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Review article

Human health and environmental impacts of coal combustion and post-combustion wastes

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ABSTRACT

Due to its high energy generation potential, coal is widely used in power generation in different countries. Although, the presence of carbon, hydrogen and sulfur in coal facilitates the energy generation in coal combustion, some pollutants including COx, SOx, NOx, particulate matter (PM) and heavy metals are accumulated in air and water and lead to severe environmental and health impacts as a result of leaching, volatilization, melting, decomposition, oxidation, hydration and other chemical reactions. In addition, fly ash, in both wet and dry forms, is mobilized and induces severe impacts including bone deformities and kidney dysfunction, particularly with exposure of radionuclides. This review will cover the impact of these major pollutants (including COx, SOx, NOx, PM, and heavy metals (traces)) on human health and the environment. Given the lack of adequate data about the cumulative health based impacts of these pollutants from coal combustion, this review can be used as a significant tool to further explore disease-association risks and design standard management protocols to overcome coal associated health and environmental assaults.

1. Introduction

Coal, currently the largest source of energy on earth, is used extensively in electricity generation in different countries (Nataly Echevarria Huaman and Xiu, Jun. 2014). Coal was formed over many years by dead plants through the process of coalification. Carbon, sulfur, oxygen, hydrogen, small amounts of nitrogen and some traces of heavy metals are the main components of coal. The burning of coal leads to the emission of poisonous gases with underlying health impacts and environmental problems (Clancy et al.; Katsouyanni et al., 2001; Gent et al., 2003). In coal combustion, the carbon, sulfur, and nitrogen react with oxygen and produce their respective oxides: carbon dioxide (CO_2) and carbon monoxide (CO), sulfur dioxide (SO_2) and sulfur trioxide (SO_3), and nitrogen dioxide (NO_2) and nitric oxide (NO), respectively. The emission of these gases has been correlated with many health problems directly and indirectly, including skin, cardiovascular, brain, blood and lung diseases, and different cancers (Badman & Jaffé, 1996; Cornell, 2016; Bascom et al., 1996; Kelsall, Samet, Zeger, & Xu, 1997; Health effects of outdoor air pollution. Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society 1996; Pope III et al., 1995). For example, CO enters into the blood stream and reacts with hemoglobin and reduces the formation of oxy-hemoglobin complex by decreasing its ability for O_2 transformation (Badman & Jaffé, 1996). Hence, the CO can alter biological functions at the cellular level and cause many abnormalities including slow reflexes, and coagulation confusion or disorders. Both CO and CO_2 cumulatively have harmful impacts on the environment in the form of global warming and greenhouse gases (GHG) emission. The CO_2 emission from coal combustion, during power generation, also leads to the interaction of CO_2 with particulate matter (PM 2.5), which thereby changes the air quality and leads to increased asthma attacks and other respiratory and cardiovascular diseases with underlying poor life expectancy rates. Inhaling particulate matters may cause some dangerous diseases, including chronic obstructive pulmonary disease (COPD) and lung cancer (Cornell, 2016).

The sulfur, in coal, oxidizes upon combustion and pollutes the air, water, and land by releasing SOx (SO_2, SO_3, SO_3^{2-} and H_2SO_4). The formation of the poisonous SO_2 gas, a major pollutant in air, may accelerate the rate of diseases and decrease life expectancy

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around power plants (Bascom et al., 1996; Kelsall et al., 1997; Health effects of outdoor air pollution. Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society 1996; Pope III et al., 1995). In addition to SO_2, other SOx like sulfate (SO_3^{2-}) and sulfuric acid (H_2SO_4), damages the environment in the form of acid rain. High exposure to SO_2 causes suffocation, wheezing, coughing, and reductions in lung function by affecting mucous and cellular mucins (Kelsall et al., 1997; Health effects of outdoor air pollution. Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society 1996; Pope; III et al., 1995; Bascom et al., 1996). SO_2 gas also damages nearby flora and crops, leading to leaf injury, affecting plant growth and reducing the diversity of plant species (Rajput, Ormrod, and Evans 1977; Winner, Mooney, and Goldstein 1985). SO_2 was also considered to be a strong phytotoxic gas causing acute foliar symptom injury in plants (Winner, Mooney, and Goldstein 1985; Barretti & Benedict, 1970). However, the damage caused by SO_2 in plants has not been clearly studied (Padhi, Dash, and Swain 2013; Swain & Padhi, 2015; Barretti & Benedict, 1970). Moreover, acid rain (H_2SO_4), a hydrated product of SO_3, potentially damages skin cells, destroys building material, and pervasively affects vegetation and food chain by contaminating the flora and fauna through the leaching of heavy metals (Kitamura & Ikuta, 2001; Singh & Agrawal, 2007; Thornton & Plant, 1980). Similar to SO_2, nitric oxide (NO_2), another major pollutant with highly corrosive properties and a strong oxidizing ability, is formed as a result of coal combustion in power plants and contaminates the air (Levy, Moxim, Klonecki, & Kasibhatla, 1999). NO_2 forms the most important part of acid rain, as nitrous acid HNO_2 and nitric acid HNO_3, which causes a large number of skin diseases (Singh & Agrawal, 2007). The entrance of SOx and NOx air pollutants into the blood stream and cells destabilizes normal heart beats (rhythms) and culminates in heart attacks and other heart related problems (Peters, PerzDöring, Stieber, Koenig, & Wichmann, 1999). In addition, high levels of NO_2 (>1500 mg/m^3) in the air causes a reduction in the pulmonary function in humans (Li, Liu, De, & Tao, 2001; Health effects of outdoor air pollution. Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society 1996), asthma attacks and genetic mutations (Arroyo, Hatch-Pigott, Mower, & Cooney, 1992; Isomura, Chikahira, Teranishi, & Hamada, 1984; Wink et al., 1991). The ozone gas formed as a result of NO_2 reaction with the volatile organic compounds in the air causes ozone-related asthma exacerbations in infants (Gent et al., 2003).

PM level, individually and in combination with NO_2 in air, increases the concentration of free radical based reactive oxygen species (ROS) and contributes to DNA mutation, and damage of protein and lipids which may constitutively activate membrane proteins which leads to the development of some serious diseases, including lung cancer, cardiovascular diseases and reproductive disorders (Hussain, Hoessli, and Fang 2016; Valko et al., 2007; Miller et al., 2007; Clancy et al.; Katsouyanni et al., 2001). The interaction of PM with DNA leads to the formation of DNA adducts impairing neurodevelopment, intelligence quotient (IQ) levels and intelligence in children (Edwards et al., 2010; Jedrychowski et al., 2003; Perera et al., 2008, 2012; Tang et al., 2008).

In this review, the roles of some major pollutants, produced during coal combustion, including COx, SOx and NOx, and heavy metal emissions in human diseases and environmental pollution are discussed. These pollutants are causing threats by interacting with the environment and having an impact on human health, both, directly and indirectly, by modulating the physiological changes at cellular level in all areas of life (from eukarya to bacteria) in the ecosystem.

2. Air pollution

2.1. Coal combustion and COx (CO_2 & CO) impacts on environment and health

Coal is an important source of energy around the world—approximately 41% of the world's electricity is generated from outdoor coal combustion (Nataly Echevarria Huaman and Xiu, Jun. 2014). However, indoor coal combustion is only used for domestic energy purposes. Both indoor and outdoor coal combustion contributes to environmental and health issues, even in the developed world. According to some recent studies, coal-based chemical processing releases CO_2 two to four times more than that of oil-based chemical processing (Ren & Patel, 2009). In outdoor power generation, the amount of possible heating of coal mainly depends on C, O_2 and H_2 contents and partially on SO_2. However, in different coal ranks, the ratio of these components varies. Different coal ranks have different amounts of coal: lignite coal has more than 60% carbon content and it increases to 80% for anthracite (Slatick August 1994).

During coal combustion both CO_2 and CO gases were mainly emitted as a result of oxidation and they lead to harmful impacts on the environment in the form of global warming and GHG. In addition, these gases are concomitantly correlated with many health issues directly and indirectly including malaria, cardiovascular diseases and asthma. CO_2 emissions are considered to be the main cause of about three-quarters of global GHG emission. Fossil fuels account for approximately 90% of the total global CO_2 emissions in 2011 (Olivier, Peters, and Janssens-Maenhout 2012). Due to continuous CO_2 emission and underlying climate change, global warming is correlated with increased overall incidences of flooding and hurricane activity (Gething et al., 2010; Henderson-Sellers, Zhang, Berz, & Emanuel, 1998; Pielke & Pielke, 1997; Simpson & Riehl, 1981), having a severe impact on agriculture and the food-web. Furthermore, an extremely hot climate leads to dehydration, cerebrovascular, respiratory, and cardiovascular disease in the developed world, including the US and China (Karl, 2009; Lan, Chapman, Schreinemachers, Tian, & He, 2002). Thus, the emission of CO_2 from coal causes air pollution and plays a key role in global warming and GHG, which directly and indirectly affects human health and the environment. At a cellular level, the CO combines with blood hemoglobin and reduces its efficiency and lower its capacity to transform O_2 (Badman & Jaffé, 1996) (Fig. 1A).

Climate change and underlying global warming phenomena induced by CO_2 emissions from coal combustion and several other resources, causes the death of around 1.1–1.27 million people due to malaria each year (Gething et al., 2010). The growth of *Plasmodium falciparum* is highly dependent on temperature, particularly around or less than 16 °C, and the larvae of *A. gambiae* do not grow into adults (Jepson, Moutia, and Courtois 1947), causing the mosquito to be confined to areas carrying ambient temperatures of below 40 °C (Lindsay & Martens, 1998). Hence, global worming by CO_2 emission may directly or indirectly increase malaria (Chaves and Koenraadt 2010) which is one of the major concerns in both developed and developing countries.

2.2. SOx (SO_2, SO_3^{2-} & H_2SO_4) impacts on environment and health

Sulfur is present in the form of sulfides, elemental sulfur, organic sulfur, and sulfates within coal (Ryan & Ledda, 1997). During coal combustion, the sulfur present in coal is released into the atmosphere and causes air, water and land pollution. In the majority of power plants, sulfur appears due to coal burning which is used to generate electricity. In the case of uncontrolled coal power plants, the emission of sulfur oxides and PM into the air was found to be