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Emerging developments in the standardized chemical characterization of indoor air quality

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ABSTRACT

Despite the fact that the special characteristics of indoor air pollution make closed environments quite different from outdoor environments, the conceptual ideas for assessing air quality indoors and outdoors are similar. Therefore, the elaboration of International Standards for air quality characterization in view of controlling indoor air quality should resort to this common basis. In this short review we describe the possibilities of standardization of tools dedicated to indoor air quality characterization with a focus on the tools permitting to study the indoor air chemistry. The link between indoor exposure and health as well as the critical processes driving the indoor air quality are introduced. Available International Standards for the assessment of indoor air quality are depicted. The standards comprise requirements for the sampling on site, the analytical procedures, and the determination of material emissions. To date, these standardized procedures assure that indoor air, settled dust and material samples are analyzed in a comparable manner. However, existing International Standards exclusively specify conventional, event-driven target-screening using discontinuous measurement methods for long-lived pollutants. Therefore, this review draws a parallel between physico-chemical processes in indoor and outdoor environments. The achievements in atmospheric sciences also improve our understanding of indoor environments. The community of atmospheric scientists can be both ideal and supporter for researchers in the area of indoor air quality characterization.

This short review concludes with propositions for future standardization activities for the chemical characterization of indoor air quality. Future standardization efforts should focus on: (i) the elaboration of standardized measurement methods and measurement strategies for online monitoring of long-lived and short-lived pollutants, (ii) the assessment of the potential and the limitations of non-target screening, (iii) the paradigm shift from event-driven investigations to systematic approaches to characterize indoor environments, and (iv) the development of tools for policy implementation.

1. Introduction

In new estimates, the World Health Organization (WHO) reports that in 2012 around 7 million people died as a result of air pollution exposure (World Health Organization, 2014). The estimates of the Global Burden of Disease Study 2013 are of the same order of magnitude (Forouzanfar et al., 2015). In this context the WHO Department of Public Health and Environment classifies air pollution as world's largest single environmental health risk. About 50% of the fatalities were linked to indoor air pollution, almost all in low and middle income countries (World Health Organization, 2014). According to the WHO Air Quality Guidelines, particulate matter, ozone, nitrogen dioxide, and sulfur dioxide are the key pollutants that pose health risks. Typically, occupants of indoor environments are exposed to substances that can be specifically apportioned to indoor sources. In newly industrialized countries, incomplete combustion processes in low-efficiency ovens dominate indoor air pollution. There are approximately 3 billion people without access to state-of-the-art energy sources. A considerable fraction of the world population still resorts to solid fuels like charcoal, wood, crop waste, and dung, often at indoor fireplaces (World Health Organization, 2005). Policy makers need to set priorities to face the most immediate problems related to indoor air pollution. In developing nations, standardization agencies start, e.g. with the elaboration of requirements for clean cookstoves and clean cooking solutions. In contrast, industrial nations set high standards with respect to energy-efficient buildings that are operated environmentally friendly and that provide a healthy indoor air quality for the building occupants.

Mold formation, (odor) emissions from materials or combustion processes and contaminations (e.g. asbestos, radon or persistent organic pollutants) belong to well-known indoor air pollution issues. In addition

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to direct emissions, indoor air trace constituents are also indirectly formed as products of physico-chemical processes (e.g. by reactions of trace gases or by condensational particle formation). Therefore, a decent understanding of indoor air chemistry and its relation to the parameters of building design and configuration is required for the standardization of tools for indoor air quality characterization. This, in turn, improves the planning of future buildings and their maintenance. Proper ventilation concepts can be a solution to indoor air pollution issues. However, ambient air can also contribute to the contamination of indoor air. Currently, the risk of indoor air pollution is exacerbated due to the increased demand for airtight, energy-efficient buildings.

Even though the characteristics of indoor and outdoor environments and the pollution therein are different, the conceptual ideas for assessing air quality indoors and outdoors are similar. These concepts comprise the harmonized sampling and analysis of air pollutants, the identification and characterization of sources of air pollutants, the description of transformation and transport processes using numerical models, and the implementation of measures for improving air quality. Therefore, the elaboration of International Standards for air quality characterization in view of controlling indoor air quality should resort to this common basis.

2. Internationally standardized tools for indoor air quality characterization

Ambient air quality standards have been established within the legal framework of many countries as a means to protect public health. Several countries have promulgated ambient air quality standards at the values layed down by the WHO Air Quality Guidelines for particulate matter, ozone, nitrogen dioxide, and sulfur dioxide (World Health Organization, 2005). Comparisons of different national ambient air quality standards are reported in literature (Boyd, 2006; Vahlsing and Smith, 2012). Various non-governmental standardization organizations have issued procedures for demonstrating compliance with ambient air quality standards.

On the contrary, there are no indoor air quality standards with broad legally binding force. However, the quality of air inside homes, workplaces, public buildings, and cabins of vehicles plays an essential role with regard to health and the individual well-being. Strongly growing interest in indoor air research emerged during the decade from 2001 to 2010. This tendency is reflected by the increasing number of scientific publications but also by the increasing number of International Standards (Weschler, 2011). To date, the consumer's demand is driven by health effect issues related to indoor air quality. Manufacturers of all kinds of everyday products are using product labels as marketing tool to indicate so-called 'low-emission' products. In 1994, standardization agencies all over the world started to face the regulatory developments and the market needs by establishing a dedicated committee within the International Organization for Standardization (ISO). To date the ISO compendium on the characterization of indoor air quality comprises about 50 International Standards (ISO Standards). This set of ISO Standards covers measurement planning (ISO 16000 parts 1, 2, 5, 8, 12, 15, 19, 26, 29, 34) as well as sampling and analysis of individual trace substances (ISO 16000 parts 13, 14, 31, 33, 35, 37–39). These ISO Standards specify the determination of trace gas concentrations as well as the concentration of airborne particles. Methods for the determination of chemical emissions from materials (ISO 16000 parts 3, 4, 6, 9, 10, 11, 23, 24, 25) facilitate the source apportionment of indoor air pollutants and the quantification of the respective source strengths. Material emission tests for the assessment of the interior air of road vehicles are specified by ISO 12219 parts 1 to 9. Odor nuisance (ISO 16000 parts 28 and 30), (visible) microbial infestation (ISO 16000 parts 16–21, 36) or contaminated buildings (ISO 16000 parts 7, 27, 32) are often reasons for complaints. These issues are covered by complementary ISO Standards (ISO 16000-1:2004; ISO 16000-2:2004; ISO 16000-3:2011; ISO 16000-4:2011; ISO 16000-5:2007; ISO 16000-6:2011; ISO 16000-7:2007; ISO 16000-8:2007; ISO 16000-9:2006; ISO 16000-10:2006; ISO 16000-11:2006; ISO 16000-12:2008; ISO 16000-13; ISO 16000-14:2009; ISO 16000-15:2008; ISO 16000-16:2008; ISO 16000-17:2008; ISO 16000-18:2011; ISO 16000-19:2012; ISO 16000-20:2014; ISO 16000-21:2013; ISO 16000-23:2009; ISO 16000-24:2009; ISO 16000-25:2011; ISO 16000-26:2012; ISO 16000-27:2014; ISO 16000-28:2012; ISO 16000-29:2014; ISO 16000-30:2014; ISO 16000-31:2014; ISO 16000-32:2014; ISO/DIS 16000-33:2015; ISO/AWI 16000-34:2013; ISO/AWI 16000-35:2013; ISO/CD 16000-36:2015; ISO/AWI 16000-37:2014; ISO/AWI 16000-38:2015; ISO/AWI 16000-39:2015; ISO 12219-1:2012; ISO 12219-2:2012; ISO 12219-3:2012; ISO 12219-4:2013; ISO 12219-5:2014; ISO/DIS 12219-6:2015; ISO/DIS 12219-7:2016; ISO/AWI 12219-8:2014; ISO/AWI 12219-9:2015).

3. The role of indoor air chemistry

Large amounts of volatile organic compounds (VOCs) are released into the earth's atmosphere from both biogenic and anthropogenic sources with an estimated global emission rate of the order of 10^{12}kg per year (Piccot et al., 1992; Guenther et al., 1995). Many VOCs detected in the air we breathe are toxic or carcinogenic and might cause respiratory and cardiovascular diseases (World Health Organization, 2000). The concentrations of VOCs measured in ambient air often underpredict prevailing indoor exposures (Yocom, 1982; Kostiainen, 1995; Kim et al., 2001). It was found that household air pollution and ambient air pollution contributed equally to the total number of fatalities worldwide. Though, household air pollution belongs to the characteristic health risk factors in developing nations. Especially countries with low and middle socioeconomic status bear most of the burden of disease from household air pollution (World Health Organization, 2014). Particulate matter air pollution from household use of solid fuels has recently been classified as a major risk (Forouzanfar et al., 2015).

The enormous emission rate of VOCs is balanced by an equally large destruction rate. The self-cleaning ability of the earth's atmosphere mainly arises from hydroxyl (OH) and nitrate (NO_3) radical-initiated oxidation processes, from ozonolysis and from photolysis of VOCs. OH is primarily formed by the photolysis of ozone (O_3), nitrous acid (HONO), as well as hydrogen peroxide (H_2O_2). During daytime, the OH plus VOC reaction is the most effective sink for ambient organic trace gases through oxidation processes. The OH-initiated oxidation of VOCs proceeds via radical chain reactions where OH is not consumed, but regenerated in catalytic cycles. In the presence of O_2 and depending on the respective compound, the OH plus VOC reaction yields hydroperoxy (HO_2) and/or organic peroxy (RO_2) radicals, collectively termed peroxy radicals. Peroxy radicals undergo radical-terminating reactions as well as radical-propagating reactions with nitrogen monoxide (NO) to form either OH or organic alkoxy radicals (RO) (Finlayson-Pitts and Pitts, 2000). The importance of OH is based on its high reactivity towards other trace gases, on its in-situ production in the sunlit atmosphere, and on its recycling in complex chain reactions. The major recycling pathway for OH radicals is the reaction of hydroperoxy radicals (HO_2) plus nitrogen oxide (NO) that also results in ozone production (Ehhalt, 1999).

The formation of radicals in indoor environments proceeds via similar reaction pathways. Thus, the radical-initiated (photo-)chemistry is relevant for the assessment of indoor air quality. Nevertheless, the physico-chemical boundary conditions indoors are quite different compared to those encountered outdoors. For example, indoor environments are exposed to less temperature changes and to less direct sunlight. The rate of OH formation through photolytic pathways indoors is influenced by the attenuation as well as the different spectral composition of solar radiation in indoor environments and by the prevailing concentrations of the photolyzed species (Gómez Alvarez et al., 2013). Furthermore, indoor environments are characterized by a larger