Environmental Chemistry Letters (2024) 22:941–944
https://doi.org/10.1007/s10311-023-01676-1

EDITORIAL

Ozone poisoning in research laboratories and in the industry

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Published online: 28 December 2023

While outdoor ozone is known to be either beneficial or detrimental, indoor ozone is an overlooked issue that might have recently amplified in research laboratories during the coronavirus 2019 pandemic. Here we discuss ozone formation, ozone in research, health risks, poisoning incidents, and guidelines for safety in laboratories.

Good up high, bad nearby

While stratospheric ozone in the upper atmosphere plays a vital role in absorbing harmful ultraviolet radiation from sunlight, tropospheric ozone at ground level is a major air pollutant and greenhouse gas, impacting Earth's radiative forcing and causing harm to terrestrial vegetation and human health (Zhang et al. 2022). Anthropogenic emissions are the most important source of tropospheric ozone, which is produced by photochemical reactions involving nitrogen oxides and volatile organic compounds under the sunlight (Li et al. 2021). Tropospheric ozone precursors include fossil fuel combustion, industrial activities, and automobile emissions (Dewan and Lakhani 2022). Standards for ground-level ozone pollution include an 'information threshold' of 180 µg/m3 and an 'alert threshold' of 240 µg/m3 for one-hour average ozone concentration (EEA 2014). Whereas outdoor ozone issues are publicly well-known, much less attention has been paid to indoor ozone, notably in laboratories (Fig. 1). Health Canada recommends a residential maximum ozone exposure limit of 40 µg/m^3 (20 ppb), based on an averaging time of eight hours (Health Canada 2010). Therefore, it is important to handle ozone in indoor laboratory spaces with due care and responsibility.

Ozone in research

While ozone has been used for disinfection purposes for over a century, the recent coronavirus disease 2019 pandemic has prompted numerous researchers to study plasma or ozone technology for virus disinfection, resulting in about 480 research publications focused on plasma or ozone-based disinfection or sterilization techniques in the Clarivate database (Wang and Chen 2020; Blanco et al. 2021; Chen et al. 2022a, b; Cheng et al. 2020; Volkoff et al. 2021; Zhang et al. 2021; Zucker et al. 2021, Clarivate 2023). In particular, cold plasma appears as a promising solution for treating air, water, and soil due to its ability to efficiently degrade contaminants and inactivate pathogens (Asilevi et al. 2021; Aggelopoulos 2022). Nonetheless, the use of non-thermal plasma actuators could induce unintended ozone production. According to Hong et al. (2014), non-thermal plasma actuators with a surface dielectric barrier discharge design can produce up to 21.2 g of ozone every hour per kilowatt of power dissipation. This rate implies that a single non-thermal plasma actuator, with a typical power dissipation of 10 watts, would generate 0.212 g of ozone per hour. In a research laboratory measuring 100 square meters with a ceiling height of 3 m, the ozone concentration could reach 700 µg/m^3 if the laboratory has a one-hour buildup of ozone concentration in the ambient air. This concentration is almost triple the European Union's Air Quality Directive's 'alert threshold' for the one-hour average of ground-level ozone pollution. Therefore, adverse health effects of high ozone concentrations in the laboratory are probably overlooked.

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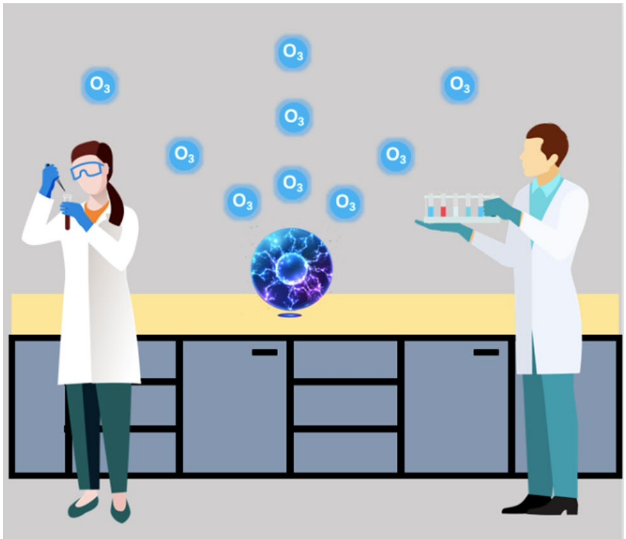

Fig. 1 A laboratory plasma device releases ozone into the ambient air

Health effects

Inhaled ozone is a harmful air pollutant inducing adverse health impacts (Fig. 2). Ozone affects the human respiratory tract by weakening immune responses, impairing lung function, and elevating the risk of asthma (Yu 2019). Short-term exposure to ozone results in coughing, wheezing, and the exacerbation of asthma, particularly for individuals with pre-existing respiratory conditions (Goodman et al. 2018). Long-term exposure to ozone contributes to the development of asthma (Zhang et al. 2019). Furthermore, in indoor environments, ozone can interact with various indoor air pollutants, giving rise to potentially harmful byproducts. Therefore, indoor ozone levels should be closely monitored to ensure the safety of workers.

Age and gender

In general, adults are more sensitive to ozone exposure than children, and this difference may be due to the longer time children require to react to ozone stress (Lu and Yao 2023). Conversely, the elderly show higher tolerance compared to adults and children, possibly due to age-related pulmonary hypofunction (Lu and Yao 2023). Females exhibit higher susceptibility to short-term ozone exposure, in agreement with animal experiments on rats (Chen et al. 2022a, b; Silveyra et al. 2021). A recent study in Shenzhen, China showed that ozone inhalation is more strongly associated with respiratory diseases in female than in male, which may be related to the estrogen levels and the differential regulation of lung immune response (Lu and Yao 2023).

Ozone poisoning incidents

Incidents of ozone poisoning due to improper operation or equipment failure are well known. In 2015, the Bernalillo County Water Authority in Albuquerque, New Mexico faced fines exceeding $144,000 due to multiple violations, with the most severe being related to hazardous ozone exposure among its employees (NM political report 2015). In 2021, a

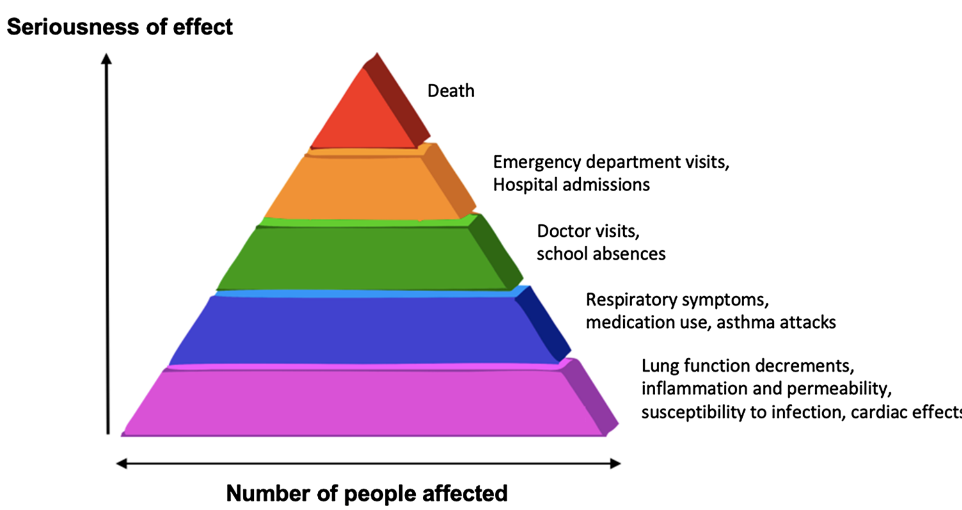

Fig. 2 The pyramid of effects caused by ozone illustrates that the least serious and most common health effects are experienced by many individuals, shown at the bottom of the pyramid. Fewer individuals experience the more severe effects, such as hospitalization or death, highlighting the varied spectrum of health outcomes associated with ozone exposure. This emphasizes the prevalence of less severe effects compared to the relatively rare occurrences of severe consequences. Redrawn based on EPA (2023a)

company in Fresno, California faced a lawsuit following an incident where two employees were injured due to an ozone leak at a water treatment plant (The Fresno Bee 2021).

Ozone-related incidents also frequently appear in the headlines in China. For instance, in 2009, an ozone poisoning incident occurred at a dairy factory in Harbin, China, sending 11 people to the hospital (DBW 2009). In 2013, an overdose of ozone in a public swimming pool poisoned 19 people in Wuhan, China, eight of whom were seriously injured (China News 2013). In 2022, a female worker at a factory in Hunan province in China was poisoned due to an unexpected operation of ozone disinfection equipment (HPHCC 2022). Taking into account the economic burden associated with ozone exposure, a nationwide study in Italy estimated that ozone exposure in 107 provinces across the country from 2015 to 2019 resulted in 70,060 deaths and $65 billion economic loss or about 0.5% of its national GDP during the study period (Wen et al. 2022). An earlier study in China estimated that life loss related to ozone pollution could amount to 2,300 billion CNY or equivalent to 2.7% of the national GDP in 2030 (Xie et al. 2019).

Improving safety

First, laboratories need to comply with the occupational safety and health administration. For example, workers should not be exposed to an average concentration exceeding 0.10 ppm, or about 200 µg/m^3, over an 8-h period (EPA 2023b). Next, incorporate engineering controls, process optimization, and robust equipment maintenance to minimize ozone production. Ozone levels in ambient air should be continuously monitored in plasma laboratories, and safety practices such as wearing personal protection equipment should minimize unsafe ozone exposure. Efficient ventilation systems and air quality management should prevent ozone buildup in indoor spaces. Laboratory managers should also take into account the age and gender-specific susceptibility of ozone exposure to ensure the safety of all team members.

Author contributions AA, CW, HS have written the first draft. JH and EL have revised the text and redrawn the figures.

Funding The authors have not disclosed any funding.

Declarations

Conflict of interest The authors have not disclosed any competing interests.

Ethical approval JH and EL are Chief Editors of Environmental Chemistry Letters.

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