manner" (94). This method offers similar advantages to the previous method and is even cheaper to reconstruct. However, the fact that the sample goes through the pump system could be considered a drawback, as it makes it incompatible with commercial vaping machines. Electrostatic precipitation is another potential method for collecting elements in e-cigarette aerosols. In two of the three cases of use, they were coupled with an impinger to collect "gas phase metals" (53,79), which raises the question of what additional benefit this device offers compared to the more classic methods. Some of these devices also involve glass, which presents an additional challenge in providing a low metal background. One researcher argued that the device is more suitable for cigarette testing than e-cigarette testing due to incomplete precipitation of e-cigarette aerosols. Additionally, preliminary experiments revealed variable trapping efficiency based on e-liquid composition and noticeable degradation of neoprene seals in the device, which caused contamination of the samples (69).

Although some research groups did great efforts validating (a part of) the sample preparation method (e.g. recovery testing), most of them only focused on validating the analytical method. Several authors calculated the method LOD based on the method of Taylor to calculate method limit of detection values (69,71,72). In order to validate the method's precision and accuracy, several researchers spiked a sample matrix with reference standards of elements of interest (72) (53). Since there are no reference matrices available, a mixture of 70% PG and 30% G was often utilized (20,37,76). Internal standards were used to ensure instrument stability and possible matrix effects. Important is to avoid metal exposure when preparing these standard solutions, which may be done by utilizing materials such as PFA, as done for example by Wang et al. (65). For a broad overview of the utilized analytical techniques utilized for elemental analysis in e-cigarette emissions, readers are referred to the review of AL-Qaysi et al (95).

Analyzing the amounts of elements in e-cigarette aerosols is important because it is a more accurate way to predict human exposure. Developing methods to perform reliable quantifications is an important step toward this goal. Importantly, the total dose of a particular element may not provide enough information to indicate its toxicity. For example, Cr (VI) is highly toxic (73), while Cr (III) is an essential micronutrient for humans [98]. The presence of multiple elemental species is a confirmed phenomenon in electronic cigarettes, as demonstrated by two research groups who conducted speciation experiments for As in the emissions (34),(37) and one research group researching the various oxidation states of metal oxides in e-cigarette aerosols using microscopy (93). One important limitation of this work is that due to the vast variety in study setups, including different e-cigarette devices, different puffing parameters and different aerosol collection conditions, it was hard to compare methods in its performance to reliably collect metal(loid)s. However, the main goal of this work was to give an overview of these methods which could help to reach a consensus towards standardization.

4. CONCLUSION

This work highlights the different techniques used to collect e-cigarette aerosols for metal and metalloid quantification, highlighting notable inconsistencies in puffing parameters, sampling techniques, and other experimental conditions. While certain collection methods, such as impingers and filters, are commonly used, the lack of standardization across studies makes it difficult to draw consistent conclusions about elemental concentrations in e-cigarette aerosols. Although some researchers have made efforts to validate sample preparation steps, most have skipped this step and neglected important steps in method development, such as assessing aerosol recoveries, not taking (appropriate) blanks, or ignoring potential matrix effects.

To advance the field, future research should focus on refining methods to detect low concentrations of metals. This work, which provides an overview of the key steps in sample preparation, can be used as a basis for the construction of new methods. In addition, regulatory frameworks and the tobacco industry could benefit from these methods by establishing explicit standards for aerosol collection and metal analysis. Such standardization would enhance the reliability and reproducibility of results, facilitating comparison between studies and making the method suitable for routine analysis. These standards should ideally include sufficient details ranging from aerosol generation including ideal parameters for puffing, to sample collection including purity of extraction solvent, methods used for pre-leaching, and other sample preparation steps, as well as criteria for validation in case a method requires optimization.

FIGURES AND TABLES

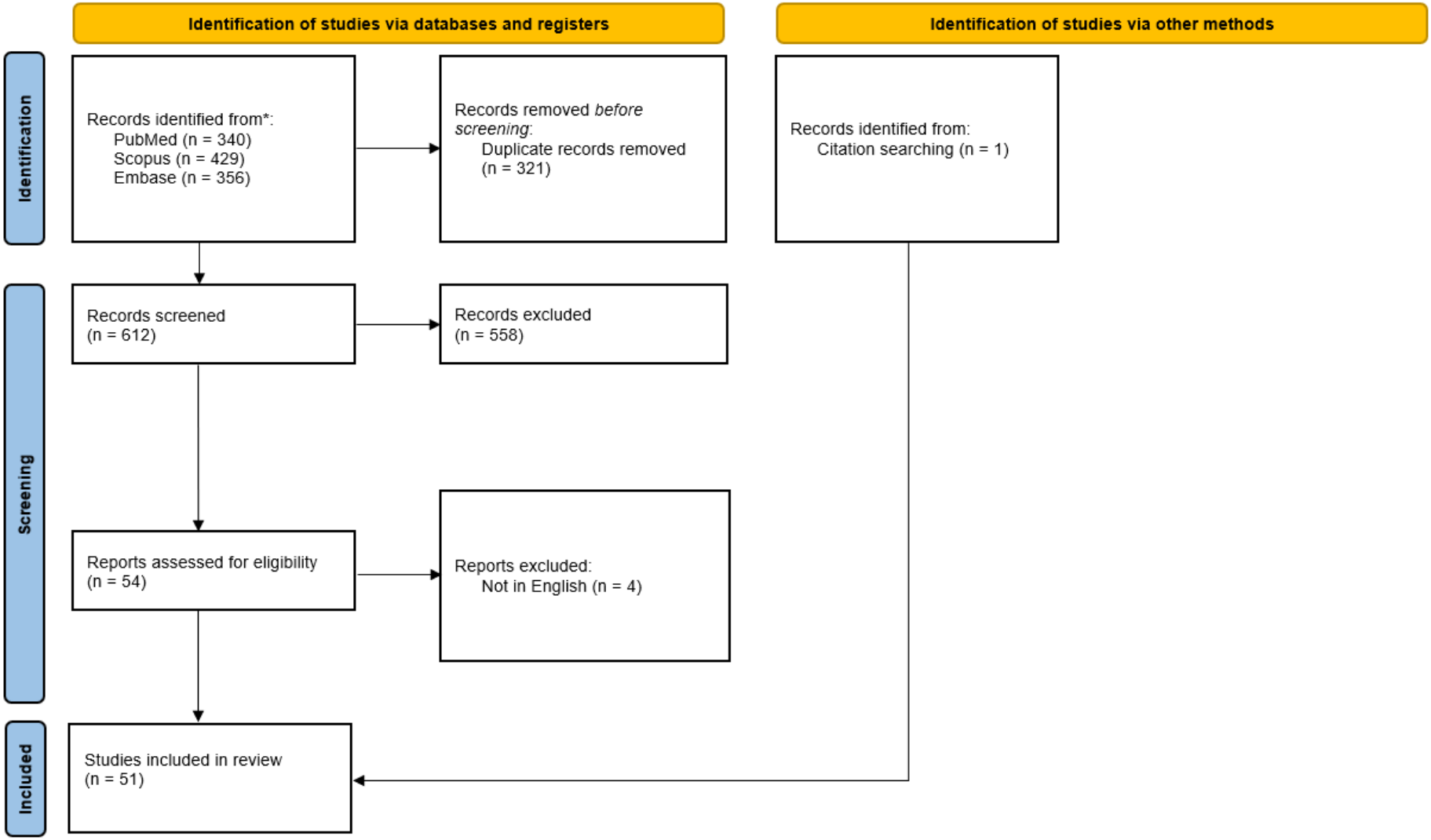

Figure 1: PRISMA diagram representing the selection process

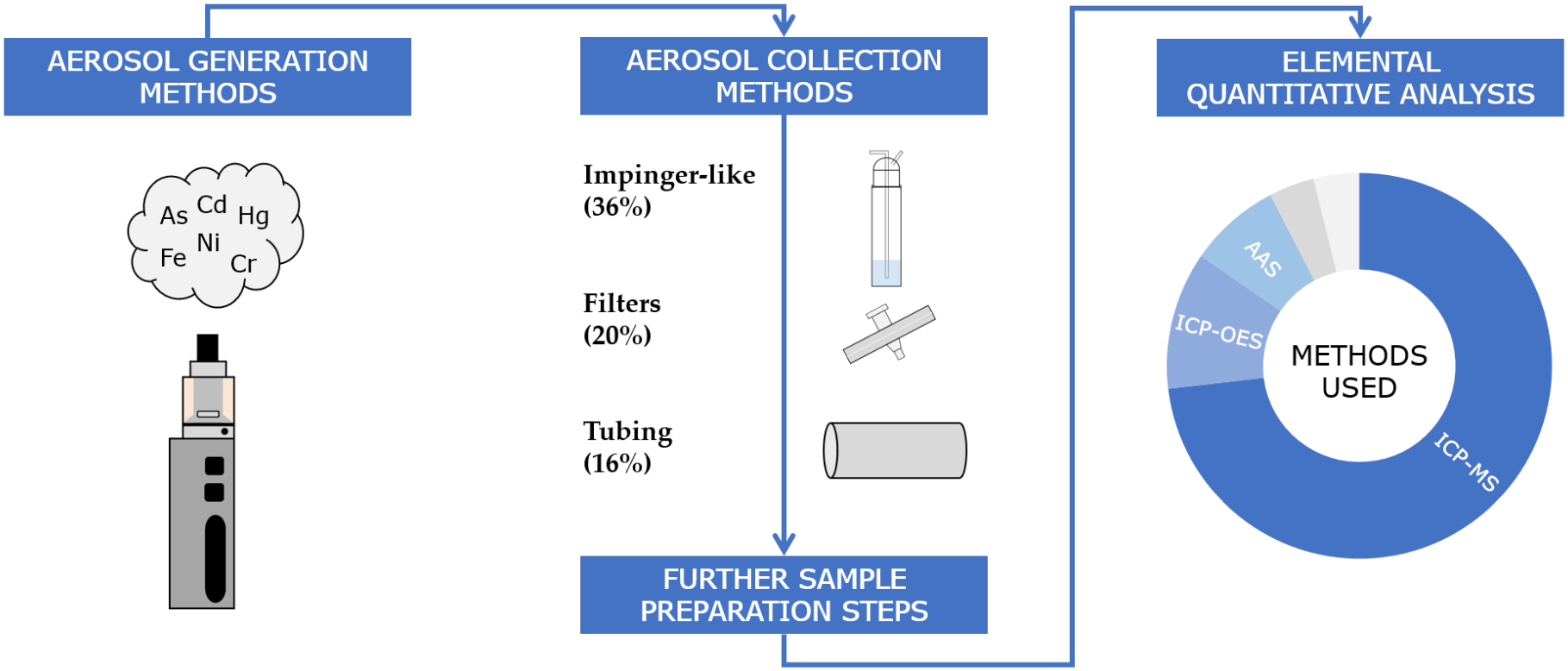

Figure 2: A schematic representation of the different steps of the experimental process of analyzing elementals in aerosols.

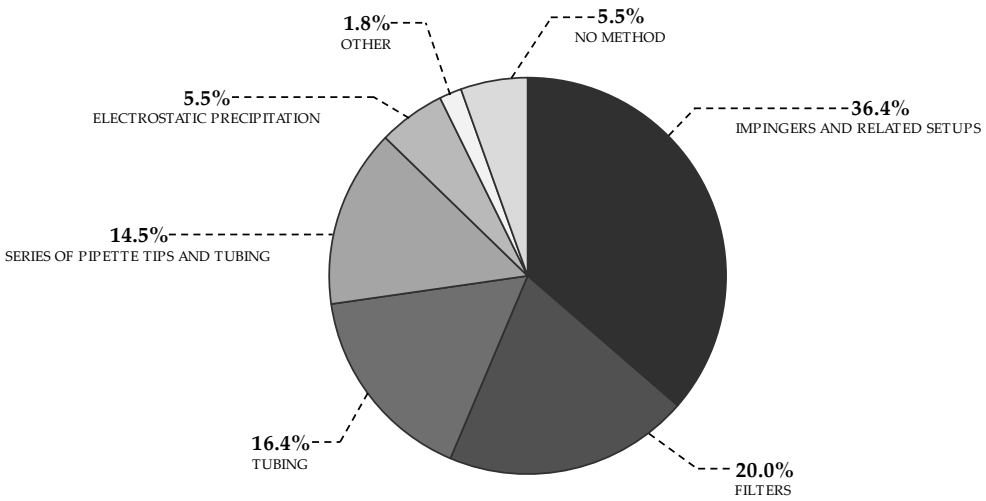

Figure 3: Various methods utilized for collecting e-cigarette aerosols for quantitative elemental analysis.

Table 1: overview of e-cigarette aerosol generation characteristics (n = 51)

Author(s)	Aerosol generation device type	E-cigarette model(s)	Puff number	Puff duration (s)	Flow rate Puff volume (ml)	Inter-puff duration (s)
Beard et al. (2024) (47)	Pump-system Manual button presses	3rd generation device with refillable tank	20	3	58,3 ml/s 175 *	30
Pappas et al. (2024) (19)	Commercial smoking machine	Pods and disposables	50	3	18.3 ml/s * 55	30
Reilly et al. (2024) (48)	"Puffing machine" (unclear whether commercial or not)	Disposables, refillables, rechargeables, variable power, cartridges, pods, pod-mods, sub-ohm mods	20 – 90	3	18.3 ml/s * 55	27
Wang et al. (2024) (65)	Commercial smoking machine	/	/	3	18.3 ml/s * 55	30
Yan et al. (2024) (61)	Commercial smoking machine	Disposables	200	3	18.3 ml/s * 55	27
Aherrera et al. (2023) (74)	Pump-system	Mods and (disposable) pods	Mods: 13 – 65 Pods: 35 – 500	4	Mods: 0.9 l/min 60* Pods: 0.7 l/min 46.7*	30
Jameson et al. (2023) (78)	Commercial smoking machine	Closed pod systems	50	3	18.3 ml/s * 55	30
Jeon et al. (2023) (38)	Commercial smoking machine	Pods	50	3	18.3 ml/s * 55	30
Su et al. (2023) (63)	Commercial smoking machine	Disposables	/	3	4.0 l/min 200	30
Tehrani et al. (2023) (34)	Pump-system	Mods: tanks and drippers/ (Non)-disposable pods		3	0.7 l/min /	30
Gray et al. (2022) (71)	Commercial smoking machine	Pods	50	3	18.3 ml/s * 55	30
Haworth-Duff et al. (2022) (57)	Pump-system	Vape pen and mod	10 puffs per 10 minutes	/	0.5 l/min /	/
Kapiamba et al. (2022) (13)	/	Mods and pods	30	2, 4 and 6	1.05 l/min 35 (for 2 s puff duration)	/

Table 1: overview of e-cigarette aerosol generation characteristics (n = 51)

Author(s)	Aerosol generation device type	E-cigarette model(s)	Puff number	Puff duration (s)	Flow rate Puff volume (ml)	Inter-puff duration (s)
Ko et al. (2022) (64)	Pump-system	sub-ohm devices	100	4	1 l/min /	18
Lin et al. (2022) (35)	Syringe	Disposables	10	/	/ /	/
Rastian et al. (2022) (22)	Pump-system	Mod	10	3	1110 ± 60 ml/min 55,5*	30
Talih et al. (2022) (67)	/	Disposables	15	4	1 l/min (for one device:/ 1.2 l/min) /	
Xu et al. (2022) (58)	Commercial smoking machine	pods and non-specified devices	100	3	18.3 ml/s * 55	30
Zhao et al. (2022) (75)	/	Open and closed systems	/	4	/ /	11 and 26
Gonzalez-Jimenez et al. (2021) (72)	Commercial smoking machine	Devices used by E-cigarette, or Vaping, Product Use-Associated Lung Injury (EVALI) cases	15	3	18.3 ml/s * 55	30
Mallampati et al. (2021) (56)	Commercial smoking machine	Cartridge connected with a mod	25 x 2 (10 min rest between)	3	25 ml/s 75*	42
McDaniel et al. (2021) (59)	Commercial smoking machine	Cartridges	50	3	25 ml/s * 75*	42
Olmedo et al. (2021) (21)	Pump-system	Tanks	/	4	1 ml/s /	30
Belushkin et al. (2020) (79)	Smoking machine (unclear whether commercial or not)	Disposable cigalikes and cartridges, tanks and mods	50	3	18.3 ml/s * 55	30
Halstead et al. (2020) (69)	Commercial smoking machine	Pods, refillable tanks, rechargables, disposables	50	3	18.3 ml/s * 55	30
Liu et al. (2020) (37)	Pump-system	Rechargables	/	/	2 ml/s /	/

Table 1: overview of e-cigarette aerosol generation characteristics (n = 51)

Author(s)	Aerosol generation device type	E-cigarette model(s)	Puff number	Puff duration (s)	Flow rate Puff volume (ml)	Inter-puff duration (s)
Nicol et al. (2020) (51)	/	Cartomizer, rechargeable device with disposable cartridge	50 and 100	2 and 3	18.3 ml/s * 55	30
Pearce et al. (2020) (70)	Commercial smoking machine	Rechargable devices with pre-filled replacable pod/cartridge, Single-use device with prefilled cartridge	75	3	18.3 ml/s * 55	30
Ting et al. (2020) (52)	Pump-system	Cartomizer	10	5	/ /	30
Williams et al. (2020) (26)	Smoking machine (unclear whether commercial or not)	Cartomizers, tanks, RDA's	/	4.3	/ /	3 different regimes
Zervas et al. (2020) (33)	Distillation setup connected with pump	No device, only the heating element	/	/	0, 0.5, 1.0 l/min /	/
Prokopowicz et al. (2019) (40)	Piston-operated system (Palaczbot)	Tanks: 2 top atomizers, bottom atomizers	215 x 4 (15 min between each set)	1.8	38.9 ml/s * 70	17
Williams et al. (2019) (45)	Pump-system	Tanks and RDA's	Cold trap: 60 Impingers: /	4.3	4, 7, 15, 19 ml/s 17.2, 30.1, 64.5, 81.7	2 different regimes
Zhao et al. (2019) (76)	Pump-system	Closed systems: cigalike, pod Open systems: tanks	15-330	4	1 ml/s /	11 and 26
Kim et al. (2018) (54)	Commercial smoking machine	sub-ohm device(s)	150	4	12.5 ml/s * 50	18
Olmedo et al. (2018) (20)	Pump-system	Tanks	/	4	1 l/min 66,67*	30
Ohashi et al. (2018) (53)	Commercial smoking machine connected to a pump system	Rechargeable battery, disposable cartomizer	50	3	18.3 ml/s * 55	30
Zhao et al. (2018) (42)	E-cig-EGS system	Disposable, pre-filled, and refillable tanks	/	2 and 4	30 l/min for 10 minutes 35 and 55	30 and 60

Table 1: overview of e-cigarette aerosol generation characteristics (n = 51)

Author(s)	Aerosol generation device type	E-cigarette model(s)	Puff number	Puff duration (s)	Flow rate Puff volume (ml)	Inter-puff duration (s)
Aherrera et al. (2017) (73)	Pump-system	1st gen (cigalikes) 2nd and 3rd gen (customizable tank-like system and/or mechanical mods (modified e-cigarettes))	/	4	1 l/min 66.7*	30
Beauval et al. (2017) (60)	Commercial smoking machine	2nd generation device	96	3	18.3 ml/s * 55	30
Kim et al. (2017) (55)	/	/	15 or 150	4	12.5 ml/s * 50	18
Lee et al. (2017) (50)	Commercial smoking machine	Rechargeable cigalike/ cartomizers	/	/	/ /	/
Palazzolo et al. (2017) (36)	Pump-system	Clearomizers	45	5	402.7 ± 0.5 and 403.1 ±10 0.4 ml/min 33.6	
Williams et al. (2017) (62)	Pump-system	Disposables	60	4.3	3 – 21 ml/s * 12.9 - 90.3	/
Margham et al. (2016) (49)	/	Cartomizer	100	/	/ /	/
Mikheev et al. (2016) (66)	Commercial smoking machine	Cigalikes, tank	75	4.3	17.5 ml/s 70*	60
Lerner et al. (2015) (68)	Commercial smoking machine	Disposables	4	4	5 l/min 333*	/
Williams et al. (2015) (23)	Pump-system	Open system	60	4.3	/ /	/
Goniewicz et al. (2014) (39)	Piston-operated system (Palaczbot)	Cartomizers and cartridges	15 x 10 (5 min between each set)	1.8	38.9 ml/s * 70	10
Tayyarah et al. (2014) (4)	Smoking machine (unclear whether commercial or not)	Disposables and rechargeables	99	/	/ 55	30

Table 1: overview of e-cigarette aerosol generation characteristics (n = 51)

Author(s)	Aerosol generation device type	E-cigarette model(s)	Puff number	Puff duration (s)	Flow rate Puff volume (ml)	Inter-puff duration (s)
Williams et al. (2013) (44)	Pump-system	Cartomizers	60	4.3	/ /	/

* Parameter was calculated based on the presence of two of the following parameters: puff volume, puff duration or flow rate.

Table 2: Overview of aerosol collection methods involving impingers and related techniques (n = 20)

Author(s)	Setup properties	Pre-cleaning method	Extraction properties	Final sample preparation steps
Yan et al. (2024) (61)	/	/	20 ml of 5% nitric acid + 2 mg/L gold mixed solution (pH 3-4)	Storage in nitric acid washed polyethylene bottles at 4-10 °C
Haworth-Duff et al. (2022) (57)	One "midget" glass impinger of 30 ml One waste glass impinger	/	Midget impinger: 20 ml of nitric acid Waste impinger: no solvent	First three washings of midget impinger with ultrapure water into volumetric flask. Then addition of Rh standard and concentrated nitric acid. Lastly, dilution with ultrapure water
Xu et al. (2022) (58)	Two impingers	/	20 ml of 2% nitric acid	/
Rastian et al. (2022) (22)	One glass impinger of 30 ml submerged in an ice bath	Cleaning with 1% nitric acid	/	/
Mallampati et al. (2021) (56)	Two glass impingers of 25 ml submerged in an ice bath	/	Two glass impingers using various solvents in various combinations: mixture of 8% V/V nitric acid and 2% V/V hydrochloric acid 10 % V/V hydrogen peroxide methanol acetone hexane	Connector tubing and glassware was washed in triplicate with a certain volume of impinger solvent. Samples collected in aqueous solvents (a and b) were diluted to 2% acid concentration. In case of organic impinger solvents (c, d and e), an evaporation step was introduced at 40 °C under nitrogen stream, followed by digestion.
	FEP tubing submerged in ice-bath (3 m, 1/4″ i.d., 96 ml of internal volume) and connected with an impinger	/	Acetone extracts: triplicate rinsing with 20 ml of acetone Aqueous extracts: five times rinsing with 5 ml aqueous impinger solution	Acetone extracts: Drying under nitrogen stream in a 55 °C water bath for 2−4 hours, followed by microwave digestion Aqueous extracts: dilution to 2% final acid concentration
McDaniel et al. (2021) (59)	Two impingers submerged in an ice bath	/	Impinger 1: 25 ml of acetone	Impinger 1: first, rinsed with acetone. Then, removal of

Table 2: Overview of aerosol collection methods involving impingers and related techniques (n = 20)

Author(s)	Setup properties	Pre-cleaning method	Extraction properties	Final sample preparation steps
			Impinger 2: 25 ml of a mixture of 8% nitric acid and 2% hydrochloric acid	acetone under nitrogen stream. Lastly, microwave digestion. Impinger 2: dilution to 2% final acid concentration
Nicol et al. (2020) (51)	One impinger for all elements except Hg. The particular matter was collected in an EP tube	/	Hg analysis: acified $KMnO_4$ Analysis of other elements: nitric acid	Hg analysis: microwave digestion followed by hydroxylamine addition Analysis of other elements: extraction of EP tube with methanol. Combining this extract with the impinger solution. Lastly, microwave digestion
Ting et al. (2020) (52)	One impinger	Tenfold rinsing with ultra-pure water, followed by soaking overnight with nitric acid	5 ml of 1% nitric acid (pH 3-4)	Storage in polyethylene bottles (4-10 °C) that were pre-washed 10 times with ultra-pure water and then overnight in diluted nitric acid
Williams et al. (2020) (26)	Two glass impingers	/	/	Storage in nitric acid washed tubes
Zervas et al. (2020) (33)	One impinger	/	/	/
Williams et al. (2019) (45)	Two glass impingers with a volume of at least 130 ml	Soaking in 2% nitric acid for 5 days. The solution was refreshed daily	2% of nitric acid	Storage in nitric acid pre-washed conical vials
	One glass round bottom flask of 500 ml covered with parafilm and a small glass capillary as exhaust. The flask was submerged in an ice-bath.	24 hours presoaking in a mixture of 10% nitric acid and 3% hydrochloric acid	Mixture of 10% nitric acid and 3% hydrochloric acid	Storage in conical vials
Prokopowicz et al. (2019) (40)	One round bottom flask of 1000 ml submerged in an ice-bath	/	10 ml of 10% V/V nitric acid	Gently swirling
Kim et al. (2018) (54)	One glass impinger of 125 ml	/	30 ml of 2% nitric acid	/

Table 2: Overview of aerosol collection methods involving impingers and related techniques (n = 20)

Author(s)	Setup properties	Pre-cleaning method	Extraction properties	Final sample preparation steps
Ohashi et al. (2018) (53)	One glass impinger, placed in series between the pump and an electrostatic precipitator	/	30 ml of 5% V/V nitric acid	Addition of internal standard, followed by dilution with nitric acid
Beauval et al. (2017) (60)	Two midget impingers	/	20 ml of 5% V/V nitric acid	3-fold dilution to obtain a 1.67% V/V nitric acid solution
Kim et al. (2017) (55)	One glass impinger of 125 ml		30 ml of deionized water	Addition of a certain mass of nitric acid to obtain a 2% acid solution
Williams et al. (2017) (62)	One glass round bottom flask of 500 ml covered with parafilm and a small glass capillary as exhaust. The flask was submerged in an ice-bath	/	Mixture of 10% nitric acid and 3% hydrochloric acid	Storage in conical vials
Williams et al. (2015) (23)	One glass round bottom flask of 500 ml covered with parafilm and a small glass capillary as exhaust. The flask was submerged in an ice-bath	/	Mixture of 10% nitric acid and 3% hydrochloric acid	Storage in conical vials
Goniewicz et al. (2014) (39)	Two glass impingers submerged in an acetone/dry ice bath	/	50 ml of methanol	Vacuum evaporation of a certain volume of extract. Addition of 70% nitric acid, followed by 8 hours of digestion at 120 °C. Finally, addition of a certain volume of deionized water and Rh internal standard
Williams et al. (2013) (44)	One glass round bottom flask of 500 ml covered with parafilm and a small glass capillary as exhaust.	/	Mixture of 10% nitric acid and 3% hydrochloric acid	Storage in conical vials

Table 3: Overview of aerosol collection methods involving filters (n = 11)

Authors	Filter properties	Pre-cleaning method	Extraction properties	Final sample preparation steps
Wang et al. (2024) (65)	Cambridge filter	/	Method 1: 40 minutes rotary shaking in 25 ml of 5% nitric acid Method 2: 40 minutes ultrasonication in 25 ml of 5% nitric acid Method 3: digestion	Method 1: filtration and centrifugation Method 2: filtration and centrifugation Method 3: dilution, followed by filtration and centrifugation
Su et al. (2023) (63)	PTFE membrane filters (0.3 µm, 37 mm Ø) installed on MOUDI impactor for aerosol size selection of 56-320 nm	/	Filters are placed in conical centrifuge tubes, filled with a mixture of nitric acid and hydrofluoric acid and sonicated for 30 minutes at 80 °C for extracting and digesting	After cooling, the digestion solution was evaporated, and the sample was redissolved in 2% nitric acid
Kapiamba et al. (2022) (13)	PTFE filters (0.3 µm, 37 mm Ø)	Soaked overnight in 67-60% nitric acid	Immediate digestion with 70% nitric acid following the digestion procedure outlined in the Environmental Protection Agency protocol 3050 B	/
Ko et al. (2022) (64)	Glass fiber syringe filter (0.22 µm)	/	a volume of 200 µl (viscosity of the collected aerosol was also checked) was diluted in 10 ml of 2%	/
Lin et al. (2022) (35)	PTFE membrane filters on MOUDI impactor	/	Performed by other lab: no further information	Performed by other lab: no further information
Talih et al. (2022) (67)	Quartz filters (Pall Type A/E, 47 mm Ø)	pre-washed in 1% nitric oxide solution, then air-dried	digesting the filter in 4 mL of nitric acid and 2 mL of hydrogen peroxide at 200°C for 20 min	Dilution in deionized water
Zhao et al. (2018) (42)	PTFE filters connected to a compact cascade impactor	Glassware used in extraction and analysis was pre-cleaned at 450 °C for 12 h	The aerosols collected on the filter were solubilized	/
Palazzolo et al. (2017) (36)	Mixed cellulose ester membrane disks (5 µm, 13 mm Ø)	/	/	MCE membranes were subject to acid digestions according to the

Table 3: Overview of aerosol collection methods involving filters (n = 11)				
Authors	**Filter properties**	**Pre-cleaning method**	**Extraction properties**	**Final sample preparation steps**
				GFAA/ICP-MS digestion procedure outlined in Environmental Protection Agency protocol 3050B
Mikheev et al. (2016) (66)	Quartz fiber filters	/	/	microwave digested in 1:1 nitric acid
Lerner et al. (2015) (68)	Methylcellulose filters (nitrocellulose filter as control?)	/	/	/
Tayyarah et al. (2014) (4)	Glass fiber filter pads (44 mm Ø)		2% V/V nitric acid and 0.5 % V/V hydrochloric acid (20 ml), 20 min in a wrist action shaker	/

Table 4: Overview of aerosol collection methods involving condensation tubing (n = 9)

Authors	Tubing properties	Pre-cleaning method	Extraction solvent	Final sample preparation steps
Pappas et al. (2024) (19)	FEP tube		Triplicate rinsing with 8 ml of 1% v/v hydrochloric acid + 2% v/v nitric acid purified in a PFA sub-boiling still	Dilution using the same acid mixture
Jeon et al. (2023) (38)	FEP tube (length not clear, 3.97 mm Ø, internal volume)	24 ml of 1% hydrochloric acid and 2% nitric acid, followed by 5 min sonication at 25 °C. Then, rinsing twice with distilled water for 10 minutes, followed by 5 min sonication at 25 °C with distilled water. Finally, drying with a filtered air system for an hour	Filling the capped tube with 50 mL of 75% methanol. Sonication for 5 min at 25 °C	Vavufigation at 60 °C with 1000 rpm for 12 h until the volume was reduced to 100 µl. Addition of 2% nitric acid solution to the dried samples
Gray et al. (2022) (71)	FEP tubing	/	"acid solution" to remove and collect aerosol condensate	
Gonzalez-Jimenez et al. (2021) (72)	FEP tube (64.1 mL internal volume, 5.18 m, 3.97 mm Ø)	Puriss. p.a. acetone and a mixture of 2% v/v nitric acid and 1% v/v hydrochloric acid followed by vacuum drying. Tygon tubing was acid cleaned as well	Flushing with 5 ml of quartz distilled DEGMEE, followed by 4 × 8 ml 2% v/v nitric acid + 1% v/v hydrochloric acid	Adding the acid rinses to the DEGMEE rinse, followed by dilution using 2% v/v nitric acid + 1% v/v hydrochloric acid in acid cleaned polymethylpentene class A volumetric flasks. Then, transfer to acid cleaned polypropylene sample tubes
Mallampati et al. (2021) (56)	Two glass impingers of 25 ml submerged in an ice bath	/	Two glass impingers using various solvents in various combinations: mixture of 8% V/V nitric acid and 2% V/V hydrochloric acid 10 % V/V hydrogen peroxide methanol acetone hexane	Connector tubing and glassware were washed in triplicate with a certain volume of impinger solvent. Samples collected in aqueous solvents (a and b) were diluted to 2% acid concentration. In case of organic impinger solvents (c, d and e), an evaporation step was introduced

Table 4: Overview of aerosol collection methods involving condensation tubing (n = 9)

Authors	Tubing properties	Pre-cleaning method	Extraction solvent	Final sample preparation steps
				at 40 °C under nitrogen stream, followed by digestion
	FEP tubing submerged in ice-bath (3 m, 1/4″ i.d., 96 ml of internal volume) and connected with an impinger	/	Acetone extracts: triplicate rinsing with 20 ml of acetone Aqueous extracts: 5 rinsing with 5 ml aqueous impinger solution	Acetone extracts: Drying under nitrogen stream in a 55 °C water bath for 2−4 hours, followed by microwave digestion Aqueous extracts: dilution to 2% final acid concentration
McDaniel et al. (2021) (59)	FEP tubing ("long length") submerged in an ice bath, followed by an impinger	/	FEP tubing: acetone rinsing Impinger: diluted acid	FEP tubing: first, rinsed with acetone. Then, removal of acetone under nitrogen stream. Lastly, microwave digestion. Impinger: dilution to 2% final acid concentration
Halstead et al. (2020) (69)	FEP tubing of various lengths: 518 cm, 3.97 mm i.d. (64 ml) 671 cm, 3.97 mm i.d. (83 ml) 914 cm, 3.97 mm i.d. (113 ml)	Cleaning with acid	Triplicate rinsing with 8 ml of 1% v/v hydrochloric acid + 2% v/v nitric acid purified in a PFA sub-boiling still	Dilution using the rinse solution in acid cleaned PMP class A volumetric flasks
Nicol et al. (2020) (51)	One impinger for all elements except Hg. The particular matter was collected in an EP tube	/	Hg analysis: acidified $KMnO_4$ Analysis of other elements: nitric acid	Hg analysis: microwave digestion followed by hydroxylamine addition Analysis of other elements: extraction of EP tube with methanol. Combining this extract with the impinger solution. Lastly, microwave digestion
Pearce et al. (2020) (70)	FEP tubing	Cleaning procedure mentioned but not disclosed	Particle analysis: ultrapure water	Particle analysis: dilution with ultrapure water

Table 4: Overview of aerosol collection methods involving condensation tubing (n = 9)				
Authors	**Tubing properties**	**Pre-cleaning method**	**Extraction solvent**	**Final sample preparation steps**
			ICP-MS analysis: Halstead et al. (69)	ICP-MS analysis: Halstead et al. (69)

AUTHOR CONTRIBUTIONS

Conceptualization, M.D., S.B., C.V. and E.D.; Analysis, M.D., S.B. and C.V.; original draft preparation, M.D.; review and editing, M.D., S.B., C.V. and E.D.; visualization, M.D., C.V. and E.D.; supervision, S.B., C.V. and E.D.; project administration, S.B. and E.D.; funding acquisition, E.D. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare that this research was conducted without any commercial or financial relationships that could be considered a potential conflict of interest.

DATA AVAILABILITY STATEMENT:

No primary research results, software, or code have been included and no new data were generated or analyzed as part of this review.

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