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Dynamic Chemistry and Toxicity of E-Cigarette Aerosols and Their Product Waste

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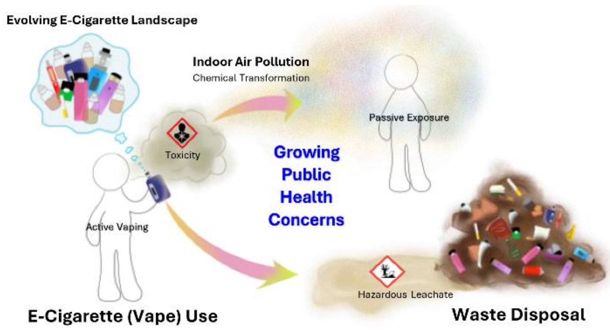
Abstract

The rapid rise of e-cigarette (vape) use over the past decade has raised significant public health and environmental concerns. While marketed as safer alternatives to combustible cigarettes, e-cigarettes generate complex aerosols that expose both users and non-users to potentially harmful compounds. Vaping produces aerosols containing active ingredients (such as nicotine or cannabinoids), flavoring agents, metals, carbonyls, reactive oxygen species, and ultrafine particles that can deposit throughout the respiratory tract. Beyond direct inhalation, non-users are also subject to secondhand and thirdhand exposure through inhalation of exhaled aerosols and contact with surface-deposited residues. These aerosols undergo dynamic physicochemical transformations, including gas-particle partitioning, oxidation, and aging processes that may enhance their toxicity by increasing the abundance of reactive and oxygenated species. Emerging evidence suggests that passive exposure may pose disproportionate risks to vulnerable populations such as children, adolescents, pregnant women, and the elderly. In addition, the rapid expansion of disposable e-cigarette products introduces new environmental hazards. Improper disposal of devices containing plastics, metals, lithium batteries, and residual e-liquids contributes to electronic waste, microplastic pollution, and the leaching of toxicants such as nicotine, heavy metals, and persistent organic pollutants. Despite growing research, critical gaps remain in understanding the long-term health effects of passive vaping, the environmental transformation of e-cigarette emissions, and the ecological consequences of disposable device waste. This review highlights current evidence on the composition, transformation, and toxicity of e-cigarette aerosols, examines the environmental burden of e-cigarette waste, and outlines future research priorities needed to inform regulatory policies and protect public health.

TOC Graphic


Evolving E-Cigarette Landscape
Indoor Air Pollution
Chemical Transformation
Passive Exposure
Toxicity
Growing Public Health Concerns
Active Vaping
Hazardous Leachate
E-Cigarette (Vape) Use
Waste Disposal

1. Introduction

Within the last decade, the use of e-cigarettes and vape products (i.e., electronic devices that deliver any aerosolized substance to the users, including nicotine and cannabinoids) has steadily increased in the United States, raising substantial public health concerns regarding the risk of passive exposure to the non-vaping population.[1] In particular, the increased usage of e-cigarettes among young adults who have never smoked traditional cigarettes has gained widespread attention. A number of factors have contributed to this upward trend, including the strategic marketing of e-cigarettes as products that are customizable (e.g., a variety of flavors) and have novel features (e.g., USB rechargeability), making them particularly appealing to young adults.[2] Furthermore, since e-cigarettes, unlike combustible tobacco cigarettes, do not release the same levels of carcinogenic substances such as tar that contains polycyclic aromatic hydrocarbons (PAHs), many users consider them to be a safer alternative to smoking.[3,4] As a result, e-cigarette use remains highly attractive, and exposure to e-cigarette aerosols is also often perceived as safer compared to traditional tobacco cigarettes.[5] Secondhand vaping is also often perceived as harmless or less harmful than secondhand smoking by both users and non-users.[6,7] However, vaping is not without health risks. The possible health risks of inhaling e-liquid ingredients when heated and the interactive effects among vaping devices, e-liquids, and user behaviors are areas of uncertainty. E-cigarette aerosols are complex, dynamic, and reactive mixtures containing numerous chemical compounds in the form of gaseous vapors and liquid droplets of varying particle sizes that can deposit in various regions of the human respiratory tract and lead to adverse health effects.[1,8,9] As shown in **Figure 1**, a person may be exposed to e-cigarette aerosols in a few ways: (1) through active inhalation of aerosols generated from the heated e-liquids and oils (known as active vaping), and (2) through inhalation of aerosols exhaled by an active user or contact with aerosols deposited on surfaces (known as passive vaping, which includes secondhand or thirdhand vaping).

Compared to active vaping, passive exposure to e-cigarette aerosols may pose an equal or greater risk of vaping-related health effects, particularly among vulnerable populations who would not have used vaping products on their own.[10,11] Prior research on passive vaping indicates that bystanders who inhale e-cigarette exhalates may be exposed to high concentrations of particulate matter in the fine (2.5 μm or less) and ultra-fine (0.1 μm or less) regions.[12] Initial exhalation may result in the emission of potentially toxic carbonyl-containing compounds, which may promote oxidative stress in non-users.[13] As many of these particles may linger in the air for several hours after emission,[14] there is also the possibility of transformation and evolution of organic compounds in the exhalate in a process known as aging.[15] Aging drastically affects the physiochemical properties of aerosols, which may in turn alter their toxicity upon exposure. While direct emissions of nicotine and other hazardous chemicals from active e-cigarette vaping have been widely studied, the interactions between e-cigarette aerosols and indoor environments to which they are emitted to change the physicochemical properties of aerosols and associated health risks upon exposure have not been well-characterized.[16] According to the 2024 Online California Adult Tobacco Survey (CATS) conducted by the California Tobacco Prevention Program in the California Department of Public Health, 38% of adults reported being exposed to secondhand e-cigarette aerosols in the past two weeks, and about half of them reported the exposure occurred on sidewalks, highlighting the urgent need for further research to better understand the potential health implications of secondhand e-cigarette aerosol exposure.[17] To minimize the secondary effects of e-cigarettes and vape products on people, it is necessary to gain a thorough understanding of the physicochemical characteristics of e-cigarette aerosols, how e-cigarette emissions may transform in the environment, and the exposure profiles and health risks associated with passive vaping. The 2018 National Academies of Sciences Engineering and Medicine report on e-cigarettes provided an important assessment of the evidence available at the time with emphasis on primary emissions and active user exposure.[18] Since the publication of that report, advances in analytical methods and exposure science have expanded understanding of e-cigarette aerosols beyond direct inhalation. Recent studies demonstrate that e-cigarette aerosols are chemically dynamic and undergo environmental transformation through oxidation and gas particle partitioning,[19–21] leading to the formation of secondary products that were not fully considered previously. These developments highlight additional exposure pathways including secondhand and thirdhand vaping and underscore the need to revisit earlier conclusions considering evolving evidence regarding aerosol aging and chemical complexity.

Additionally, e-cigarette and vape product usage may have negative impacts on the environment due to their improper disposal. Disposable vaping device waste is comprised of electronic waste, plastic and metallic device construction materials (e.g., printed circuit boards, plastic casings, metallic heating elements, and lithium batteries), and numerous hazardous chemical residuals from remaining e-liquids (e.g., nicotine, base solvents, and flavoring chemicals).[22] The plastic casings of disposable e-cigarettes can degrade and produce micro- and nanoplastic particles that may become airborne and dispersed in the environment. Lithium batteries can explode if subjected to high temperatures or physical damage, posing a serious fire hazard, or they can leach metals and halogenated flame retardants into the environment, contributing to environmental pollution. The volatile organic compounds from the remaining e-liquids can continue to evaporate and release into the atmosphere. Other metals and less volatile e-liquid residual chemicals also have the potential to leach into the environment through littering or improper disposal into the municipal solid waste, potentially leading to their release into landfill leachates and surrounding environmental matrices.[23] According to a recent report based on data from a weekly cross-sectional survey of US residents aged 15–24,[24] young people in the US who use disposable e-cigarettes primarily discard their spent disposable e-cigarettes in the regular trash or keep them, which raises environmental and safety concerns regarding disposal methods for these new and emerging tobacco products. Most tobacco product waste (TPW) research to date has focused on cigarettes and their littered butts. Less is known about the waste generated by these single-use, so-called "disposable" vaping devices, which contain numerous harmful and potentially harmful substances.[16] Research into the impacts of disposable vaping devices is urgently needed to understand the full scope of their contributions to environmental burden and risks posed to the surrounding communities.

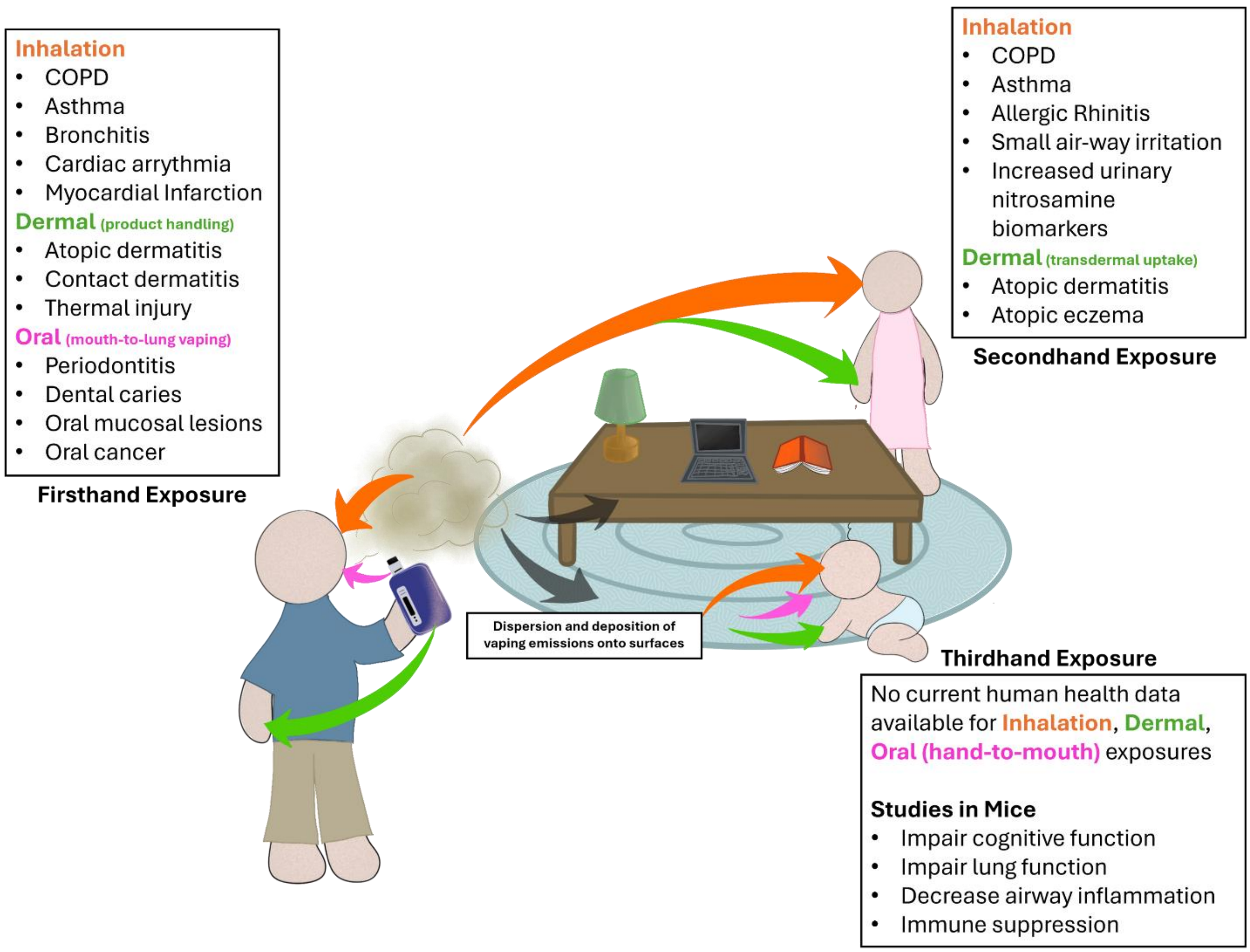


Figure 1. Exposure routes and health outcomes associated with firsthand,[1,25–28] secondhand,[10,11] and thirdhand[29,30] exposures to e-cigarette use and vaping emissions. Dermal toxicity due to secondhand exposure has been extrapolated using common indoor air pollutants not specific to e-cigarette emissions (e.g., particulate matter, volatile organic compounds, and heavy metals). Due to a lack of sufficient epidemiological data, health effects associated with thirdhand exposure are currently limited to animal studies.

2. Formation and Chemical Composition of E-Cigarette Aerosols

During the vaping process, constituents from the e-liquids are heated and converted into gaseous and aerosolized emissions.[31] Major components within these emissions are composed of parent compounds that are found in the e-liquids, such as nicotine, flavoring compounds, and carrier solvents (e.g., propylene glycol (PG), vegetable glycerin (VG), medium chain triglyceride (MCT) oil, and vitamin E acetate (VEA)).[8,31] Most of these compounds in the e-liquids have been regarded as safe for oral consumption, and most of the flavor additives and carrier solvents are considered as GRAS or Generally Recognized As Safe.[32] However, unlike oral exposure, inhalation of these compounds could pose different risks to users of e-cigarettes. As shown in **Figure 2**, the toxicity of e-cigarette aerosols can be mediated by a multitude of biochemical mechanisms that induce deleterious cellular responses. Inhalation of glycols and glycerol has been linked to decreased respiratory function in cases of occupational exposure, and both compounds have been shown to induce *in vitro* cytotoxicity and inflammation.[33,34] Flavor additives are present in e-liquids in significant concentrations, and single e-liquid flavors can consist of dozens of different flavoring compounds. Some common flavor additives, such as ethyl maltol and vanillin, exhibit significant cytotoxicity in exposed BEAS-2B cells, and mixture effects have been observed where a larger variety of flavor chemicals in e-liquids is associated with decreased cell viability in exposed cells.[35] Some flavor additives, such as benzaldehyde and cinnamaldehyde, have been shown to be potent respiratory toxins in human embryonic and lung cells by inducing changes in cell morphology, DNA damage, and cell death.[36] Additionally, some controversial flavor additives such as diacetyl have been associated with bronchiolitis obliterans, a form of lung damage characterized by fibrosis of the bronchioles.[37] In addition to traditional flavoring compounds, many e-cigarette products contain cooling agents such as menthol and synthetic analogs including WS-3 (N-ethyl-2-isopropyl-5-methylcyclohexanecarboxamide) and WS-23 (2-isopropyl-N,2,3-trimethylbutyramide).[38] These compounds activate transient receptor potential channels associated with cooling sensations and can reduce perceived harshness during inhalation.[39] As a result, cooling agents may indirectly influence puffing behavior by enabling longer puff durations or higher power operation.[39] In turn, this can affect aerosol mass yield and thermal degradation pathways. Although menthol has been studied more extensively, relatively little is known about the thermal stability and transformation products of synthetic cooling agents under vaping conditions. The presence of these additives may therefore contribute to changes in aerosol chemistry and exposure profiles. Past *in vitro* and *in vivo* studies have exhibited greater toxicity associated with vaping emissions compared to unvaped e-liquids. This implies the presence of novel chemical compounds that are produced during the vaping process, which possess different toxicological properties than the parent compounds found in the e-liquids. **Table l** summarizes various vaping parameters that affect e-cigarette aerosol composition.

Coil temperatures during vaping can vary widely between 150 – 1000 °C, depending on operating conditions and wick saturation.[40] At these high temperatures, parent compounds in e-liquids can decompose to produce thermal degradation products that are known to be potent pulmonary toxins. At these high temperatures, dehydration, dehydrogenation, C-C bond cleavage, and C-O bond cleavage are commonly observed.[41] These degradation mechanisms allow for the formation of simple volatile compounds such as formaldehyde and acrolein. Many studies have confirmed this and shown the production of reactive carbonyl species such as formaldehyde, acetaldehyde, propionaldehyde, and acrolein from the thermal degradation of e-liquids.[9,42–44] It has been reported that PG and VG can directly degrade into formaldehyde under pyrolyzing conditions, which shows that the toxic effect of vaping is not only mediated through nicotine and flavor additives.[41] These carbonyl compounds have been reported to be formed in significant quantities albeit in lower levels compared to traditional cigarette smoke.[41] These compounds are classified as Group 1 and Group 2 carcinogens by the International Agency for Research on Cancer (IARC) and the acute cytotoxicity of these carbonyl species have been well characterized with multiple *in vitro* and *in vivo* studies that report the development of oxidative stress and genotoxicity from acute formaldehyde exposure.[43,45,46] It has also been reported that benzene is produced during vaping.[47] Benzene is a known Group 1 carcinogen that is associated with acute myeloid leukemia (AML) and acute lymphoblastic leukemia (ALL) resulting from chronic exposure to benzene.[48] Pankow et al. reported that propylene glycol and glycerol can undergo dehydration and subsequent cyclization reactions to form benzene in low quantities.[47] During vaping, decarboxylation of benzoic acid may take place to form benzene.[47] Some mixed claims have shown trace levels of some polycyclic aromatic hydrocarbons (PAHs) in vaping emissions.[47,49,50] When VEA is used as the carrier solvent, it can thermally degrade into duroquinone.[51] Duroquinone may mediate the toxicity of VEA vaping by its redox-cycling ability to induce the formation of intracellular reactive oxygen species (ROS) and subsequent oxidative stress.[51] Additionally, it is believed that reactive radical intermediates are formed during the thermal decomposition of e-liquid constituents.[52] The formation of OH radicals during vaping was found to be dependent on the e-liquid composition as well as the pH.[53] Other factors such as operating voltage and device variability can also influence radical production.[53] The production of OH radicals during vaping can be dependent on the presence of metals and O_2, with Cu-Ni alloys being able to enhance the production of OH radicals resulting from the pyrolysis of VEA.[54] The presence of all these newly formed reactive compounds that are not originally present in e-liquids creates an emission type that carries risks of pulmonary damage when inhaled which goes against the harm reduction purposes associated with e-cigarettes.

It has been noted that the formation of the aforementioned compounds during vaping requires a high temperature environment. Varying the voltage output of e-cigarette devices allows for users to change the coil temperature during vaping. Product distribution is largely dependent on the operating temperature during vaping.[55] Not only are higher coil temperatures associated with larger puff volumes and aerosol mass yield, but higher temperatures have also been associated with greater carbonyl production.[56] Differences in product distribution are also observed at different operating temperatures, where greater temperatures are associated with lower molecular weight degradation products. Geiss et al. observed that as coil temperature increases, novel degradation products are seen that aren't present at lower temperatures, such as acrolein.[55] The device type can greatly influence carbonyl production during vaping. It has been reported that newer generations of e-cigarettes can produce greater amounts of carbonyls compared to the older types of e-cigarettes. Even though the newer 4th generation e-cigarettes operate at lower temperatures, carbonyl yield per puff was still greater than that produced by the 3rd generation devices.[56] Differences in the bulk composition that make up the device, such as the coil material, changes with each e-cigarette type and may have an influence on the generation of carbonyls during vaping. A common phenomenon that is observed in vaping studies is the enhanced generation of carbonyls during the event of "dry puffing." [57] In this scenario, the wick cannot sufficiently saturate the heating coil during vaping which causes localized spots of extreme temperature to form in the coil region. In turn, this greatly enhances the thermal degradation of e-liquids which is responsible for the production of carbonyls. In events of dry puffing, researchers have observed drastically increased production of aldehydes. In some cases, dry puffing induced a 30-250-fold increase in carbonyl production.[57] While it is widely noted that users typically avoid dry puffing conditions due to the unpleasant burnt taste, studying these extremes remains critical for identifying the mechanistic upper bounds of toxicant formation and understanding how device failure or misuse can impact user safety. Even in cases where the same device is used, there may be large variation in carbonyl production due to manufacturing variations which cause slight changes in operating temperature. Talih et al. observed that poor quality control amongst e-cigarette manufacturers may lead to devices that are more prone to dry puffing and act as super emitters of carbonyls during vaping.[58] Lastly, puffing topography has been shown to have significant impacts on the rate of carbonyl production during vaping. Longer puffs and shorter puff intervals have been associated with increased carbonyl production, likely due to the greater temperatures experienced under these puffing regimes.[59]

Metals can also be found within vaping emissions.[60–62] Originating from metallic components within the e-cigarette device, metals are released into the aerosol phase during vaping which is a process that is facilitated by many factors such as device composition, coil temperature, airflow rate, device age, and potentially e-liquid pH.[61] It is proposed that a large portion of metals are originated from the heating element. Metal coils in e-cigarettes and vape products are commonly composed of stainless steel, kanthal, or nichrome, which allows for a significant amount of Fe, Ni, and Cr to be released into vaping emissions. Monique et al. reported that metal species found in other components such as wires, wicks, sheaths, and joints may leach into the e-liquid or aerosol during vaping.[62] Many past reports have shown that a large variety of metal species are present in vaping emissions and these metals are being emitted as nanoparticles. SEM-EDS analysis of dissected e-cigarettes and cartomizers revealed the presence of multiple metal species that make up individual device components as well as contaminants within the e-liquid. TEM analysis showed the presence of metal nanoparticles in vaping emissions that are largely composed of nickel and chromium due to the presence of a nichrome heating element.[60] These authors also concluded that the device quality and manufacturing variation may play a role in the leaching and release of metals into the e-liquid and aerosol. Surprisingly, atomizers and other metallic components that make up e-cigarettes have not changed much since their inception and their bulk composition has been reported to be very similar across brands.[62] Many of these metals are considered redox-active, such as Fe, Cu, and Mn. Vaping emissions can also contain toxic heavy metals, such as Pb, Cd, and As. Analysis of emissions produced from more recent 3rd and 4th generation devices, confirmed the presence of heavy metals such as Pb and As, but they are found in lesser abundance compared to the non-heavy metal species.[61] However, some devices have been measured to emit levels of Ni, Cr, Pb, and Mn that exceed health-based limits and may result in detrimental health effects when inhaled.[61] It has been previously reported that coil age has an impact on the release of metals during vaping. Jeon et al. reported that older heating coils tend to leach greater amounts of metals into the aerosol phase which created more oxidative emissions that were characterized by enhanced *in vitro* toxicity.[63] Pearce et al. found that oxidative stress in cells exposed to vaping emissions was positively correlated with the abundance of metals within the aerosols.[64] Recent work has also highlighted the neurotoxic potential associated with vaping due to heavy metal exposure. Sub-chronic exposure to vaping emissions induced accumulation of metals in the central nervous system of mice.[65] Although the reported tissue concentrations of heavy metals were below known neurotoxic thresholds, it is proposed that prolonged exposure to vaping emissions may lead to greater metal accumulation and chronic toxicity may be observed once that threshold is reached.[65]

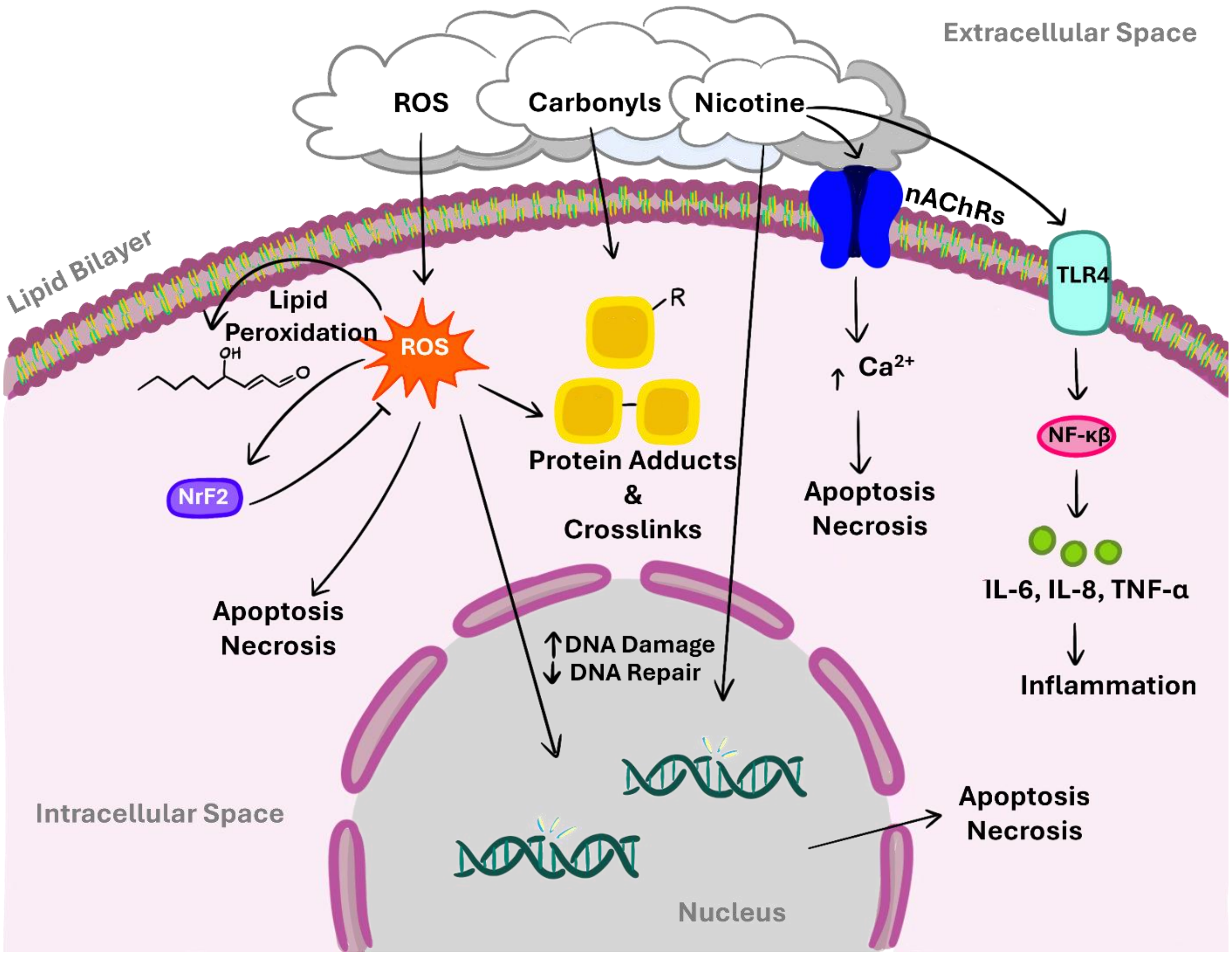


Figure 2. Molecular mechanisms driving the toxicity of nicotine and PG/VG-derived active vaping aerosols.

Table 1. Vaping parameters that affect e-cigarette aerosol composition

Parameter	Change in Aerosol Composition	
Carrier solvent	Higher PG:VG ratio • ↑ aerosol mass[66] • ↑ carbonyls[67] • ↑ ROS[68] • ↑ nicotine yield[66] • ↑ ultrafine particles[66]	More VEA • ↑ formaldehyde, hexanal, glyoxal, diacetyl[67] • ↑ duroquinone[69,70] • ↑ ketene[71,72] • ↑ carbonyls[54] • ↓ phytol[69]

Active ingredient	Nicotine (relative to no active ingredient) • Conflicting data: either no significant influence on metal emissions or can increase emissions of some metals[73,74] • No significant influence on particle size[75] • ↓ Aerosol mass as nicotine concentration increases[76]	• ↑ Cr, Cu, Mn[77] • Unclear influence on carbonyl emissions[78] THC/Cannabinoids (relative to no active ingredient) • ↑ butyraldehyde , acetaldehyde[79] • ↑ CBD-quinone[80,81] • Ketene[82]
Nicotine formulation	Benzoate salt (relative to freebase) • ↑ aerosol mass[53,66] • ↑ nicotine yield[66] • ↑ formaldehyde[66] • ↑ ROS[53] Lactate salt (relative to freebase) • ↑ aerosol mass[53,66] • ↑ nicotine yield[66] • ↑ metals[83]	• ↓ ROS[53] Citrate Salt (relative to freebase) • ↓ aerosol mass[53,66] • ↓ nicotine yield[66] • ↑ acetaldehyde, acrolein[66] • ↑ ROS[53] Malate Salt • ↑ formaldehyde, acrolein[66]
Flavor additives	The addition of flavorings and their subsequent aerosolization can create new chemical substances not initially present in the e-liquids. • Aldehyde flavorings like those for vanilla, cherry, citrus, and cinnamon can react with PG and VG to form acetals.[84] • The vaping process can thermally transform flavoring compounds into toxic byproducts.[85,86]	
Generation of device	Mods • Higher aerosol mass[56] • Higher Al, Cr, Cu, Fe, Mn, Pb, Sn, As[61]	Pods • Lower aerosol mass[56] • Higher Co and Ni[61]
Coil type (resistance and metal)	Higher coil resistance • ↓ aerosol mass[56] • ↑ formaldehyde, propionaldehyde, acetaldehyde, acrolein[56,87] • Without nicotine, ↓ formaldehyde, acetaldehyde, acrolein[87]	• ↓ dihydroxyacetone[56] • ↓ ROS[87] Metal type • No significant influence on carbonyls[56] • Need more data on the influence of metal type (Nichrome, Kanthal, Stainless Steel) on metals emissions and ROS
Temperature/Voltage	Higher Temperature/Higher Voltage • ↑ aerosol mass[56,67,76]	• ↑ 3 µm > particles > 1 µm[76] • ↑ ROS[68,88]

	• ↑ overall metals (e.g., Cu, Zn, Cr) but may not be true for all metals • ↑ overall carbonyls[67]	Lower Voltage • ↑ particles < 1 µm[76]
Puff volume	No significant influence of particle size distributions or particle mass concentration[75] • ↑ aerosol mass[89] • ↑ particle number concentration[90]	
Puff (heating) duration	Higher puff duration • ↑ aerosol mass[67] • Increase in metal emissions[77] • No significant influence of puff duration on metals normalized by aerosol mass[73]	
Aged coil	Older coil age/highly used coil • ↓ propionaldehyde, acrolein, glycolaldehyde, acetic acid[56,78] • Conflicting data: ↑ formaldehyde, acetaldehyde;[91] ↓ formaldehyde, acetaldehyde[56,78]	• ↑ methylglyoxal, dihydroxyacetone, hydroxyacetone, glyoxal, lactaldehyde[56,63] • ↑ Al, Cr, Cu, Rb, Pb[63] • ↑ Cr, Cu, Mn[77] • ↑ ROS[63,78]

3. Environmental Transformation and Aging of E-Cigarette Aerosols

Upon release into the indoor environment, e-cigarette aerosols are subject to a variety of physical and chemical transformation processes that substantially alter their properties, composition, and toxicity over time.[20,21] Understanding these processes is critical for assessing the true public health impacts of secondhand and thirdhand vaping exposure. There is a growing body of literature examining passive vaping, particularly with respect to exposure characterization, chemical composition, and toxicological mechanisms of secondhand and thirdhand vaping; however, studies directly linking these exposures to long-term human clinical outcomes remain limited.[29,92,93] The current knowledge on the environmental transformation of e-cigarette aerosols focuses on physicochemical changes, secondary pollutant formation, and evolving toxicological profiles.[19–21,94] These works have started to consider the aging process of vaping emissions in the environment, aided by ambient atmospheric oxidants such as ozone (O_3), to create secondhand and thirdhand emissions that have the potential to be more harmful than the primary emissions directly produced by e-cigarettes. Secondhand vaping refers to the exposure of non-users to the aerosols emitted during the vaping process.[11] These secondhand e-cigarette aerosols can be residuals from the e-cigarette device, but many of these secondhand aerosols are being exhaled by the user.[95] These secondhand aerosols can be directly inhaled by non-users, which leads them to be exposed to similar compounds that the primary users are also exposed to, such as nicotine and formaldehyde.[11] Although the exposure concentrations during cases of secondhand vaping are lower than that experienced by primary users, certain non-users may be more susceptible to experiencing pulmonary toxicity from the inhalation of these aerosols, albeit in small quantities.[10,11] In contrast, thirdhand vaping refers to the exposure of non-users to the aerosols that have deposited onto indoor surfaces, such as walls and furniture.[29] The surface residues that form from e-cigarette aerosol deposition may off gas volatile organic compounds (VOCs) as well as resuspend particles to induce inhalation exposure.[96] People are most commonly exposed through dermal routes by unknowingly touching these residues and allowing dermal absorption of the compounds present in these residues.[29] Children can be at the greatest risk of thirdhand exposure due to their greater hand-to-mouth tendency which can lead to oral ingestion of residues.[29] Although the routes of exposure and chemical profile of secondhand and thirdhand vaping emissions are different, both forms constitute significant and prolonged exposure pathways, particularly in poorly ventilated indoor spaces.[97]

Human exhalation studies demonstrate that a substantial fraction of inhaled e-cigarette aerosol constituents is not absorbed and are instead exhaled back into the environment.[98] Exhaled products typically include carrier solvents (PG and VG), nicotine, flavoring chemicals, and ultrafine particles (UFPs).[95,98] Research has indicated that passive exposure to exhaled e-cigarette constituents, most notably nicotine, may be associated with acute effects such as upper airway irritation and bronchitic symptoms.[99] As a result, passive vaping has been identified as a potential public health concern, warranting further investigation. Although the composition of passive vaping aerosols heavily consists of the parent compounds found in the e-liquid, it has been shown that there are significant differences in the chemical composition and size distribution of passive vaping aerosols compared to their freshly generated counterparts.[19,20,100] As shown in **Figure 3**, these changes have been attributed to the physicochemical transformations that take place in the environment such as gas-particle partitioning, and chemical aging. Upon entering the indoor environment, e-cigarette aerosols undergo rapid equilibrium partitioning between the gas and particle phases.[21] This physical process can be influenced by indoor temperature, humidity, aerosol loading, and surface availability.[101,102] Semi-volatile and low-volatility organics redistribute dynamically, affecting aerosol volatility and size.[102,103] Preferential accumulation of lower volatility compounds is observed in secondhand e-cigarette aerosols as the aging time increases.[21] In the presence of ambient oxidants, chemical transformations within the secondhand aerosols can take place, and this process has been noted as "chemical aging".[15] As described in **Table 2**, the chemical aging process of aerosols can be influenced by many different factors. Chemical aging processes are initiated through reactions with indoor oxidants such as ozone (O_3), hydroxyl radicals (OH), and nitrate radicals (NO_3).[104] These reactions can substantially modify the molecular structure of aerosol constituents, increasing oxygen content, reducing volatility, and leading to the formation of secondary organic aerosols (SOA) that can be inhaled through secondhand exposure or deposited onto surfaces for potential thirdhand exposure.[105] In terms of number concentration, fresh e-cigarette aerosols are dominated by ultrafine particles (<100 nm in diameter).[20] However, over time, particle size distributions of e-cigarette aerosols can evolve due to evaporation, condensation of oxidized organics, and particle coagulation.[21,106] A net shift toward larger particle sizes has been observed during indoor aging, driven primarily by the condensation of newly formed low-volatility products onto existing particle surfaces as well as particle coagulation.[20] These changes have implications for particle deposition in the human respiratory tract and associated health effects. In simulated indoor conditions, Li et al. observed that particle number concentrations (PNC) could reach up to 10^9 particles/cm^3, and $PM_{2.5}$ mass concentrations could spike to levels 100 times above background levels in vape shop environments.[107] Additionally, size distribution measurements revealed particle sizes shifting to larger diameters, indicating significant growth due to hygroscopic effects and condensation of low-volatility compounds.[16,107]

Similar to the thermal degradation of e-liquids, the chemical composition of e-cigarette aerosols evolves significantly following environmental release. O_3-mediated aging processes increase the abundance of oxygenated volatile organic compounds (OVOCs), peroxides, and secondary oxidized species within vaping emissions.[19,20] In particular, the oxidation of carrier solvents and flavoring chemicals generates a complex mixture of secondary products, including dicarbonyls, organic acids, and oligomeric species.[20] This compositional shift results in aerosols that are chemically distinct from their original form, with enhanced reactivity and potential toxicity. A major concern associated with the indoor aging of e-cigarette aerosols is the formation of reactive carbonyl species. During the vaping process, degradation of propylene glycol, vegetable glycerin, and flavoring agents yields significant quantities of formaldehyde, acetaldehyde, glyoxal, and methylglyoxal.[55,56,87] The formation of these carbonyls is also observed from the chemical reactions induced by O_3, even at typical indoor concentrations.[20] As potent respiratory irritants and probable carcinogens, elevated carbonyl levels may contribute substantially to the health risks associated with secondhand and thirdhand vaping exposure.[108] Environmental aging processes also enhance the oxidative potential of e-cigarette aerosols. O_3-mediated aging of vaping emissions has been shown to produce reactive oxygen species (ROS), including hydroperoxides and secondary radicals.[19,109] Acellular and cellular assays have demonstrated that aged e-cigarette aerosols contain greater amounts of ROS than fresh aerosols, suggesting an increased capacity to induce oxidative stress and inflammatory responses upon inhalation.[19,109] Additionally, the size of the aerosol has been shown to be a major influence on its oxidative ability. UFPs in aged vaping emissions contain the greatest amount of ROS along with the greatest abundance of metals.[109] Once in solution, these UFPs have been shown to undergo Fenton-like reactions that facilitate the decomposition of peroxides and enhance the production of OH radicals.[109]

The physicochemical transformations described above have profound effects on the toxicological properties of e-cigarette aerosols. Overall, aged vaping emissions exhibit greater cytotoxicity, oxidative stress induction, and inflammatory activity in cellular models compared to their fresh counterparts.[19,20] The generation of toxicants, particularly carbonyls and oxidized organic species, is believed to be a key driver of this increased toxicity.[20] Moreover, prolonged exposure to aged aerosols and thirdhand residues may pose cumulative health risks, especially for vulnerable populations such as children and individuals with preexisting respiratory conditions.[11,96,99] In summary, the environmental transformation of e-cigarette aerosols significantly enhances their chemical complexity, oxidative potential, and toxicity. Partitioning dynamics, indoor chemical aging, and secondary pollutant formation all contribute to the evolution of secondhand and thirdhand vaping emissions. Future research should prioritize real-world exposure assessments, mechanistic studies of secondary product formation, and evaluations of long-term health impacts to fully elucidate the risks associated with environmental e-cigarette aerosol exposure.

Table 2. Environmental factors that affect aerosol composition.

Parameter	**Change in Aerosol Composition**	
Oxidants	Ozone • ↑ carbonyls[105,110] • ↑ ROS[19] • ↑ ultrafine particles[109,111] OH Radicals • ↑ carbonyls[112] • ↑ ROS[113]	NO_x • ↑ carbonyls[112] • ↓ ROS[114] • ↑ nitroaromatics[115] • ↑ nitrosamines[116]
Humidity	Low Humidity • ↓ molecular mobility and heterogeneous reactions[117,118] • ↓ hygroscopic growth[119] • ↓ semi-volatiles in particle phase[120]	High Humidity • ↑ molecular mobility and heterogeneous reactions[118,121] • ↑ hygroscopic growth and particle size[119] • ↑ semi-volatiles in particle phase[120]
Surface Types	Organic-Rich Surfaces • ↑ adsorption[122,123] • ↑ nitrosamines[116] • ↑ ROS[124] Inorganic Surfaces • ↓ adsorption[122,123] • ↑ Fenton-like reactions and ROS[125,126]	Aqueous Surfaces • ↑ adsorption[127] • ↑ ROS[128] • ↑ carbonyls[129] • ↑ organic acid[130]
Gas-Particle Partitioning	• Compounds with lower volatility will be partitioned into the particle phase[21,102] • Compounds with greater volatility will be partitioned into the gas phase[21,102]	
Temperature	Lower Temperature • ↑ semi-volatiles in particle phase[103,131] • ↓ aging[132]	Higher Temperature • ↓ semi-volatiles in particle phase[103,131] • ↑ aging[132]

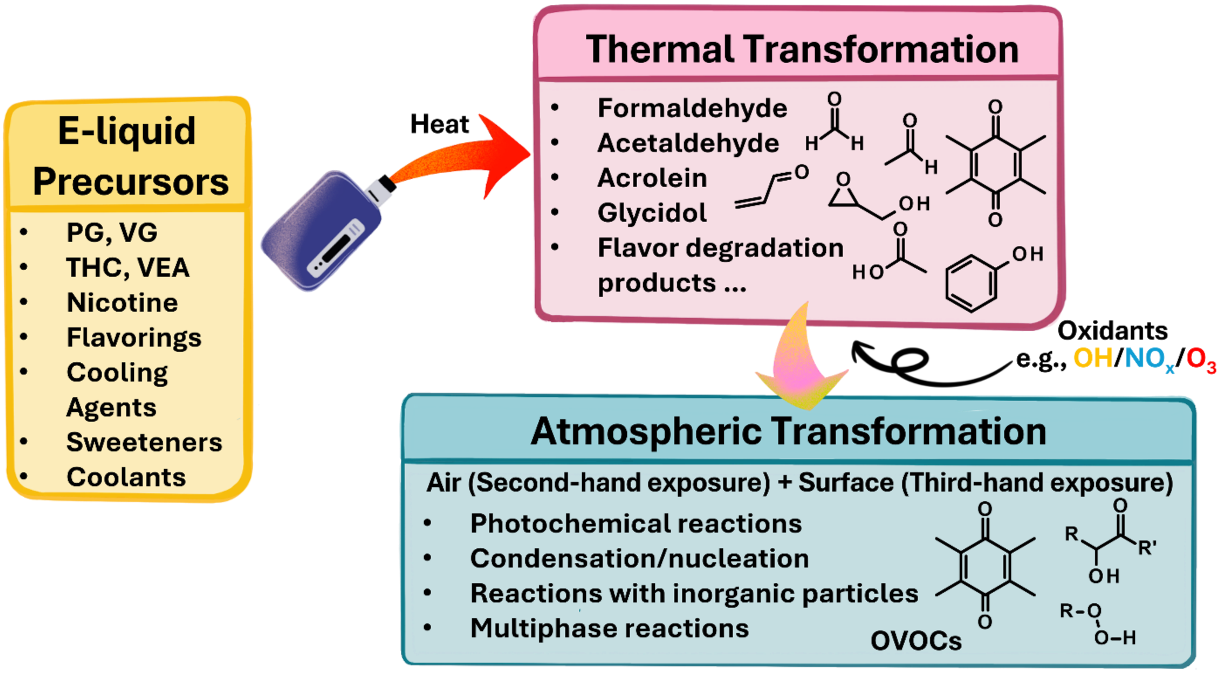


Figure 3. The transformation of e-liquid components and e-cigarette aerosol constituents via thermal and environmental processes.

4. The Fate and Potential Impacts of E-cigarette Product Waste

While the immediate human health hazards of e-cigarettes and vape products in the common vaping scenarios have been widely studied, the environmental consequences of vaping product waste have been much neglected. After the usage of e-cigarettes, their disposal often does not follow standard protocols for discarding electronic waste or household hazardous waste. Although the batteries of some e-cigarette devices (e.g., pod and mod systems) can be reused, disposable e-cigarettes have a limited lifespan, typically lasting for a few hundred to a couple thousand of puffs before they are depleted and discarded.[133,134] In fact, the sales of disposable e-cigarettes have significantly increased in the US market primarily due to their appealing flavors, ease of use, affordability, and a shift in regulatory focus away from flavored cartridges, leading to a surge in disposable products with various flavors, particularly among younger users.[135–137] This is further fueled by the perception of these products as a less restrictive alternative compared to other e-cigarettes subject to stricter regulations, given that they were exempted from federal restrictions in 2020 that only removed flavored pod-based e-cigarettes from the market.[138] Disposable e-cigarettes house an e-liquid-soaked wick which is wrapped around a coil and connected to a battery in one complete piece that cannot be easily taken apart, making proper disposal challenging. The leaching of e-liquid chemicals, especially nicotine, poses significant ecological hazards by contaminating soil and waterways. Studies on aquatic ecosystems have found that nicotine can be harmful and toxic to small invertebrates like water fleas (*Daphnia magna*) and fish.[139,140] Because these organisms are a critical part of the food web, their decline can have widespread ecological consequences. The airborne micro- and nanoplastic particles from the degraded plastic casings of disposable e-cigarettes may contain toxic chemical additives (like bisphenol A and phthalates) or adsorb other environmental contaminants while they transport and disperse in the environment, which can pose significant health risks for respiratory diseases.[141,142] Improper disposal of lithium-ion batteries causes hazardous metals like Pb, Cr, Tl, Co, Cu, Ni, and Mn leaching into the environment,[143] which can contaminate ecosystems and potentially harm human health. E-liquid residuals and other contaminants from discarded e-cigarettes and vape products can be continuously released and transformed into other hazardous chemicals over time. Despite the rapid rise in e-cigarette use, there is limited scientific data on the full life cycle of e-cigarettes.[144] Research into the impacts of disposable e-cigarettes is urgently needed to understand the full scope of their contributions to environmental burden and long-term health consequences posed to the surrounding communities.

5. Conclusions and Future Directions

In this review, we highlight the dynamic chemistry and toxicity of e-liquids, e-cigarette aerosols, and their product waste. As the landscape of the e-cigarette market rapidly evolves, and new formulations, flavors, and device designs continue to emerge, there are substantial concerns about their long-term health effects. For e-liquids, depending on the chemical nature of the active ingredients in vaping devices (i.e., nicotine in the form of a free base or a nicotine salt, CBD, or THC), the use of various carrier solvents (e.g., PG, VG, and MCT oil) in different formulations and ratios to manage potency, flavor, and user experience has been reported. Multiple classes of flavoring chemicals have also been detected and quantified in e-liquids, such as terpenes, esters, aromatics, lactones, ketones, alcohols, and more.[35] The diverse formulations of e-liquids will ultimately lead to a broad spectrum of thermal oxidation products that users may be exposed to, making the chemical landscape of emitted aerosols from vaping devices extremely complex. As regulatory agencies continue to evaluate the safety profiles of these products, it is important to consider the interactions between these chemicals and their transformation byproducts during vaping processes for developing effective regulations and ensuring consumer safety. Consumer awareness regarding ingredient differences and potential risks will also become increasingly crucial.

Furthermore, different parameters, such as PG/VG ratios, temperatures, coil resistance, device generation type, and coil age, can affect the e-cigarette aerosol composition and the formation of carbonyls as toxic byproducts. Release of metals, ROS, pesticides, plasticizers, flame retardants from the protective casing of the atomizer, and short-chain perfluoroalkyl substances (PFAS) during the manufacturing process or from contact with packaging materials has been reported in both e-liquids and e-cigarette aerosols.[17, 146–148] Given that how these contaminants may introduce additional health risks is not well understood, more studies are required to characterize these chemicals of emerging concern. Although individual chemical classes present in e-cigarette aerosols such as carbonyls, metals, radicals, and oxidized organic species have been studied independently, far less is known about how these constituents interact within complex aerosol mixtures. Potential chemical interactions and matrix dependent effects may lead to emergent toxicological properties that are not predictable from single compound exposures alone.[109] The limited number of studies addressing mixture effects represents a significant gap in current literature and future work should prioritize controlled investigations of multipollutant interactions and their influence on aerosol toxicity.

In terms of indoor air quality and passive vaping exposures for non-users that are in close proximity, it has been demonstrated that the thermal oxidation products emitted from these devices can undergo secondary oxidation from indoor oxidants, creating aged aerosols.[20] Recent studies have shown that these aged vaping emissions may be more harmful than "fresh" e-cigarette aerosols. The aging processes can lead to the formation of more ultrafine particles and oxygenated species, which may be the reason for higher cytotoxicity observed in *in vitro* tests. Thirdhand exposures can also be an issue since e-cigarette aerosols can deposit and land on surfaces in public and residential spaces. Such exposure is especially problematic for young children who have higher hand-to-mouth behavior. Thus, not only are emitted aerosols from e-cigarette devices relatively unhealthy to consume for the user, but also those aerosols can introduce health hazards to non-users in the same room even hours after emissions. Unlike active vaping, the aging process associated with secondhand and thirdhand vaping is still not well understood. More work needs to be done to understand the effects that the environment has on the chemical composition and toxicity of secondhand and thirdhand vaping emissions. Additionally, the 2019 e-cigarette or vaping product use–associated lung injury (EVALI) outbreak highlights how limited ingredient disclosure and incomplete regulatory oversight can contribute to severe and unanticipated health outcomes following inhalation exposure. While the present review does not aim to predict future outbreaks, the physicochemical complexity of e-cigarette aerosols including thermal degradation products, secondary oxidation products, and environmentally aged species, suggests that unrecognized risks may arise as device designs and e-liquid formulations continue to evolve. These observations underscore the need for improved ingredient transparency, standardized reporting, and independent chemical characterization to better inform risk assessment and prevent future vaping-associated health events.

Lastly, to reduce the effects of TPW from discarded e-cigarette products on the environment and surrounding communities, especially for vulnerable populations, a thorough understanding of the fate, transport, dispersion, and environmental health impacts of hazardous chemicals leaching into the environment is required. For example, the characterization of used or residual e-liquids before the leaching processes and the monitoring of concentrations of nicotine, metals, other organic contaminants, and their transformation products over time under various environmental conditions (e.g., environmental matrices, pH of the leachates, temperatures, etc.) will provide valuable information to understand the leaching processes of hazardous chemicals. These results can inform both regulatory frameworks to establish more stringent regulations regarding the disposal of e-cigarettes, as well as public health initiatives regarding the appropriate disposal of e-cigarette waste. The findings could also serve as an incentive for additional research into the development of more sustainable methods for recycling these devices.[149] By developing effective waste management strategies and promoting recycling initiatives, we can mitigate the negative consequences of these products on both the environment and public health.

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ABBREVIATIONS

CBD – Cannabidiol

EDS – Energy Dispersive X-Ray Spectroscopy

EVALI – E-Cigarette or Vaping Use Associated Lung Injury

GRAS – Generally Regarded as Safe

PAH – Polycyclic Aromatic Hydrocarbon

MCT – Medium Chain Triglyceride

OVOC – Oxygenated Volatile Organic Compound

PFAS – Polyfluorinated Alkyl Substances

PG – Propylene Glycol

PNC – Particle Number Concentration

ROS – Reactive Oxygen Species

SEM – Scanning Electron Microscopy

SOA – Secondary Organic Aerosol

TEM – Transmission Electron Microscopy

THC – Tetrahydrocannabinol

TPW – Tobacco Product Waste

UFP – Ultrafine Particle

VEA – Vitamin E Acetate

VG – Vegetable Glycerin

VOC – Volatile Organic Compound

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Biographies

Wonsik Woo is a doctoral candidate in Environmental Toxicology at the University of California, Riverside. His research focuses on the chemistry and toxicity of passive vaping aerosols, with emphasis on how interactions with environmental oxidants and aerosol aging influence the formation of secondary toxicants relevant to secondhand and thirdhand exposure. Using analytical chemistry techniques and *in vitro* exposure models, his research aims to elucidate mechanisms underlying e-cigarette aerosol driven oxidative stress and genotoxicity.

Lillian Tran is a doctoral student at the University of California, Riverside, specializing in the environmental chemistry of per- and polyfluoroalkyl substances (PFAS). Her research evaluates the thermal degradation and transformation pathways of persistent contaminants. Prior to her doctoral studies, she established expertise in aerosol chemistry and mass spectrometry through extensive research into e-cigarette emissions. Her published work includes the characterization of carbonyls across diverse e-liquid constituents and vaping scenarios, the role of acids in nicotine salts on free radical production, and the toxicological impacts of Vitamin E Acetate in murine models.

Linhui Tian is an environmental and analytical chemist with expertise in the molecular-level characterization of complex atmospheric and indoor aerosols and their associated health impacts. Her research focuses on the composition, transformation, and toxicity of emerging pollutants, including e-cigarette emissions, secondary organic aerosols, and indoor oxidation products. She has extensive experience in non-target and targeted analysis using high-resolution mass spectrometry (LC-HRMS, GC-MS, and CIMS) to identify reactive organic species and transformation products. Her work integrates advanced analytical measurements with *in vitro* toxicological assays to elucidate links between aerosol chemistry and adverse biological responses.

Alexa Canchola is an Assistant Project Scientist at the University of California, Riverside (UCR), specializing in the chemical and toxicological properties of emerging contaminants. She earned her Ph.D. in Environmental Toxicology from UCR, where she investigated the thermal degradation of vitamin E acetate in vaping and revealed its transformation into emissions with enhanced lung toxicity. Her current work employs machine learning and artificial intelligence approaches to address complex challenges in environmental health.

Ying-Hsuan Lin is an Associate Professor at the University of California, Riverside. Her research investigates the fate, transport, health effects, and climatic impacts of atmospheric aerosols and emerging contaminants from diverse sources. Her group integrates analytical and computational approaches with *in vitro* cellular models to characterize the physicochemical and toxicological profiles of these pollutants. Current research focuses on e-cigarette emissions, indoor chemical aging, and tobacco product waste. By examining how environmental transformations drive vaping aerosol toxicity, her work provides critical insights into biological perturbations for both active and passive exposures.