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Review Article

Smog induces oxidative stress and microbiota disruption

Tit-Yee Wong*

Department of Biological Sciences, University of Memphis, Memphis, TN 38120, USA

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ABSTRACT

Smog is created through the interactions between pollutants in the air, fog, and sunlight. Air pollutants, such as carbon monoxide, heavy metals, nitrogen oxides, ozone, sulfur dioxide, volatile organic vapors, and particulate matters, can induce oxidative stress in human directly or indirectly through the formation of reactive oxygen species. The outermost boundary of human skin and mucous layers are covered by a complex network of human-associated microbes. The relation between these microbial communities and their human host are mostly mutualistic. These microbes not only provide nutrients, vitamins, and protection against other pathogens, they also influence human's physical, immunological, nutritional, and mental developments. Elements in smog can induce oxidative stress to these microbes, leading to community collapse. Disruption of these mutualistic microbiota may introduce unexpected health risks, especially among the newborns and young children. Besides reducing the burning of fossil fuels as the ultimate solution of smog formation, advanced methods by using various physical, chemical, and biological means to reduce sulfur and nitrogen contains in fossil fuels could lower smog formation. Additionally, information on microbiota disruption, based on functional genomics, culturomics, and general ecological principles, should be included in the risk assessment of prolonged smog exposure to the health of human populations.

1. How smog is formed

Smog is an irritating mixture of gasses and particulates in the air formed by smoke and fog under the sun. Formation of smog is directly related to the weather and the topography of the land [1]. Air temperature decreases at about 6.4°C per kilometer in climbing altitude. Under normal conditions, warmer air on the ground rises to the upper atmosphere continuously. This constant air movement spreads pollutants around and thus prevent smog to accumulate on the ground. Sometimes, the temperature gradient is reversed; and the air on top is warmer than the air below it, a phenomenon called temperature inversion [2,3]. Temperature inversion can happen in many ways. When a warm and less dense air mass moves over a cold and dense air mass, or when warm air moves across a cold ground, the air temperatures near the

* *Corresponding author*. Department of Biological Sciences, University of Memphis, LS Building, 3798 Walker Avenue, Memphis, TN 38120, USA.
E-mail address: tywong@memphis.edu.
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ground, the troposphere, can be cooler than the air temperature above it. When an atmospheric inversion layer is closer to the ground, it works like a lid to prevent air upflow that spreads and dilute the pollutants. Temperature inversion explains why wintertime weather often favors smog formation on the ground [4]. The landscape of the land also plays a role in creating temperature inversion. When cold air from mountain peak flows down into valleys, the cold air pushes the warmer air in the valleys upward, creating an inversion. Because of their geographical location (they are built on low basins or valleys), cities such as Los Angeles [5], London [6], Taipei [7], Beijing [8], Tehran [9], and Mexico City [10] are prone to smog accumulation.

Smog can form naturally. Plants emit a plethora of volatile organic compounds (VOCs) as a defensive mechanism against herbivore attack [11]. Upon reaction with the sunlight, VOCs become a major source of ozone (O_3) in the atmosphere [12–14]. Volcano eruption produces airborne ash and gasses with high concentrations of SO_2 and H_2S [15,16], which can contribute to smog formation. Likewise, forest fire also produces a significant amount of smog [17,18]. The 2015 massive fires in Sumatra and Kalimantan in Indonesian Borneo, for example, has produced a persistently hazardous air pollution across downwind Indonesia, Malaysia, and Singapore. It was estimated that the toxic haze from this fire has caused more than 100,000 premature adult deaths in areas closest to the blazes [19]. These pollutants have been related to childhood leukemia [20].

Smog is also anthropogenic. The first and second industrial revolutions have replaced manpower with machines in many production processes. The increase in production of goods and expansion in human population has changed the ways we communicate. The transportation evolution allows massive and rapid transfer of humans and goods. The energy generated from burning coal and other fossil fuels have replaced the traditional source of energy provided by animals. However, coal burning causes the pollution of the air. In 1948, for example, severe industrial air pollution created a deadly smog in Donora, Pennsylvania, which made thousands of people sick [21]. Similarly, in 1952, smog from factories and home fireplaces killed at least 4000 people in London over the course of several days [22–24]. Nowadays, cars, trucks, trains, airplanes, and ships are the major means of transportation on land, air, rivers, canals, and seas. They have become major sources of air pollution [25–31]. Human population expansion also complicates the air quality. Treatment of human wastes, such as incinerators, landfills, and sewage treatment plants, produces various toxic gasses that are air polluting [32–35]. More than 100 toxic gasses are released from landfills [36,37]. Some of them, such as methane and hydrogen sulfide, are most abundant. Others, such as those polyaromatic hydrocarbons and polychlorinated biphenyl released in landfill fires and incinerators, are carcinogenic [38]. Toxins leachates from landfills are a potential pollutant to ground waters [39].

2. Sources of pollutants

It is important to identify where the pollutants are released to the air. Pollutants generated from stationary sources, such as power plants, industrial and commercial boilers, paper and wood mills, smelters, refinery processing plants, chemical processing plants, and petroleum storage tanks, are considered point-source air pollution. The nonpoint source of air pollution includes some stationary and mobile sources that are individually small, but collectively, they generate a large volume of pollutants. Wood stoves, motor vehicles, ships and boats, and controlled burning of farm wastes by farmers are considered nonpoint sources of air pollution. Since 1972, The U.S. Environmental Protection Agency (EPA) has categorized information of different industrials and compiled them in its so-called AP-42 report [40,41] to regulate the emissions factors of the air of the United States.

The Clean Air Act passed by the U.S. Congress in 1970 and amended in 1990 sets limits on how much of a pollutant is allowed in the air in the United States [42]. The EPA has set national air quality standards for six major air pollutants: carbon monoxide (CO), lead (Pb), nitrogen oxides (NO_x), ozone (O_3), sulfur dioxide (SO_2), and particulate matters (PMs). Whereas CO, Pb, NO_x, and SO_2 are the results of direct emissions from a variety of sources, the formation of PMs is the result of direct emissions and aggregates of emitted gasses in the atmosphere. Most of the fine particle pollutants are aggregated through a complex interaction of VOCs and sunlight. Sunlight also activates the reaction between NO_x and VOCs, leading to the formation of O_3. Because O_3 is not produced directly from emission, O_3 in the troposphere is often referred as secondary pollutant [43].

The EPA refers to chemicals that cause serious health and environmental impacts as air toxics. Many chemicals (total of 187), such as benzene, chloroform, acetaldehyde, dioxin, polycyclic organic matter, chromium, lead, nickel, and mercury compounds, are recognized among the many air toxics. Air toxics can cause cancer and other serious health, including human reproduction, and birth defects. Air toxics also cause adverse environmental and many ecological problems [44].

We briefly introduce the six main air pollutants related to human health.

VOCs are produced from trees, plants, cars, or industrial emissions. VOCs react with nitrogen oxides in the presence of sunlight to form ground-level ozone, a primary ingredient in smog. Many VOCs have been linked to birth defects, cancer, and other serious illnesses [45]. For example, polycyclic aromatic hydrocarbons, a common product of biomass combustion [46], is highly genotoxic [47]. Benzene in the air is strongly correlated to childhood leukemia [20]. The EPA estimates that the air toxics emitted from cars and trucks—which include benzene, acetaldehyde, and 1,3-butadiene—account for half of all cancers caused by air pollution. VOC emissions are tracked by the National Emissions Inventory [48,49].

Nitrogen oxides (NO_x). Nitrogen can combine with oxygen in many forms, such as nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O). NO_x is a generic term for NO and NO_2 [50]. While lighting, free-living bacteria and symbiotic nitrogen-fixing bacteria can produce NO_x naturally [51]; combustion of nitrogenous containing compounds, such as the burning of coal, oil, or natural gas, and during processes such as arc welding, electroplating, engraving, and dynamite blasting, can produce NO_x [52]. The toxicity of NO_x has been well studied [53–55]. NO_x not only causes lung irritation and