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SHORT RESEARCH AND DISCUSSION ARTICLE

Chemical components of electric vehicle and internal combustion engine vehicle fire smoke and their mutagenic effects

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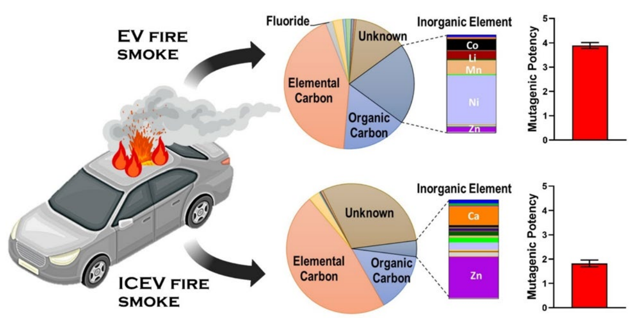
Abstract

Lithium-ion (Li-ion) batteries have become the primary power source for electric vehicles (EVs) around the world. However, this technology comes with important risks during EV fires if the batteries are damaged, improperly overcharged, or overheated, leading to intense heat and considerable amounts of smoke, which may have different properties than those from fires in internal combustion engine vehicles (ICEVs). Chemical components of smoke emissions from EV fires and their potential health risks are not fully understood. In this study, full-scale fire tests of six EVs and two ICEVs were conducted to simulate real-world fire scenarios. Respirable particulate matter (PM) in the smoke emissions was collected for chemical analyses and mutagenicity tests using the Ames assay. Results showed that the EV smoke PM contained more metals than the ICEV smoke samples, but the mass fractions of the PM varied depending on vehicle models. While Li, Mn, Co, and Ni were the predominant metals of the EV fire smoke emissions, Zn was a primary contributor to the total metal content of the ICEV fire smoke PM. In addition, fluoride was strongly enriched in the EV fire smoke samples. On an equal mass basis, most EV fire smoke PM induced more substantial mutagenic potencies compared to the ICEV fire smoke samples. These findings provide an initial understanding of the chemistry and potential health effects associated with EV fire smoke exposures and could inform protective strategies for emergency responders to EV fire events.

Graphical Abstract



Keywords Electric vehicle fire · Lithium-ion battery fire · Combustion smoke · Particulate matter · Mutagenicity · Metals

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Introduction

Global demand for lithium-ion (Li-ion) batteries is rapidly increasing because of their high-energy capacity and the increasing popularity of electric vehicles (EVs), consumer electronic goods, and sustainable energy options. However, high-energy Li-ion batteries are vulnerable to failure when they are overheated, overcharged, or damaged, resulting in explosions and/or uncontrolled fires (Zalosh et al. 2021). Since Li-ion batteries account for 15–20% of the EV's weight (Berjoza and Jurgena 2017), fires in EVs behave differently from those in conventional internal combustion engine vehicles (ICEVs). While EV fires are less frequent than ICEV fires, they are more challenging to extinguish and also producing substantial amounts of smoke and intense heat, which cannot only threaten the health of vehicle drivers, firefighters, and other first responders, but also have detrimental effects on the environment (Hynynen et al. 2023). Some studies to date have examined chemical components of smoke released from EV fires; however, there are no scientific reports on adverse health outcomes associated with exposure to the smoke emissions (Arvidson and Westlund 2023; Chiu et al. 2025; Hynynen et al. 2023; Kang et al. 2025; Sturm et al. 2022; Zhao et al. 2024). Thus, there is a critical gap in fire service knowledge and public safety education pertaining to health risks associated with EV fires. In addition to the typical combustible materials used in all vehicle construction, EV fires generate smoke that also includes products released when the Li-ion battery burns, leading to distinct chemical characteristics involving metals and fluoride compounds. Notably, because many EVs are produced with more plastics to offset the heavier weight of Li-ion batteries, the additional amount of plastics that may include additives such as flame retardants could increase the release of toxic gases and vapors as well as bioactive components such as polycyclic aromatic hydrocarbons (PAHs), dioxins, and furans during EV fires. In addition, carbonaceous components (e.g., graphite anodes and electrolytes) of Li-ion batteries could be another source of organic compounds (e.g., PAHs) in the smoke emitted from EV fires. Numerous studies have shown that exposure to metals, fluoride, and PAHs, often found in smoke and other environmental matrices, can have various toxic effects on human health (Ando et al. 2001; Bergström 1977; Mallah et al. 2021; Olasehinde and Olaniran 2022; Szűcs-Somlyó et al. 2023). However, there is still a lack of knowledge about how many chemicals are released from EV fires, whether they are different from ICEV fires, and how such differences promote similar or distinct health outcomes.

Of the complex chemical components in EV fire smoke, PAHs are major factors of concern because they are widespread environmental pollutants generated from incomplete combustion of various sources and their exposure (particularly long-term exposure) can cause DNA damage, leading to mutations and potentially increasing the risk of cancer (DeMarini and Linak 2022). While there are several mutagenicity assays that are used to evaluate the mutagenic potential of various compounds, the *Salmonella* (Ames) assay has been widely used in the field of environmental toxicology for more than 50 years (Claxton et al. 2010). Importantly, since many chemicals are directly mutagenic in their original forms but may also require metabolic transformation within living organisms to elicit mutagenicity, the Ames assay is designed to detect direct and indirect mutagenic substances by exposing genetically modified bacteria to the chemicals in the absence and presence of metabolic activation to simulate mutagenic activity in vitro.

In the present study, we performed full-scale fire testing of six EVs and two ICEVs and collected respirable particulate matter (PM) of the combustion smoke to evaluate mutagenic potentials. As noted earlier, there are no studies integrating analysis of chemical and toxicology data from real fire scenarios for EVs and ICEVs and examining potential health effects as compared to other combustion smoke exposures. To our knowledge, this is the first study to investigate differences in chemical profiles of the smoke PM emitted from EV and ICEV fires and associated mutagenic risks, which are relevant to firefighters and others who may be exposed to vehicle fire smoke.

Methods

Full-scale EV and ICEV fire testing

Full-scale fire experiments involving both EVs and ICEVs were completed at an indoor large-fire laboratory (UL Solutions, Northbrook, IL, USA). Fire effluent was removed from the lab at a rate of 28.3 m^3/s throughout the experiments and passed through a regenerative thermal oxidizer prior to release to the environment. A total of six EV models (EV1, EV2, EV3, EV4, EV5, and EV6) and two ICEV models (ICEV1 and ICEV2) were used for the full-scale fire testing. Full specifications of the vehicles are listed in **Supplementary Table S1**. Note that EV6 and ICEV1 shared the same platform (chassis and body structure) but with different propulsion systems. The vehicles were placed near the center of the room, inside of a metal pan, that was situated on a metal frame, which raised the vehicle approximately 52 cm from the lab floor (Fig. 1). Vehicles remained intact and were filled with gasoline (for ICEVs) or charged to near maximum capacity (for EVs). The windows were lowered, and vehicles

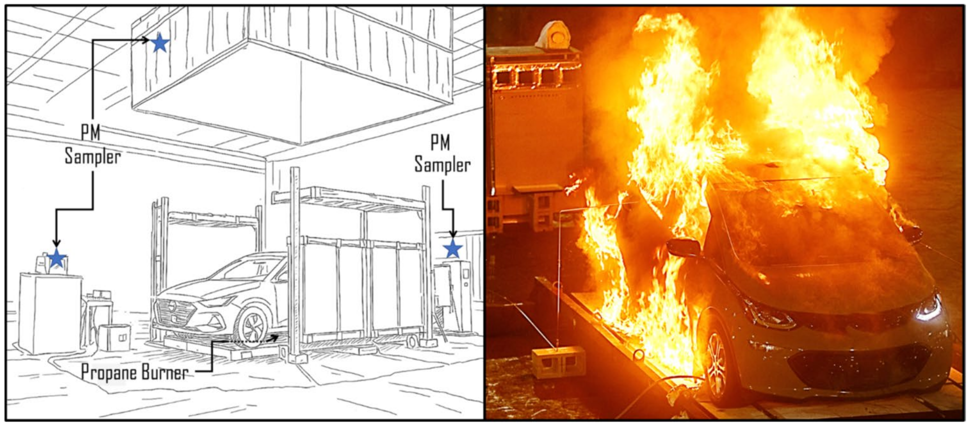

Fig. 1 Schematic of full-scale EV and ICEV fire testing (left) and one of the vehicles during the fire event (right)

were placed in the "ON" position prior to ignition. Vehicles were ignited using a propane burner that was placed under the battery in the EVs and under the engine bay in the ICEVs. Gas flow to the burner was regulated to produce an output of 30 kW and was shut off when the fire had transitioned to the vehicle. Vehicles were allowed to burn until the consumption of all combustible materials.

Smoke PM sampling and extraction

This work is part of a larger study that conducted measurements of the thermal properties and chemical characterization of the effluent from EV and ICEV fires. While vehicle mass loss, temperature, heat flux, and gas/particle components were measured to characterize the heat release rate and physico-chemical properties of the fires (Dehghani et al. 2025; Kesler et al. 2025), this study is focused on the particulate matter (PM) which was collected using high-volume air samplers (Staplex, Cincinnati, OH, USA) from two different locations during the full-scale fire experiments. These samplers were positioned 1.5 m high, approximately 3 m in front, and 4.5 m behind the vehicle (Fig. 1), representing potential exposure locations for emergency first responders (e.g., firefighters and paramedics) during fire events. For a subset of tests, an additional high-volume air sampler was placed in the plume area near the ceiling (8.3 m above the vehicle's ground level), representing the worst-case scenario of fire smoke exposures. The samplers were equipped with 90-mm quartz fiber filters and operated at a flow rate of 10 ft^3/min (approximately 280 l/min). The smoke PM was extracted from the filters through sonication in methanol. PM samples were resuspended in methanol and filtered (Syringe Strainer, pluriSelect, El Cajon, CA, USA) to remove non-respirable particles larger than 10 µm. The smoke samples were diluted to a concentration of 1 mg/ml, and chemically analyzed and tested for mutagenic effects. For chemical analysis, three aliquots of each sample containing 200 µg of PM were added to pre-cleaned 15 ml polypropylene DigiTubes (SCP Science, Champlain NY, USA) and submitted for analyses of organic carbon (OC), elemental carbon (EC), inorganic elements, and ions. For mutagenicity testing, separate samples of the EV and ICEV fire smoke PM were suspended in dichloromethane (DCM) at a concentration of 10 mg/ml.

Smoke PM analysis

For the inorganic elemental analysis, an aliquot of the PM extract containing 100 µg of PM was transferred into an acid-cleaned SCP Science DigiTube. Then, 0.5 ml of HNO_3 – HCl (3:1) mixture was added, capped, and placed on a DigiPrep Jr block digester (SCP Science, USA) at 65ºC for 3 h. Following this step, the tubes were withdrawn, 0.5 ml of deionized water was added, and they were returned to the DigiPrep Jr and heated at 95 °C for an additional 2 h. The resulting solution was allowed to leach overnight. The following day, 9 ml of deionized water was added to each DigiTube, and the contents were vortex-mixed and then centrifuged at 2000 rpm for 30 min. An aliquot of the supernatant was subsequently transferred for elemental analysis, following further dilution to achieve a final nitric acid concentration of 2%. Inorganic elemental analysis was performed using high-resolution inductively coupled mass spectrometry (HR-ICP-MS; Nu AttoM ES; Nu Instruments Ltd, Wrexham, UK). Samples were introduced to the plasma using a SC-FAST flow injection multivalve system and MC2 peristaltic pump (Elemental Scientific Inc., Omaha, NE, USA) with online internal standard Indium at 2 ppb. Up to 42 elemental isotopes were analyzed, including typical metals found in lithium-ion batteries such as Al, Co, Li, Mn, Ni, Pb, and Sb. Analytical calibration was performed using multielement standards (SCP Science, USA). NIST SRM 1643a and 1640a were analyzed in each analytical sequence as a quality control measure. For water-soluble anion analysis, samples were diluted to 5 ml using Milli-Q water (Millipore Sigma, MA, USA) prior to transfer into Thermo Scientific Dionex vials and Guardcaps. Ion chromatography analysis was performed on a Dionex ICS-2000 (Chromeleon software v6.8) equipped with a 200-µl injection loop, Thermo Scientific Dionex IonPac AS18 anion-exchange analytical (4 × 250 mm, pn060549), and AG18 guard columns (4 × 50 mm, pn060551) utilizing a 30 mM potassium hydroxide (KOH) isocratic separation method, based on EPA Method 300.0(A). The system was calibrated using a Thermo Seven Anion standard (pn056933) of fluoride, chloride, nitrite, bromide, sulfate, nitrate, and phosphate. Each sample was injected and analyzed twice to observe precision. For carbon species analysis, samples were analyzed using a Sunset Laboratory Model 5L Thermal-Optical Carbon Analyzer (Sunset Laboratory Inc., Tigard, OR, USA). In preparation for analysis, each sample solution was homogenized using a vortex mixer for 1 min. An aliquot of 20 µl was extracted from the well-mixed solution using a syringe and directly spiked onto the center of a pre-baked quartz filter punch. The spiked filter punch was dried using the equipment's drying cycle function to ensure methanol evaporation. Once dried, the OC/EC analysis was conducted using NIOSH 870 parameters (NIOSH Method 5040). The resulting organic carbon (OC), elemental carbon (EC), and total carbon values were recorded.

Mutagenicity assay

Smoke PM samples from burning six EVs and one ICEV were used for mutagenicity analysis. We extracted the organics from the smoke PM with dichloromethane (DCM), and then solvent-exchanged the extractable organic material (EOM) into dimethyl sulfoxide (DMSO) as described previously (Kim et al. 2018, 2021). Smoke EOM samples were tested for mutagenic potential in a bacterial reverse mutation assay using *Salmonella typhimurium* tester strains TA98 and TA100. Experiments in TA98 were done in the presence and absence of S9, and those in TA100 were done only in the presence of S9 due to the limited amount of sample. The metabolic activation (S9 mix) contained 1 mg of S9 protein (Moltox, Inc., Boone, NC, USA) made from the livers of Aroclor-induced Sprague–Dawley rats; mutagenesis experiments were conducted at Inotiv, Inc. (Research Triangle Park, NC, USA). In the presence of S9, both strains primarily detect PAHs, and strain TA98 is also sensitive to aromatic amines; in the absence of S9, strain TA98 primarily detects nitro-PAHs (nitroarenes). Strain TA100 + S9 detects primarily PAHs. The smoke samples were evaluated using 3 doses (50, 100, and 200 µg EOM/plate) at one plate/dose; samples were evaluated in two independent experiments in each strain/S9 combination. We defined a positive mutagenic response as a reproducible, dose-related increase in revertants per plate relative to the DMSO control. The mutagenic potency (MP) of the EOM (revertants/µg EOM) was the slope of the linear regression over the initial linear portion of the dose-response curve created by combining the data (rev/plate) from the independent experiments.

Mutagenicity score calculation

We used MP to calculate a mutagenicity score (MS) of smoke samples from each vehicle burn. The MS of each bacteria strain was calculated by $(MP_{sample} - MP_{minimum})/(MP_{maximum} - MP_{minimum})$ and a total mutagenicity score (TMS) for each smoke sample was calculated as the sum of MS of each strain (Ghosh et al. 2024); $TMS = MS_{TA98+S9} + MS_{TA98\text{-}S9} + MS_{TA100+S9}$. The TMS was used to rank the relative mutagenicity of the smoke samples using a scale from 0 to 3, with 0 being less mutagenic and 3 being more mutagenic.

Statistical analysis

We used one-way analysis of variance (ANOVA) followed by Dunnett's multiple comparison test to compare the mutagenic potencies. This analysis was performed using GraphPad Prism software (version 10.2.2, GraphPad Software Inc., San Diego, CA, USA). Data were expressed as mean ± standard error of the mean (SEM). The statistical significance level was assigned at a probability value of $p < 0.05$.

Results and discussion

EV fire smoke differs from ICEV fire smoke

Smoke PM collected from burning six EVs and two ICEVs was chemically analyzed for organic carbon, elemental carbon, ions, and inorganic elements and their characteristics are summarized in Fig. 2 and **Supplementary Tables S2** and **S3**. Note that some EV smoke samples (EV6 and ICEV1) were collected from two different locations at 1.5 m above ground level and in the plume area near the ceiling to examine chemical transformations potentially taking place within smoke plumes. Our findings indicate that the chemical profiles of the ground-level smoke and the rising smoke plume were similar (**Supplementary Figure S1**). Thus, we combined them into one sample before proceeding further. All other smoke samples in this study were ground-level smoke samples. Depending on the vehicle model, we found that EV fires emitted 2–7 times more inorganic elements (mostly Ni, Mn, Co, and Li) than ICEV fires. Specifically, the mass

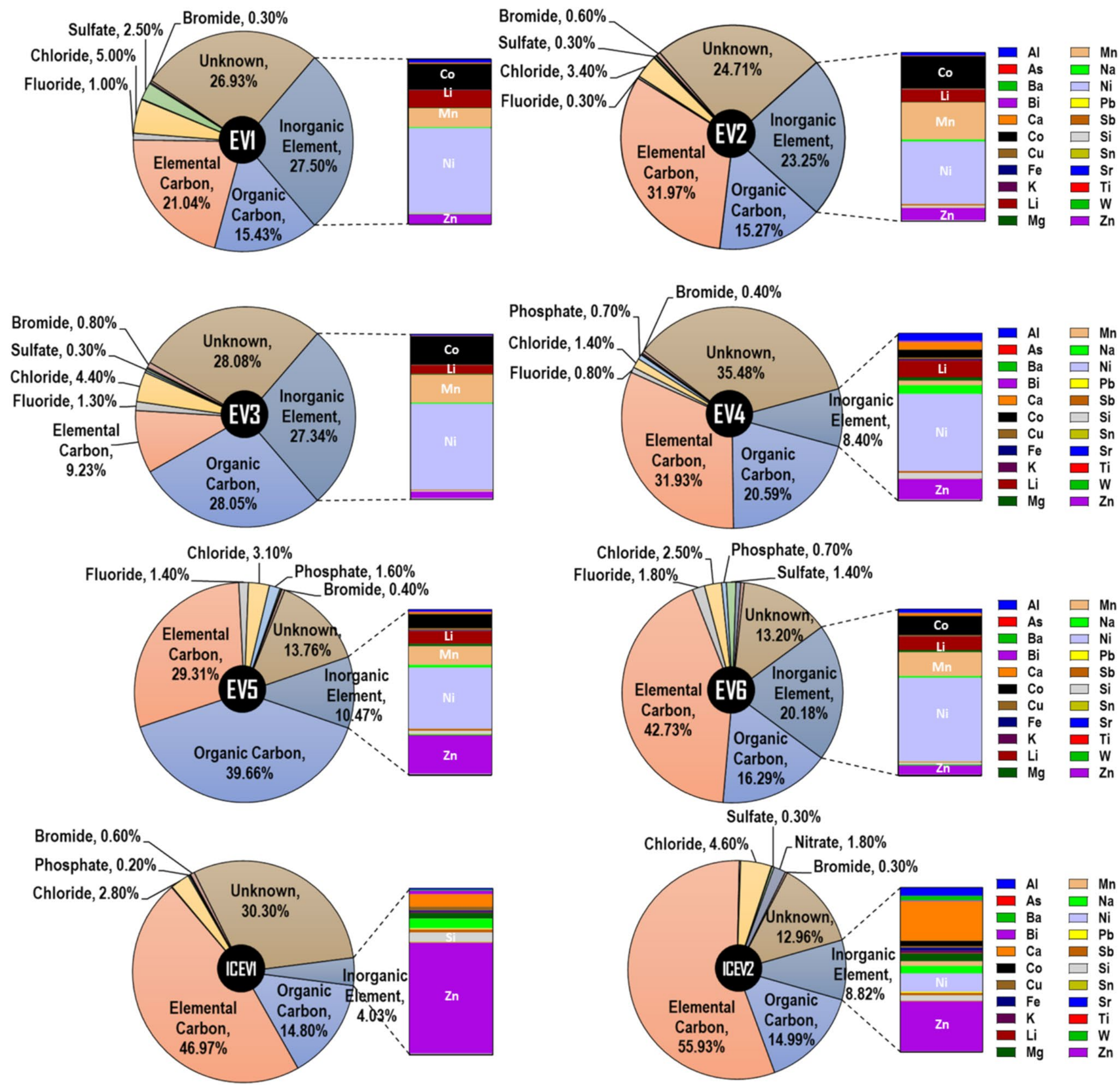

Fig. 2 Mass balance of major chemical components of smoke PM samples from EV and ICEV fires. Unknown: unquantified oxygen and hydrogen derivatives. EV6 and ICEV1 were the same vehicle model but with different propulsion systems

fraction of inorganics was largest in the smoke sample from the EV1 fire (27.5%) and the lowest mass fraction was measured in the EV4 sample (8.4%), but their mass fractions were still higher than the average mass fractions (6.4%) of two ICEV smoke samples. This difference can be explained by the fact that lithium-ion batteries account for about 20% of the EV's weight, such that fires in EVs release more metals associated with the battery burns. Interestingly, mass fractions of inorganic elements in the smoke samples from the burning of EV4 and EV5 that had relatively high-energy capacity batteries (> 80 kWh) were noticeably lower than other EV smoke samples (9.4% vs. 24.6%). It was assumed that the mass yield of inorganic elements would be primarily dependent upon battery capacity, where increasing capacity would result in increased mass yields. However, our findings illuminate that other factors such as battery chemistry (e.g., cathode and anode materials), battery enclosure design and materials, cell form factor, and battery integration into the vehicle chassis likely play a significant role in mass yields released into the surrounding environment.

While the ICEV smoke samples had lower levels of metals than the EV smoke samples, they contained the largest fraction of Zn. It has been well reported that Zn is a chemical compound commonly used as an antiwear/antioxidant additive in engine oils, transmission fluids, and hydraulic oils to protect ICE systems (da Cruz et al. 2021; Ferguson et al. 2015; Li et al. 2019; Zięba-Palus and Kościelniak 2000). This difference in metal profiles can be clearly observed in samples collected from burning the same vehicle model with different propulsion systems (EV6 vs. ICEV1), suggesting that ICEV fires are not simply less impactful on metal emissions but rather produce unique heavy metal (mainly Zn) profiles that could negatively affect human health (Lönnermark and Blomqvist 2006). This provides scientific evidence that the propulsion system is a key factor influencing smoke characteristics. Moreover, understanding differences in chemical components of EV and ICEV fires is important because it can provide protective strategies or interventions to reduce exposure and to minimize the health effects of smoke emissions from different vehicle fire events. It is well established that exposures to zinc oxide smoke (or Zn fume) can lead to local inflammation in the lungs as well as systemic inflammatory responses (Krabbe et al. 2023; Rohrs 1957; Szűcs-Somlyó et al. 2023; Yang et al. 2021). While Zn-rich smoke emissions from ICEV fires can pose substantial health risks, more attention should also be given to the other metal oxides (NiO, MnO, and Li_2O) emitted from EV fires because their mass fractions of PM reached up to 30%. This is significantly higher than metal mass fractions measured from various other types of combustion smoke emissions (e.g., wildfire smoke, burn pit smoke, coal power plant smoke) (Gilmour et al. 2004; Kim et al. 2021, 2018). There have been numerous studies that examined inhalation toxicity of NiO, MnO, and Li_2O particles (Bergström 1977; Dunnick et al. 1988; Greenspan et al. 1986; Rebar et al. 1986). Similar to ZnO, their exposures may also increase potential risks to several major organs beyond the respiratory system through mechanisms involving oxidative stress, inflammation, and DNA damage.

Notably, not only were larger mass fractions of the metals detected, but we also found that EV fires generated considerable amounts of fluoride (up to approximately 2% of PM mass) compared to ICEV fires. Fluoride particulate in the smoke emission is generally of concern because it can form hydrofluoric acid (HF) on contact with water. Regardless of the route of exposure (e.g., inhalation or dermal exposure), fluoride particulate could elicit adverse effects or exacerbate the effects from concomitant exposure (Lee and Jeong 2021). While there are no studies directly demonstrating inhalation exposures to fluoride particulate or HF from Li-ion battery fires or EV fires, a few studies reported adverse health effects from fluoride in factory workers at various industrial sites (Ando et al. 2001; Choubisa and Choubisa 2016; Song et al. 2025). Note that the nitric acid digestion method was used to solubilize chemicals in the smoke PM samples in the present study, but it did not fully dissolve all components, resulting in unidentified substances accounting for approximately 13–35% of the PM samples that were likely to be carbonaceous and ionic species composed of nitrogen, oxygen, and hydrogen derivatives (Cho et al. 2009; Kim et al. 2022). Taken together, our findings indicate that the chemical profiles of the smoke PM emitted from vehicle fires were varied with respect to vehicle models but were impacted more by different powertrains (electric motor vs. internal combustion engine). Regardless of the powertrain, adequate occupational safety and health measures should be in place to reduce exposures to the particulate portion of the smoke during all vehicle fire events.

EV and ICEVs fire smoke show distinct mutational signatures

Alongside investigating chemical differences of the smoke PM from EV and ICEV fires, we also sought to determine how differences in organic materials present in the smoke PM contribute to different mutagenic effects. Mutation spectra of organics from the EV and ICEV fire smoke emissions are shown in Fig. 3 and **Supplementary Table S4**. In the present study,

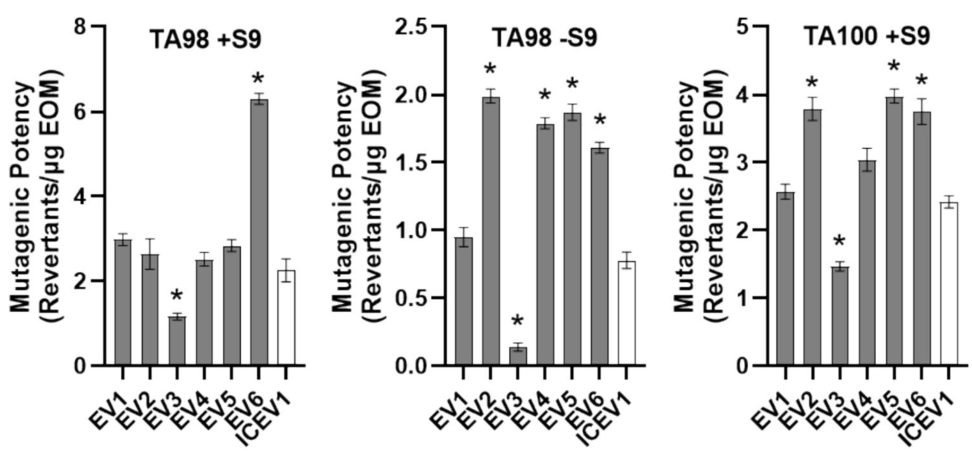

Fig. 3 Mutagenic potency of EOM from EV and ICEV fire smoke samples in the TA98 ± S9 and TA100 + S9 *Salmonella* strains. EV6 and ICEV1 were the same vehicle model but with different propulsion systems. Data are presented as mean ± SEM. *$p < 0.05$ compared with the ICEV1

mutagenic potency is a measure of how many mutant colonies (revertants) of *Salmonella* bacteria are produced per µg of EOM in the EV and ICEV fire smoke PM. These mutagenic potency measures have previously been shown to positively correlate with PAHs, nitroarenes (nitro-PAHs), and aromatic amines in smoke PM samples from various sources (DeMarini and Linak 2022; Kim et al. 2021, 2018). Aromatic amines and nitroarenes induce frameshift mutations through the addition or deletion of one or more DNA bases and this process can be detected by the TA98 strain, specifically while TA98 with S9 activation can acetylate aromatic amines into acetylated aromatic amines which can bind to DNA (typically guanine) forming DNA adducts, in the absence of S9, this strain is sensitive to the mutagenicity of nitroarenes (direct-acting mutagens). It is reported that nitroarenes are derived mostly from the combustion of carbonaceous materials and are associated with lung cancer risk (Tokiwa and Sera 2000; Zhang et al. 2021). Among organic chemicals, PAHs play a predominant role in base substitution mutations where one nucleotide (e.g., guanine) is replaced by another (e.g., thymine) resulting in a single amino acid change in the protein (mutation). This is processed by the error-prone DNA polymerase (pKM101) and can be detected by the TA100 strain in the presence of S9 (DeMarini and Linak 2022). This mutation (a guanine to thymine base substitution) has been found to be associated with the *TP53* and *KRAS* genes in lung cancer patients exposed to PAH-rich coal smoke (DeMarini et al. 2001). Although comparing mutation spectra of a mutagen (e.g., nitroarenes) in TA98 to those of the agent in other systems (e.g., mammalian cell, rodent, and human systems) have not been proven, numerous studies have demonstrated the same primary class of base substitution induced by a variety of mutagens (e.g., PAHs) across species, from bacteria to humans (DeMarini 2000; Dogliotti et al. 1998), suggesting that our findings could provide insights to understand mutation spectra between TA100 and the *TP53* gene in human tumors.

In this study, the EV6 smoke sample showed the highest mutagenic response in strain TA98 with a metabolic activation, while more direct mutations in the form of frameshift mutations were observed from the EV2, the EV4, the EV5, and EV6 samples. All of these responses on an equal EOM mass basis were significantly higher than the mutagenic potency of the ICEV1 smoke sample, indicating that aromatic amines and nitroarenes played a greater role in the mutagenicity of the EV smoke samples (except EV3). Three EV smoke samples (EV2, EV5, and EV6) also had the highest mutagenicity in the strain TA100 + S9, indicating a dominant role of PAHs in these samples. Note that the present study was limited to measuring total organic carbon which does not specify organic species (e.g., PAHs) in the smoke samples. While this is an analytical limitation of this study, it is well documented that much of the mutagenicity and carcinogenicity of PM from various combustion emissions (e.g., diesel exhaust, cigarette smoke, charcoal smoke) is mostly associated with organic extracts (primarily PAHs, aromatic amines and nitroarenes). These organic compounds have been associated with a variety of health effects like neurological disorders, cardiovascular issues, and cancer susceptibility (Boström et al. 2002; DeMarini and Linak 2022; Mallah et al. 2021; Olasehinde and Olaniran 2022). Overall, most of the smoke samples from EV fires in this study, specifically EV6, appeared to contain more organic components associated with both direct- and indirect-acting mutagens, compared to the ICEV fire smoke.

In addition to the mutagenic potency expressed as mutagenicity per mass of EOM, we calculated the mutagenicity score (MS) of each smoke sample to understand the relative mutagenic effects (Fig. 4). The highest MS was obtained from the EV6 smoke sample, followed by the EV5, the EV2, the EV4, and the EV1 samples. All five of these EV smoke samples generated a higher MS than the ICEV1 sample. Consistent with the relatively lower level of mutagenicity in all strains, TA98 ± S9 and TA100 + S9 (Fig. 3), the EV3 smoke sample had the lowest calculated MS. Although we did not directly measure PAHs and PAH derivatives from EV and ICEV fire smoke, we previously demonstrated a strong correlation between mutagenic potency and PAH emissions from the burning of anthropogenic materials (Kim et al. 2021). A few studies have also shown that notable amounts of PAHs are found in combustion byproducts from Li-ion battery fires (Bordes et al. 2024; Held et al. 2022). Because EV6 and ICEV1 share the same vehicle platform but use different propulsion systems, our findings from the mutagenicity assay support the notion that vehicle fires involving Li-ion batteries can produce more mutagenic organic compounds (e.g., PAH derivatives) than ICEV fire smoke, potentially leading to more genotoxic and ultimately carcinogenic effects in humans.

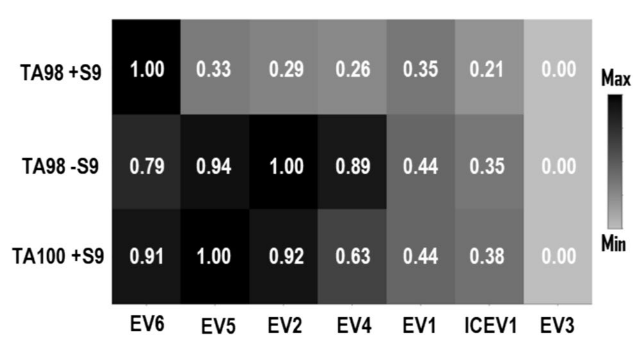

Fig. 4 Mutagenicity score (MS) of each smoke sample from EV and ICEV fires. A higher score indicates intensified mutagenicity. Total mutagenicity scores (TMS) of the EV6, the EV5, the EV2, the EV4, the EV1, the ICEV1, and the EV3 smoke samples are 2.70, 2.27, 2.21, 1.78, 1.23, 0.94, and 0.00, respectively. EV6 and ICEV1 were the same vehicle model but with different propulsion systems

While the EV fire smoke samples were found to be more mutagenic than the ICEV fire smoke, it is also important to compare their mutagenicity with other types of combustion emissions published in the literature (DeMarini and Linak 2022) (Fig. 5). Interestingly, the EV3 smoke sample, which is the least mutagenic sample in this study, was still more mutagenic than smoke emissions from the combustion of residential woods, natural gas and biodiesel on an equal EOM mass basis. Since combustible materials of ICEVs include plastics, engine fluids, and the fuel system, the mutagenic potency of the ICEV1 fire smoke was found to be similar to that of smoke from the kerosene fires and also fell between the mutagenic potencies of the crude oil and the plastic burns. Although most mutagenic potencies of the EV fire smoke samples (EV1, EV5, EV2, and EV4) in the present study were lower than that of smoke from the plastic and petroleum diesel fires, the EV6 smoke sample elicited a much higher mutagenic response. Considering this wide range of results, further studies are needed to elucidate the relative impact of battery type (e.g., chemistry and energy capacity), battery construction, and battery enclosure design on PM-associated mutagenicity. Nevertheless, the potential mutagenicity of vehicle fire smoke, regardless of the powertrain, should not be underestimated. Our sample size was small, so additional mutagenetic evaluations of vehicle fire smoke would help validate these findings.

While some of the mutagenic potentials were likely due to the PAH composition of the smoke, many PAHs are also generally anticipated to be human carcinogens which can cause DNA mutations upon prolonged exposure; however they can also cause respiratory problems even after a short period of exposure. Previously, we found that PAH levels of combustion smoke PM were positively correlated with inflammatory responses in the lungs (Kim et al. 2021, 2018). Importantly, we also demonstrated that PM-associated heavy metals were key drivers for severe lung toxicity outcomes when they accounted for a substantial fraction of PM mass (e.g., > 20%) (Kim et al. 2022). Note that a limitation exists as adverse effects of EV fire smoke PM on the lungs were not assessed explicitly in the present study. Despite this limitation, the chemical analysis results with the large mass fractions of the metals (> 10%) in the smoke samples suggest that the EV fire smoke, even smoke from the EV3 fire that had the lowest mutagenic potency, could have a greater potential to cause inflammation in the lungs than the ICEV smoke sample. Taken together, when compared with previous studies which mainly focused on analyzing chemical components of EV fire smoke emissions (Arvidson and Westlund 2023; Chiu et al. 2025; Hynynen et al. 2023; Kang et al. 2025; Sturm et al. 2022; Zhao et al. 2024), our study has several innovative aspects, both technically and scientifically, including simulation of full-scale EV and ICEV fires and evaluation of mutagenicity following exposure to the smoke PM, particularly in comparison to combustion byproducts from various sources, all aimed at understanding the potential genetic impact of EV fire smoke exposure which is essential for creating safety guidelines and regulations.

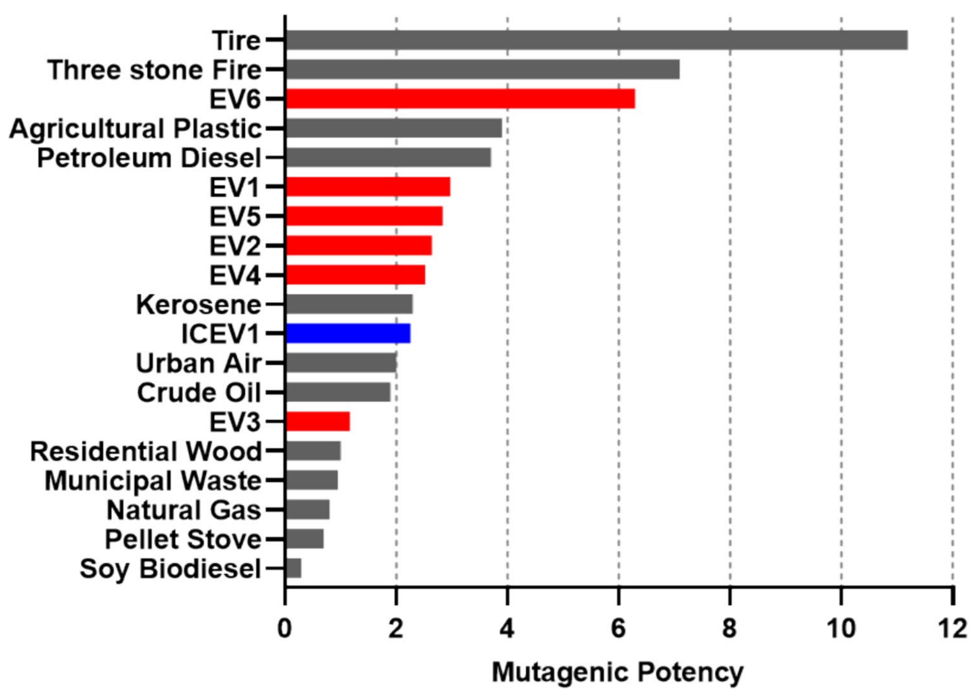

Fig. 5 Comparison of mutagenic potency of EOM in the TA98 + S9 *Salmonella* strain from a variety of combustion emissions. Data for the combustion smoke emissions except for the EV and ICEV fires are obtained from the published literature (DeMarini and Linak 2022). EV6 and ICEV1 were the same vehicle model but with different propulsion systems

Conclusions

We demonstrated that the smoke PM collected from full-scale EV fire tests contained large amounts of metals (mostly Ni, Mn, Co, and Li) accounting for up to 28% of the mass, but much lower mass fractions (4–9%) of metals (mostly Zn) were measured in the ICEV fire smoke PM. Moreover, most of the EV fire smoke PM tested here produced greater mutagenic potencies than the ICEV fire smoke sample. Our findings suggest that exposure to EV fire smoke emissions (associated with metals, fluoride particulate, PAHs, and other organic compounds) may pose a wide range of short- and long-term health risks, but these health consequences could vary depending on vehicle models and battery design. More research is needed to understand how battery design, chemistry, housing, and other materials impact the mutagenic potential of vehicle fire smoke. Notably, the organic composition contributing to this increased mutagenic potential from EV fires is not fully understood, which may require more careful consideration of potential health risks associated with long-term exposures. There are likely organic compounds other than PAHs that contributed to the mutagenicity of the EV fire smoke PM. Moreover, our mutagenic assays did not evaluate the mutagenic potential from inorganic elements. The higher quantities of metals in the EV fire effluent would likely increase the mutagenic potential of the smoke even more. Because of the chemical complexity, it is important to understand the proper level of personal protective equipment (PPE) worn for both EV and ICEV fires. Selected PPE that offers protection from metals or fluoride compounds can reduce exposure to high levels of the unique hazards emitted from EV fires, though there are other hazards present in both EV and ICEV fires that are not characterized here. Further research is needed to understand tactics and appropriate PPE to protect first responders from all vehicle fire hazards, particularly since some chemicals, when in contact with water, could form reactive and hazardous compounds (e.g., hydrofluoric acid). Collectively, our results address the timely issue of potential health effects from EV fire emissions and can inform air quality managers, health and fire service professionals about the appropriate measures to mitigate risks and provide public safety education in the event of EV fires.

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Declarations

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