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Assessment of indoor air quality in office buildings across Europe – The OFFICAIR study

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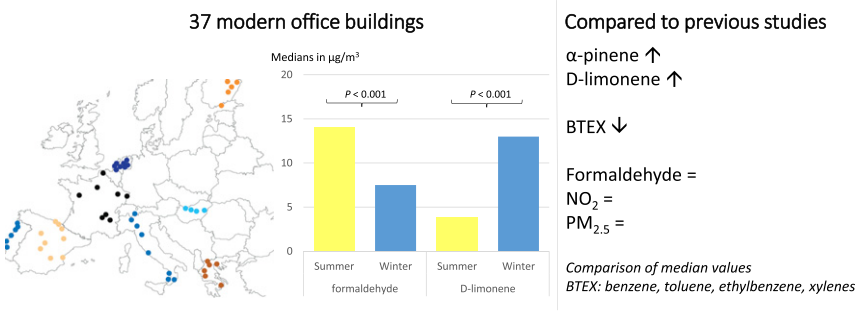
HIGHLIGHTS

- VOCs, aldehydes, O_3, NO_2 and $PM_{2.5}$ were measured in 37 office buildings in 2 seasons.
- The α-pinene and D-limonene concentrations were higher compared to those from past studies.
- The indoor concentrations in summer and winter varied significantly.
- An influence of floor level on indoor concentrations was observed for some pollutants.
- An evaluation of IAQ in terms of respiratory health effects was performed.

GRAPHICAL ABSTRACT



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ABSTRACT

The European project OFFICAIR aimed to broaden the existing knowledge regarding indoor air quality (IAQ) in modern office buildings, i.e., recently built or refurbished buildings. Thirty-seven office buildings participated in the summer campaign (2012), and thirty-five participated in the winter campaign (2012 – 2013). Four rooms were investigated per building. The target pollutants were twelve volatile organic compounds, seven aldehydes, ozone, nitrogen dioxide and particulate matter with aerodynamic diameter <2.5 µm ($PM_{2.5}$). Compared to other studies in office buildings, the benzene, toluene, ethylbenzene, and xylene concentrations were lower in OFFICAIR buildings, while the α-pinene and D-limonene concentrations were higher, and the aldehyde, nitrogen dioxide and $PM_{2.5}$ concentrations were of the same order of magnitude. When comparing summer and winter, significantly higher concentrations were measured in summer for formaldehyde and ozone, and in winter for

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VOC
Terpene
Particulate matter
Seasonal variability
Spatial variability

benzene, α-pinene, D-limonene, and nitrogen dioxide. The terpene and 2-ethylhexanol concentrations showed heterogeneity within buildings regardless of the season. Considering the average of the summer and winter concentrations, the acetaldehyde and hexanal concentrations tended to increase by 4–5% on average with every floor level increase, and the nitrogen dioxide concentration tended to decrease by 3% on average with every floor level increase. A preliminary evaluation of IAQ in terms of potential irritative and respiratory health effects was performed. The 5-day median and maximum indoor air concentrations of formaldehyde and ozone did not exceed their respective WHO air quality guidelines, and those of acrolein, α-pinene, and D-limonene were lower than their estimated thresholds for irritative and respiratory effects. $PM_{2.5}$ indoor concentrations were higher than the 24-h and annual WHO ambient air quality guidelines.

1. Introduction

A growing fraction of the active population is working in office buildings worldwide. Existing studies on indoor air quality (IAQ) in office buildings have focused on specific issues such as emissions from printers and photocopiers (Cacho et al., 2013; Tang et al., 2012), the efficiency of outdoor air filtration (Fisk et al., 2000), or hot and humid climatic zones (Zuraimi et al., 2004). Existing studies have also dealt with some specific parameters such as relative humidity (Wolkoff and Kjærgaard, 2007), man-made vitreous fibers (Salonen et al., 2009a), particulate matter (PM) (Horemans and Van Grieken, 2010) or semi-volatile organic compounds (Fraser et al., 2013; Watkins et al., 2013). The BASE (Building Assessment Survey and Evaluation) study performed in 100 office buildings across the United States over a five-year period (1994–1998) is one of the first large studies regarding volatile organic compounds (VOCs) in indoor air within offices (http://www.epa.gov/iaq/base/). In Europe, Finnish studies provided insights on VOCs, aldehydes, ammonia, and PM in office buildings (Lappalainen et al., 2013; Salonen et al., 2009b). Moreover, several EU-funded projects (IAQ-AUDIT, HOPE and AIRMEX) performed IAQ measurements in office buildings. Within IAQ-AUDIT (European Audit Project to Optimize Indoor Air Quality and Energy Consumption in Office Buildings), fifty-six office buildings in nine European countries were audited during the heating season of 1993–1994 (Bluyssen et al., 1996). The main aim was to develop assessment procedures and guidance on ventilation and source control to assure good IAQ and optimize energy use in office buildings. The HOPE (Health Optimization Protocol for Energy Efficient Buildings) project aimed to determine if energy efficiency, IAQ, comfort and occupant satisfaction can be achieved simultaneously in European buildings; IAQ measurements were performed in a subsample of two offices in the UK (Aizlewood and Dimitroulopoulou, 2006). Lastly, in the AIRMEX (European Indoor Air Monitoring and Exposure Assessment) project, hydrocarbons, aromatic compounds, alcohols, and carbonyls were monitored in the period 2003–2008 in buildings from eleven European cities, including offices (Geiss et al., 2011; Kotzias et al., 2009).

Office buildings have extensively evolved to become controlled environments with sophisticated ventilating and air-conditioning systems. However, little is known about IAQ in these so-called 'modern' office buildings. In recent years, office buildings have not been extensively studied compared to other equally important indoor environments in terms of time spent by the population, such as dwellings and schools. Moreover, in addition to the reported health effects due to indoor air pollutants (World Health Organization [WHO], 2010), the indoor environmental quality in offices may affect cognitive performance and even subclinical disturbances may lead to losses in work productivity (Wargocki and Wyon, 2013).

To increase knowledge about IAQ in modern office buildings, the European OFFICAIR project was focused on office buildings built or refurbished after 2001. The objectives were manifold (Bluyssen et al., 2016) and included three field campaigns with dedicated objectives and methods. One objective was targeted at identifying possible characteristics in terms of indoor air pollutants and/or concentrations to better understand their variabilities over time and space and to assess the associated health effects. One of the three field campaigns, namely the 'detailed study', specifically targeted this objective. It comprised IAQ measurements in office buildings distributed among the eight participating countries: Finland, France, Greece, Hungary, Italy, the Netherlands, Portugal, and Spain. The measurements were repeated in two seasons, with the heating off (called the summer campaign) and with the heating on (called the winter campaign). In addition, a technical description of the investigated rooms was performed, an on-line questionnaire on the perceived comfort and health was filled in by the office workers, and on-line performance and reactivity tests were performed by the same workers.

This paper presents the results of the IAQ measurements, the IAQ seasonal and spatial variabilities, and the evaluation of IAQ in terms of potential adverse health effects based on WHO air quality guidelines or estimated thresholds for irritative and respiratory effects.

2. Materials and methods

2.1. Building recruitment

Each country independently selected the buildings from the approximately 20 investigated in the first phase of the project (Bluyssen et al., 2016). The selection was carried out based on several common criteria, especially the willingness of the building manager to take part in this further step of the project and at least 40 workers to achieve enough participants for the questionnaires and performance tests. Moreover, the 'detailed study' included questionnaires on perceived IAQ and comfort as well as performance tests. Therefore, buildings with symptoms that are associated with environmental parameters other than air quality were excluded. These symptoms include stress and/or work overload and were identified during the first phase of the project (Bluyssen et al., 2016).

Thirty-seven office buildings took part in the 'detailed study' summer campaign, among which two office buildings withdrew for the winter campaign. The buildings were located in Finland (3 buildings), France (9), Greece (5), Hungary (5), Italy (4), the Netherlands (4), Portugal (4), and Spain (3). The locations of the buildings are shown in Fig. S1 in the Supplementary material. The summer campaign occurred between June 18, 2012 and October 19, 2012. Four buildings were investigated between May 13, 2013 and June 14, 2013. The winter campaign occurred between November 5, 2012 and April 19, 2013. Two buildings were investigated between November 15 and November 22, 2013.

2.2. Target pollutants

The target pollutants were twelve VOCs, seven aldehydes, ozone (O_3), nitrogen dioxide (NO_2) and particulate matter with aerodynamic diameter <2.5 μm ($PM_{2.5}$). The VOCs and aldehydes are listed in Table 1. These pollutants were chosen based on a literature review of indoor air pollutants in office environments published in the framework of the OFFICAIR project (Wolkoff, 2013) and based on their potential