

方知库
Eco-Environmental
Knowledge Web

环境科学

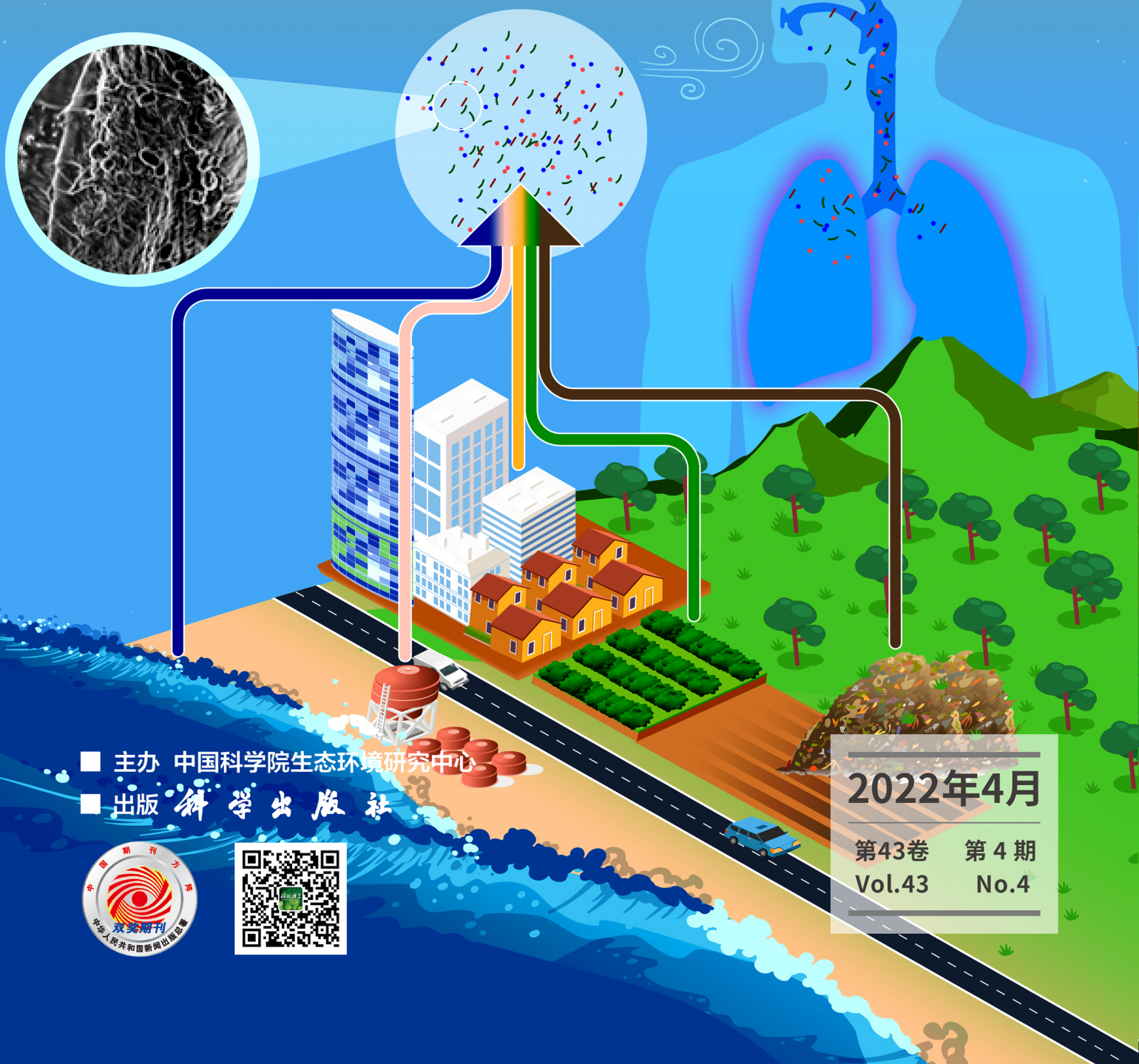
ENVIRONMENTAL SCIENCE

ISSN 0250-3301 CODEN HCKHDV

HUANJING KEXUE

大连海岸带夏、秋季大气沉降(微)塑料的赋存特征及其表面生物膜特性

涂晨, 田媛, 刘颖, 张馨宁, 骆永明



■ 主办 中国科学院生态环境研究中心

■ 出版 科学出版社



2022年4月

第43卷 第4期
Vol.43 No.4

目次

2015~2019年河南省PM _{2.5} 时空特征与驱动因素分析	葛昱序, 刘岩, 杨洪, 郭恒亮 (1697)
郑州市大气PM _{2.5} 中重金属的污染特征、来源及健康风险评估: 基于高分辨数据	曲光辉, 孙俊苹, 王申博, 姜楠, 李利萍, 刘洋, 陈红阳, 马双良 (1706)
宁波市春节期间水溶性离子污染来源和特征分析	杨梦蓉, 潘勇, 黄仲文, 张晶晶, 黄显军, 何萌萌, 肖航 (1716)
上海城区PM _{2.5} 中有机组分及硝基芳香化合物分布特征	庄旻, 马英歌, 程玉璜, 周敏, 戴海夏, 黄成, 郁建珍, 朱书慧, 乔利平, 童张法 (1725)
南京北郊大气细粒子硝基苯酚类化合物污染特征与来源	陈美娟, 钱姿合, 顾陈娟, 张书萌, 刘智艺, 王新峰, 盖鑫磊 (1738)
春节与疫情管控期间珠三角VOCs的组成和来源变化	江明, 袁鸾, 温丽容, 张莹, 方洪波, 杨满芽, 李成柳 (1747)
重庆市主要工业源VOCs组分排放清单及其臭氧生成潜势	李陵, 李振亮, 方维凯, 王晓宸, 蒲茜, 汪凌韬, 袁睿, 张卫东, 翟崇治 (1756)
珠三角石化园区VOCs排放特征及影响评价	张雪驰, 沙青娥, 陆梦华, 王毓铮, 饶思杰, 明桂英, 李勤勤, 吴淑珠, 郑君瑜 (1766)
基于隧道测试的机动车VOCs排放特征及源解析	刘鑫会, 朱仁成, 金博强, 梅慧, 祖雷, 尹沙沙, 张瑞芹, 胡京南 (1777)
基于多通道分布式VOCs在线监测质谱系统精准识别企业污染源	韦啸, 张永杰, 王沛涛, 洪燕, 夏瑞, 高伟 (1788)
基于SOA和O ₃ 生成潜势的杭州市PM _{2.5} 和O ₃ 协同控制	林旭, 严仁婧, 金嘉佳, 许凯儿 (1799)
超低排放燃煤电厂中湿式电除尘器对可凝结颗粒物排放特性的影响	王鹏程, 袁畅, 梁胜文, 蒋鹭翔, 成海容, 许睿光, 虞晓晗, 王祖武 (1808)
西安市住宅室内空气污染物实测分析与叠加效应	王秀茹, 樊灏, 范洁, 沈振兴 (1814)
大连海岸带夏、秋季大气沉降(微)塑料的赋存特征及其表面生物膜特性	涂晨, 田媛, 刘颖, 张馨宁, 骆永明 (1821)
基于在线观测本地因子的长三角家禽养殖氨排放时空分布特征	高宗源, 徐昶, 倪远之, 沈根祥, 苗文亮, 王振旗, 付侃, 钱晓雍, 曹国民 (1829)
西宁市农牧源氨排放清单及其分布特征	杨益, 姬亚芹, 高玉宗, 林孜, 林宇, 马妍 (1844)
“三水”统筹视角下京津冀地区城市水生态环境保护策略分析	廖雅, 侯晓妹, 任晓红 (1853)
中国居民饮用水镉暴露非致癌风险的年龄分层权重	秦宁, 阿依博塔·吐尔逊别克, 刘运炜, 侯荣, 徐翔宇, 官家丞, 段小丽 (1863)
新疆博尔塔拉河流域平原区地表水与地下水水化学特征及转化关系	雷米, 周金龙, 张杰, 陈亚鹏, 滕杰, 吴彤, 徐东升, 孙英, 纪媛媛 (1873)
珠江源区小黄泥河流域地表水水化学组成特征及控制因素	涂春霖, 尹林虎, 和成忠, 寸得欣, 马一奇, 令狐昌卫 (1885)
河套灌区浅层地下水NO ₃ ⁻ -N时空变化及驱动因素	袁宏颖, 杨树青, 张万峰, 王波, 韩天凯, 丁雪华 (1898)
盐城地区地下水溶质来源及其成因分析	王建, 张华兵, 许君利, 李永山 (1908)
白洋淀不同水体氢氧同位素特征及其指示意义	王雨山, 尹德超, 祁晓凡, 徐蓉桢 (1920)
东部地区大型湖库有色可溶性有机物来源组成及潜在驱动因素	陈丽丽, 肖启涛, 俞晓琴, 陈慧敏, 周蕾, 周永强, 韩龙飞 (1930)
松花湖沉积物溶解性有机质荧光光谱特性	程云轩, 赵可, 张越, 张渝婷, 焦立新 (1941)
区域土地利用类型对水源水中溶解性有机物丰度和荧光组分的影响	高静, 蒲晓, 张玉虎, 程红光, 张瑞宁, 刘训良, 董雪, 许新瑶 (1950)
南北水调东线枢纽湖泊表层水体甲烷释放特征及潜在影响因素	朱俊羽, 彭凯, 李宇阳, 俞晓琴, 陈慧敏, 周蕾, 周永强, 丁艳青 (1958)
千岛湖水体中邻苯二甲酸酯(PAEs)的分布特征及健康风险评价	弥启欣, 国晓春, 卢少勇, 邓义祥, 卢洪斌, 李响, 刘晓贺, 陈金明 (1966)
蓝藻越冬期湖湾沉积物磷吸附特征和释放风险	靳郑海, 涂成琪, 王书航, 陈俊伊, 卢昶雨, 黄威 (1976)
基于植物多样性的北京市湿地生态质量评价	李果, 孙光, 赵梓伊, 刘冬梅, 肖能文, 赵志平, 罗遵兰 (1988)
小清河专项治理对莱州湾环境和浮游植物的影响	张晶晶, 王玉珏, 李凡, 刘珂, 王英, 于洋, 高彦洁, 肖晓彤, 吕振波 (1997)
不同曝气方式对人工湿地细菌多样性、代谢活性及功能的影响	王飞鹏, 黄亚玲, 张瑞瑞, 岳琛, 李飞翔, 张超月, 穆景利 (2007)
南宁市老城区降雨径流溯源及污染特征分析	岳桢桢, 李一平, 周玉璇, 郑可, 于珊, 伍彬 (2018)
老化作用对微塑料吸附铅的影响及其机制	王俊杰, 陈晓晨, 李权达, 金成俊, 黄艺佳, 范露健, 张剑宇, 刘宪华, 徐开钦 (2030)
碳化泡沫负载Co ₃ O ₄ 活化过硫酸盐降解罗丹明B	王渊源, 阎鑫, 艾涛, 李卓, 牛艳辉 (2039)
低总氮浓度下Fe ²⁺ 促进ANAMMOX生物膜反应器脱氮	郑旭文, 秦嘉富, 汪晓军, 陈浩川, 朱梓静, 陈振国 (2047)
污水管道增强通风作用下臭气气液传质特性	杨洲, 张志强, 杨静, 卢金锁 (2055)
长江经济带工业区土壤重金属污染特征与评价	张义, 周心功, 曾晓敏, 冯娇, 刘玉荣 (2062)
中国北方典型设施菜地土壤稀土元素分布特征及环境意义	王祖伟, 刘雅明, 王子璐, 苗钰婷 (2071)
贵州省典型铅锌矿区潜在有毒元素(PTEs)物源甄别、生态风险评价及控制因素	张富贵, 彭敏, 贺灵, 马宏宏 (2081)
地质高背景与污染叠加区不同土地利用方式下土壤重金属分布特征	王雪雯, 刘鸿雁, 顾小凤, 涂宇, 于恩江, 吴攀 (2094)
矿区周边农田土壤重金属分布特征及污染评价	王海洋, 韩玲, 谢丹妮, 胡慧娟, 刘志恒, 王祯 (2104)
农田-泥炭藓系统重金属富集特征与生态风险评价	朱迪, 张朝晖, 王智慧 (2115)
安顺市土壤pH空间变异及影响因素分析	陈清霞, 陆晓辉, 涂成龙 (2124)
方解石基组配钝化剂与低积累玉米协同修复效果	任超, 任或仲, 李竞天, 王浩, 朱利文, 肖建辉, 赵瑞, 杜倩倩 (2133)
伯克氏菌Y4对水稻幼苗损伤和镉吸收的影响	张雅荟, 刘月敏, 王常荣, 刘雅萍, 庞杰, 黄永春, 刘仲齐, 张长波 (2142)
我国长江中下游平原典型稻田含碳温室气体通量变化特性	刘硕, 甄晓杰, 刘钢, 冯兆忠 (2151)
地膜覆盖和生物炭添加对菜地N ₂ O排放的影响	胡剑, 江长胜, 陈鑫童, 熊艳芳, 郝庆菊 (2163)
氮肥运筹对稻田CH ₄ 和N ₂ O排放的影响	郑梅群, 刘娟, 姜培坤, 吴家森, 李永夫, 李松果 (2171)
松花江下游滨岸带典型植被根际土壤细菌群落结构与功能多样性	王露莹, 孙慧珍, 杨雪 (2182)
棉秆还田对咸水滴灌棉田土壤酶活性和细菌群落结构多样性的影响	周永学, 陈静, 李远, 侯振安, 阎伟 (2192)
pH对水稻土全程氨氧化细菌丰度和群落结构组成影响	马瑞, 赵永鹏, 王智慧, 蒋先军 (2204)
生物炭对紫色土坡耕地侵蚀性耕层土壤有机碳的影响	张健乐, 曾小英, 史东梅, 倪书辉, 夏蕊, 王荣浩 (2209)
有机肥替代化肥对旱地黄壤有机碳矿化及活性有机碳的影响	林仕芳, 王小利, 段建军, 皮义均, 郭琴波, 龙大勇, 徐彬, 杨宏伟 (2219)
九龙江河口潮滩湿地土壤有机碳储量、活性组分及稳定性沿淹水梯度的分布特征	黄小清, 全川, 罗敏, 杨洋, 谭凤凤, 潘哲妍, 刘娜, 陈欣, 黄佳芳 (2226)
碳中和战略下煤矿区生态碳汇体系构建及功能提升展望	刘祥宏, 阎永军, 刘伟, 黄占斌 (2237)
《环境科学》征订启事(1929)	《环境科学》征稿简则(1975)
信息(1996, 2029, 2080)	

西安市住宅室内空气污染物实测分析与叠加效应

王秀茹, 樊灏, 范洁, 沈振兴*

(西安交通大学环境科学与工程系, 西安 710049)

摘要: 为了解居民住宅室内空气污染现状和保障公众健康, 于2017年12月~2020年12月对西安市住宅小区830户居民住宅室内污染物[甲醛、苯、甲苯、二甲苯、总挥发性有机物(TVOC)、乙酸正丁酯、乙苯、苯乙烯和十一烷]浓度进行了实测分析和健康效应评估, 并对污染物的叠加作用进行了分析。结果表明, 室内甲醛、苯、甲苯、TVOC和二甲苯浓度超标率分别为92.1%、39.7%、11.7%、8.9%和1.2%, 其中甲醛污染最为严重, 不同房间类型中污染物超标情况差异不大。受温湿度等因素的影响, 污染物浓度水平夏季最高。人体健康风险评估表明, 不同年龄段人群(儿童、青少年、成人和老人)均受到室内甲醛和苯的致癌风险, 且儿童和老人受到的风险更大, 二甲苯、乙苯和甲苯处于低风险($HI < 1$)。污染物叠加效应表明, 室内污染物之间存在叠加作用导致污染物毒性明显增大。结果对西安市室内住宅污染物特征及健康影响提供了基础数据和科学依据。

关键词: 室内空气; 甲醛; 苯; 季节变化; 健康风险评估; 叠加效应

中图分类号: X511 文献标识码: A 文章编号: 0250-3301(2022)04-1814-07 DOI: 10.13227/j.hjxx.202108307

Measurement Analysis and Superposed Effect of Residential Indoor Air Pollutants in Xi'an

WANG Xiu-ru, FAN Hao, FAN Jie, SHEN Zhen-xing*

(Department of Environmental Science and Engineering, Xi'an Jiaotong University, Xi'an 710049, China)

Abstract: To understand the levels of indoor air pollution and protect public health, our research group conducted monitoring of the concentrations of indoor pollutants (formaldehyde, benzene, toluene, xylene, total volatile organic compounds (TVOC), *n*-butyl acetate, ethylbenzene, styrene, and undecane) and a health effect assessment for 830 households of Xi'an City from December 2017 to December 2020. Simultaneously, the superposed effect of pollutants was analyzed. The results showed that the exceedance rates of formaldehyde, benzene, toluene, TVOC, and xylene were 92.1%, 39.7%, 11.7%, 8.9%, and 1.2% respectively, among which formaldehyde was the most serious pollutant. There was no significant difference in pollutant concentration and exceedance among different room types. The concentration of pollutants was the highest in summer due to the influence of temperature, humidity, and other factors. The results of the human health risk assessment showed that there were carcinogenic risks of formaldehyde and benzene for different age groups (children, adolescents, adults, and the elderly); children and the elderly were more at risk, whereas xylene, ethylbenzene, and toluene were at low risk ($HI < 1$). The superposed effect of pollutants showed that superposition between indoor pollutants did exist, resulting in the obvious increase in pollutant toxicity. This study provides data reference and scientific basis for the characteristics and healthy effects of indoor residential pollutants in Xi'an City.

Key words: indoor air; formaldehyde; benzene; seasonal variation; health risk assessment; superposed effect

2016年10月25日,中共中央、国务院发布的《“健康中国2030”规划纲要》中明确提出“共建共享、全民健康”是建设健康中国的战略主题。然而,现如今建筑装饰材料和家居产品的广泛使用导致室内空气质量日渐恶化。挥发性有机化合物(volatile organic compounds, VOCs)作为主要的室内污染物,其室内浓度比室外高出5倍^[1]。许多室内存在的VOCs与人体日常中的皮肤刺激、头痛、呼吸困难和哮喘甚至癌症有关,甲醛和苯会加剧血液和呼吸道等问题^[2~5]。室内空气污染已然成为一个公共健康问题^[6]。

为了预防和控制室内环境污染,保障公众健康,我国制订了《民用建筑工程室内环境污染控制标准》(GB 50325-2020),对污染物浓度限值进行了重新规定,Ⅰ类民用建筑中甲醛、苯、甲苯、二甲苯和总挥发性有机物(total volatile organic compounds, TVOC)的限值分别为0.07、0.06、0.15、0.20和0.45 $\text{mg} \cdot \text{m}^{-3}$,该标准比《空气质量标准》(GB/T

18883-2002)中的限值要求更严格。因此,迫切需要收集和报告新的住宅室内污染物浓度数据。Zhang等^[7]的研究表明,卧室中 ρ (甲醛)和 ρ (TVOC)的范围分别为0.06~0.10 $\text{mg} \cdot \text{m}^{-3}$ 和0.08~0.20 $\text{mg} \cdot \text{m}^{-3}$ 。Chang等^[8]的研究发现卧室中甲醛和TVOC略高于客厅、厨房和浴室。Huang等^[9]研究了西安市住宅污染物中甲醛癌症风险为 5.73×10^{-5} ,家具和建材贡献最大。国际癌症研究机构(IARC)将甲醛和苯列为第一类人类致癌物,其在室内的污染也很普遍^[10, 11]。现已确定,幼时暴露于环境污染物中的儿童患慢性病的风险会明显增加^[12]。然而,目前对于污染物浓度水平及分布特征研究较多,健康风险多是针对特定场所,如加油站^[13],对于家庭环境中不同年龄段群体受到的健康风险研究较

收稿日期: 2021-08-28; 修订日期: 2021-09-22

基金项目: 国家自然科学基金项目(41877383)

作者简介: 王秀茹(1997~),女,硕士研究生,主要研究方向为室内污染物特征, E-mail: xiuruwang@163.com

* 通信作者, E-mail: zshen@mail.xjtu.edu.cn

少.此外,多种低浓度污染物叠加后的综合影响研究极为少见.

考虑到不同地区人居行为特征及环境条件的差异性,本文以西北地区最大城市西安市居民住宅为研究对象,通过实测住宅室内 9 种主要污染物(甲醛、苯、甲苯、二甲苯、TVOC、乙酸正丁酯、乙苯、苯乙烯和十一烷)浓度水平,分析了季节变化对污染物浓度的影响和多种污染物叠加效应,并评估了室内污染物对不同年龄群体的健康风险,以期为进一步研究室内住宅污染物特征及其影响提供一定的科学依据.

1 材料与方法

1.1 样品的采集与分析

本研究样品于 2017 年 12 月~2020 年 12 月对西安市住宅小区共 830 户居民住宅室内污染物浓度进行监测,其中包括卧室(1 254 个)、客厅(1 072 个)、书房(272 个)和儿童房(461 个)这 4 种房间类型.监测指标为甲醛、苯、甲苯、二甲苯、TVOC、乙酸正丁酯、乙苯、苯乙烯和十一烷这 9 种污染物,并对小气候(温度、相对湿度)和装修时间等可能影响室内污染物浓度的因素进行了记录.

采样前,所有监测房间至少关闭 1 h 以上,采样期间门窗全部关闭,以确保监测得到稳定的污染物浓度.甲醛采用气泡样管采样器(QC-2,北京市劳动保护科学研究所)采集,苯酚试剂分光光度法分析,分析方法细节参考国家标准(GB/T 18204.26-2000);VOCs 采用恒流采样器进行,配有 FID 检测器的气相色谱仪分析(GC9790,浙江福立分析仪器有限公司),色谱条件参考国家标准(GB 50325-2001).取样装置安装在距地面高度约 1.5 m 处,采样流量为 0.5 L·min⁻¹,采样时间 20 min.同时,还测量了室外的对照样品和空白样品.

1.2 人体健康效应

依据美国环境保护署(USEPA)健康风险评估模型^[14],参考环境保护部和中国环境暴露行为研究报告,甲醛和苯的健康风险可通过下式计算:

$$CR = I \times CSF$$

式中,CR 表示致癌风险;I 表示每日摄入量,mg·(kg·d)⁻¹;CSF 表示致癌斜率因子,kg·d·mg⁻¹.其中甲醛为 0.046 kg·d·mg⁻¹,苯为 0.027 kg·d·mg⁻¹

根据毒性效应的阈值机制^[15],苯、甲苯、乙苯和二甲苯的非致癌风险可通过下式计算:

$$HI = I/RfD$$

式中,HI 表示风险指数;RfD 为参考剂量;根据综

合风险信息系统(IRIS)提供的 RfD 值,苯、甲苯、乙苯和二甲苯的参考剂量分别为 0.0025、1.43、0.29 和 0.029 mg·(kg·d)⁻¹,其他相关参数列于表 1.

$$I = c_i \times IR \times EF \times ED / (BW \times AT)$$

式中, c_i 表示污染物浓度,mg·m⁻³;IR 表示呼吸速率,m³·d⁻¹;EF 表示暴露频率,d·a⁻¹;ED 表示暴露持续时间,a;BW 表示体重,kg;AT 表示终身寿命,25 550 d.

表 1 人体健康风险评估相关参数^[16-19]

Table 1 Related parameters of human health risk assessment				
项目	体重/kg	呼吸速率 /m ³ ·d ⁻¹	暴露频率 /d·a ⁻¹	终生暴露 时间/a
儿童	36.0	6.04	351	70
青少年	53.0	13.91	189	70
成年人	78.0	16.68	158	70
老年人	75.0	13.39	342	70

1.3 污染物叠加特性

根据指数评价模型并参考室内空气品质评价方法^[20],采用加权平均值和沈晋明等^[21]的方法计算室内多种污染物叠加指数 P 值,其中:

加权平均值计算公式如下:

$$P_i = C_i/S_i$$

$$P = \sum_{i=1}^n W_i P_i$$

文献[21]计算方式为:

$$P = \sqrt{\left[\max\left(\frac{C_1}{S_1}, \frac{C_2}{S_2}, \dots, \frac{C_n}{S_n}\right) \right] \times \left(\frac{1}{n} \sum \frac{C_i}{S_i} \right)}$$

式中,P 表示污染物叠加综合污染指数; P_i 表示第 i 种污染物分项污染指数; W_i 表示第 i 种污染物的权重. C_i 表示第 i 种污染物的实测浓度,mg·m⁻³; S_i 表示第 i 种污染物的标准值,mg·m⁻³,n 为污染物个数.各污染物分项污染指数和权重取值列于表 2.

经叠加后各污染物浓度值为:

$$C = C_i \times P$$

表 2 各污染物分项污染指数和权重取值

Table 2 Sub-pollution index and weight value of each pollutant					
项目	甲醛	苯	甲苯	二甲苯	TVOC
P_i	1.706	1.001	0.742	0.291	0.676
W_i	0.319	0.372	0.149	0.112	0.050

2 结果与讨论

2.1 污染物浓度水平

本次监测的西安市 3 059 个样本中室内污染物基本情况列于表 3,污染物总体超标率高达 30.7%,主要污染物包括甲醛、苯、甲苯、二甲苯、TVOC、

乙酸正丁酯、乙苯、苯乙烯和十一烷. 其中, ρ (甲醛) 主要分布在 $0.06 \sim 0.18 \text{ mg}\cdot\text{m}^{-3}$ (图 1), 平均值为 $0.12 \text{ mg}\cdot\text{m}^{-3}$, 超标率高达 92.1%. 苯的最高超标倍数为 8.23 倍, 超标率为 39.7%, 甲苯、二甲苯和 TVOC 的超标率分别为 11.7%, 1.2% 和 8.9%. 苯系物当中, 甲苯最为丰富, 约占 40%, 其次为苯和二甲苯, 这与 Du 等^[22] 的研究结果一致. Chang 等^[23]

研究了 2014 ~ 2015 年西安市住宅污染物情况, 甲醛超标率为 83.6% (标准值 $0.10 \text{ mg}\cdot\text{m}^{-3}$), 未出现苯超标 (标准值 $0.11 \text{ mg}\cdot\text{m}^{-3}$). 本文所用的最新《民用建筑工程室内环境污染控制标准》(GB 50325-2020) 中甲醛和苯的标准值分别为 $0.07 \text{ mg}\cdot\text{m}^{-3}$ 和 $0.06 \text{ mg}\cdot\text{m}^{-3}$, 污染物限值要求更加严苛, 故超标情况更严重, 超标率更高.

表 3 西安市室内空气污染物检测结果
Table 3 Detection results of indoor air pollutants in Xi'an City

污染物	监测数量	超标个数	超标率/%	平均值 / $\text{mg}\cdot\text{m}^{-3}$	最大值 / $\text{mg}\cdot\text{m}^{-3}$	最高超标 倍数	标准 ^[24] / $\text{mg}\cdot\text{m}^{-3}$
甲醛	3 059	2 816	92.1	0.12	0.30	4.23	0.07
苯	3 059	1 214	39.7	0.06	0.49	8.23	0.06
甲苯	3 059	359	11.7	0.11	1.21	8.07	0.15
二甲苯	3 059	36	1.2	0.06	0.98	4.90	0.20
TVOC	3 059	271	8.9	0.30	2.27	5.05	0.45
乙酸正丁酯	3 059	—	—	0.01	0.09	—	—
乙苯	3 059	—	—	0.04	0.78	—	—
苯乙烯	3 059	—	—	0.02	0.50	—	—
十一烷	3 059	—	—	0.00	0.40	—	—

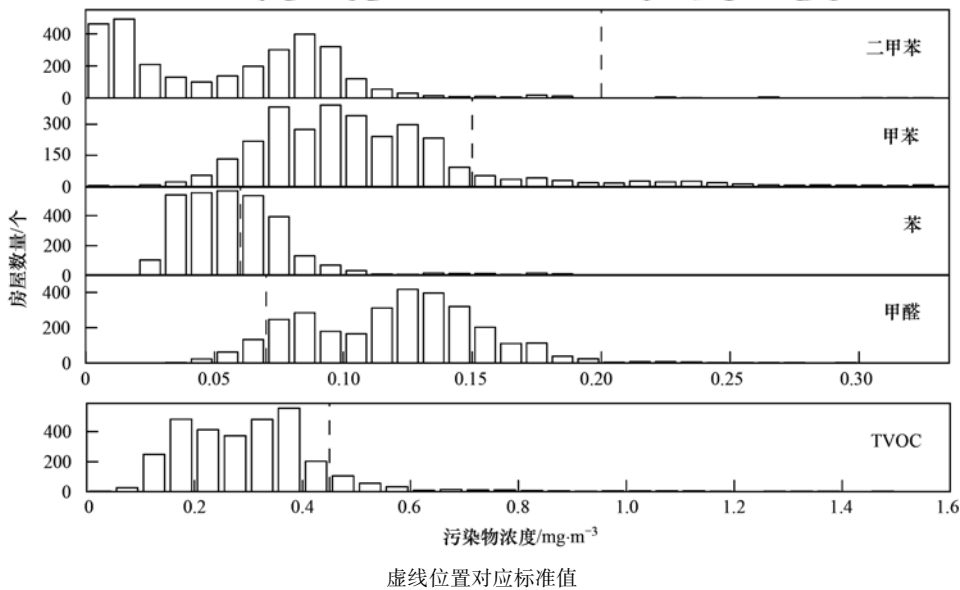


图 1 不同污染物浓度下房间数量分布

Fig. 1 Room quantity distribution under different pollutant concentrations

Pearson 相关性检验表明 (表 4), 各污染物浓度水平存在统计上的显著正相关 ($P < 0.01$), 其中 TVOC 和苯系物之间的相关系数范围为 $0.614 \sim 0.747$, 具有高度的统计显著相关性, 意味着它们具有相同或相似的来源. 有研究表明, 住宅污染多来源于室内污染^[25,26]. 甲醛多来源于壁纸、粘合剂和胶合板等装饰材料; 苯及其同系化合物主要来自于家具漆、墙漆和各种内墙涂料^[27,28]. 正是由于人们多样化的需求导致房屋过度装修, 只注重美观性而忽视了环保性和健康性, 因而造成室内空气质量日趋变差.

4 种房间类型 (卧室、客厅、书房和儿童房) 中污染物浓度及超标情况列于表 5. 卧室中污染物超标率相对最高, 客厅相对最低. 卧室由于空间较小, 家具陈列较为密集, 且通常会依据个人喜好涂装各种墙壁图案, 放置家用纺织品、化妆品和其他药品^[29], 因而超标较为严重; 与卧室相比, 客厅面积较大, 多以瓷砖铺地, 且长期开放, 通风情况更好^[30,31]. 总体来看, 不同房间类型中污染物浓度超标情况差异不大. Friedman 检验结果表明, 卧室、客厅、书房和儿童房中甲醛浓度差异不显著 ($P > 0.05$), 这与 Dingle 等^[32] 的研究结果一致. 而苯、二

甲苯和 TVOC 浓度具有统计学相关性 ($P < 0.05$), 其中, 书房中苯系物平均值最高, 主要是各种书籍文

件、打印机中油墨、颜料和合成材料等释放的污染物所致^[33,34].

表 4 室内空气污染物 Pearson 相关系数¹⁾

Table 4 Pearson correlation coefficients of indoor air pollutants									
	甲醛	苯	甲苯	二甲苯	TVOC	乙酸正丁酯	乙苯	苯乙烯	十一烷
甲醛	1								
苯	0.289 **	1							
甲苯	0.316 **	0.376 **	1						
二甲苯	0.182 **	0.258 **	0.303 **	1					
TVOC	0.334 **	0.614 **	0.747 **	0.619 **	1				
乙酸正丁酯	0.125 **	0.197 **	0.175 **	0.441 **	0.418 **	1			
乙苯	0.171 **	0.328 **	0.387 **	0.121 **	0.639 **	0.085 **	1		
苯乙烯	0.171 **	0.274 **	0.410 **	0.307 **	0.681 **	0.177 **	0.797 **	1	
十一烷	0.118 **	0.139 **	0.044 *	0.257 **	0.245 **	0.140 **	0.005	0.074 **	1

1) ** 和 * 表示皮尔逊相关分析, 分别为 $P < 0.01$ 和 $P < 0.05$

表 5 不同房间类型污染物浓度及超标情况

Table 5 Pollutant concentrations and standard exceedance in different rooms									
	房间类型	数量	范围 /mg·m ⁻³	算术平均 /mg·m ⁻³	标准偏差	中位数 /mg·m ⁻³	超标 个数	超标率 /%	P 值
甲醛	卧室	1254	0.04~0.30	0.12	0.04	0.125	1170	93.30	0.114
	客厅	1072	0.04~0.28	0.12	0.03	0.119	982	91.60	
	书房	272	0.04~0.23	0.12	0.03	0.122	252	92.65	
	儿童房	461	0.03~0.26	0.12	0.04	0.122	412	89.37	
苯	卧室	1254	0.02~0.49	0.06	0.03	0.057	556	44.34	0.041
	客厅	1072	0.01~0.41	0.05	0.03	0.051	349	32.56	
	书房	272	0.02~0.38	0.07	0.04	0.059	115	42.28	
	儿童房	461	0.02~0.32	0.06	0.03	0.056	194	42.08	
甲苯	卧室	1254	0.00~0.47	0.12	0.06	0.105	178	14.19	0.169
	客厅	1072	0.00~1.21	0.10	0.06	0.093	80	7.46	
	书房	272	0.03~0.83	0.12	0.07	0.109	36	13.24	
	儿童房	461	0.03~0.52	0.12	0.06	0.104	65	14.10	
二甲苯	卧室	1254	0.00~0.97	0.06	0.06	0.058	13	1.04	0
	客厅	1072	0.00~0.73	0.05	0.05	0.054	9	0.84	
	书房	272	0.00~0.98	0.07	0.07	0.069	4	1.47	
	儿童房	461	0.00~0.66	0.06	0.06	0.064	10	2.17	
TVOC	卧室	1254	0.07~1.64	0.32	0.15	0.307	134	10.69	0
	客厅	1072	0.01~1.75	0.28	0.14	0.265	60	5.60	
	书房	272	0.10~2.27	0.33	0.18	0.325	25	9.19	
	儿童房	461	0.08~1.38	0.32	0.16	0.312	52	11.28	

2.2 季节变化影响

考虑到季节变化对污染物的影响^[35], 图 2 展示了污染物浓度随季节变化的趋势为: 夏季污染物浓度最高, 春秋两季浓度下降, 冬季部分污染物浓度略有回升. 甲醛、苯和甲苯浓度冬季最低, 二甲苯和 TVOC 浓度秋季最低. 其原因可能是西安冬季较为寒冷, 供暖期室内温度升高, 同时门窗长期关闭导致通风频率降低. Spearman 秩相关分析表明绝大多数污染物与温湿度具有统计学相关性 ($P < 0.01$), 温度与所监测的 9 种污染物均为正相关, 湿度与甲醛、苯和乙苯正相关, 与二甲苯、乙酸正丁酯、苯乙烯和十一烷负相关(表 6). 其中, 甲醛受温度和湿度影

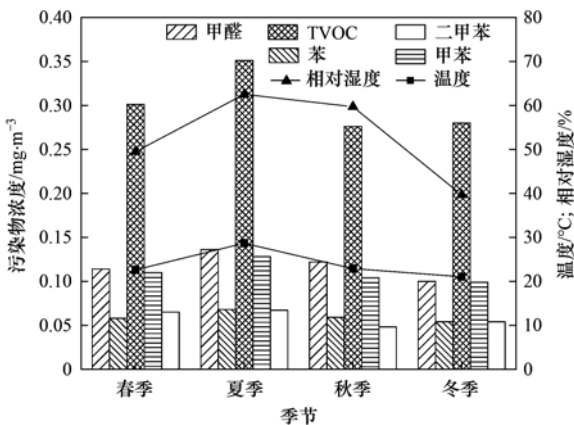


图 2 不同季节各污染物浓度变化情况
Fig. 2 Variation in pollutant concentration in different seasons

响最敏感,由于甲醛易溶于水,相对湿度较大时胶黏剂中脲醛树脂水解,从而释放甲醛;而温度较高甲醛易从木质家具中蒸发,不断向空气中扩散^[36~38]. 本研究结果与相关报道一致^[39,40]. 表7所示当温度

高于25℃,湿度超过60%时,甲醛和苯的浓度更高,其中温度对其贡献率分别为60%和67%. 这可能是由于西安地处西北内陆地区,全年气候干燥,降雨量相对较少,故湿度影响较小.

表6 温湿度与室内空气污染物 Spearman 相关系数¹⁾

Table 6 Spearman correlation coefficients between temperature and humidity and indoor air pollutants

	甲醛	苯	甲苯	二甲苯	TVOC	乙酸正丁酯	乙苯	苯乙烯	十一烷
温度	0.337 **	0.170 **	0.163 **	0.083 **	0.170 **	0.091 **	0.130 **	0.141 **	0.075 **
湿度	0.273 **	0.092 **	0.02	-0.147 **	-0.015	-0.079 **	0.082 **	-0.062 **	-0.138 **

1) ** 表示秩相关分析, $P < 0.01$

表7 温湿度对甲醛和苯综合效应的贡献率

Table 7 Contribution rate to combined effects of temperature and humidity on formaldehyde and benzene

污染物类型	温度/℃		相对贡献率/%	湿度/%		相对贡献率/%
	<25	≥25		<60	≥60	
甲醛	0.110	0.131	60	0.114	0.128	40
苯	0.057	0.064	67	0.059	0.063	33

2.3 人体健康效应

甲醛、苯和乙苯已被世界卫生组织国际癌症研究机构列为致癌物质,甲苯和二甲苯虽未被列为致癌物质,但它们仍具有一定的致癌毒性,对人体健康的影响不容忽视^[41,42]. 有研究表明,家庭环境对总平均健康风险的贡献约为96%^[43]. 在本研究中,甲醛和苯的致癌风险范围分别为 $5 \times 10^{-4} \sim 9.04 \times 10^{-4}$ 和 $1.36 \times 10^{-4} \sim 2.46 \times 10^{-4}$ (图3),均超过USEPA可接受的风险阈值(1×10^{-6}),且甲醛的致癌风险更高. 不同年龄群体中,儿童和老人对污染物的暴露更加敏感,主要由于他们长时间呆在室内,持续性暴露时间更长,加之自身免疫力较低,因而致癌风险更高. 范洁等^[44]研究了公共场所甲醛和苯的致癌风险范围分别为 $1.73 \times 10^{-5} \sim 1.25 \times 10^{-4}$ 和 $1.64 \times 10^{-5} \sim 2.89 \times 10^{-4}$,可见室内致癌风险明显高于公共场所,之前研究也获得相同结论^[45]. 因此,必须重视室内污染物对人体健康的不利影响.

图4绘制了苯、乙苯、甲苯和二甲苯的非致癌风险情况. 4种污染物的风险指数对不同年龄群体表现出一致性趋势,即:老人>儿童>青少年>成人,这与大众的普遍认知相一致. 苯的风险指数最高,其次为二甲苯、乙苯和甲苯. 其中,苯具有明确的致癌风险($HI > 1$),其对成人的非致癌风险值已超过2,致癌毒性必须引起重视. 二甲苯、乙苯和甲苯处于低风险水平($HI < 1$),但它们对人体健康的有害影响依然值得重视.

2.4 污染物叠加特性

考虑到室内污染物以混合形式存在会产生一定的协同或拮抗效应,尤其是前者会对人体健康造成更大的潜在威胁^[46]. 污染物叠加前后超标变化情况

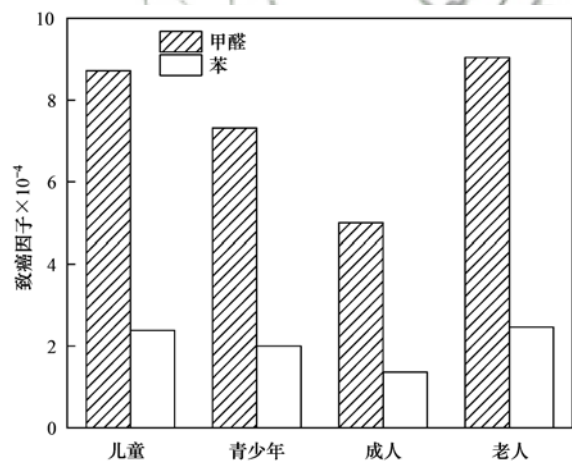


图3 甲醛和苯的致癌风险评估

Fig. 3 Carcinogenic risk assessment of formaldehyde and benzene

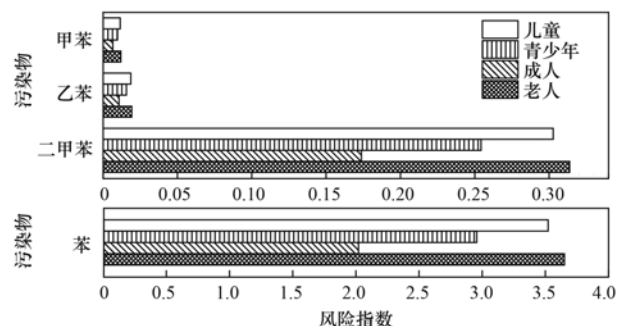


图4 苯系物的非致癌风险评估

Fig. 4 Non-carcinogenic risk assessment of BTEX

显示(图5),加权平均值计算所得甲醛和苯的超标率分别增大至95.1%和51.4%;沈氏模式得到甲苯和TVOC的超标率变为28.4%和25.6%. 可以发现,两种计算方式所得污染物超标情况不完全一致,这是由于沈氏模式兼顾了最大单因子指数,但未充分反映各污染物之间水平差异的信息,故而其综合

指数略大,但两种方法均获得一致性结论,即:污染物叠加之后毒性明显增强.室内污染物多以低浓度形式混合共存,即使个体未超过标准阈值也并不意味着对人体无害,尤其是多种污染物之间协同作用的发生导致毒性明显增大,对人体造成更大的潜在威胁,因此,必须重视多重污染物的叠加影响.

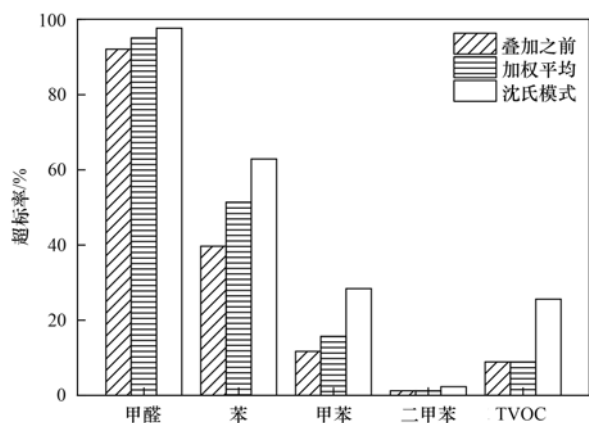


图5 叠加前后污染物超标率

Fig. 5 Pollutant exceedance rate before and after superposition

3 结论

(1)监测的9种污染物中甲醛污染最为严重,超标率高达92.1%,其次为苯、甲苯、TVOC和二甲苯,超标率依次为39.7%、11.7%、8.9%和1.2%。甲醛浓度集中在 $0.06 \sim 0.18 \text{ mg} \cdot \text{m}^{-3}$,平均浓度为 $0.12 \text{ mg} \cdot \text{m}^{-3}$ 。4种房间类型污染物浓度总体水平及超标情况差异不大。

(2)污染物随季节变化明显,夏季污染物浓度最高,甲醛、苯和甲苯浓度冬季最低,二甲苯和TVOC秋季最低。温度与监测的9种污染物浓度水平均为正相关,湿度与各污染物相关性正负不一,其中甲醛受温、湿度影响最为敏感。

(3)健康风险评估表明,甲醛和苯对不同年龄群体(儿童、青少年、成人和老人)均存在致癌风险,甲醛的致癌风险更高,且儿童和老人受到的致癌风险更大。苯具有明确致癌风险($HI > 1$),二甲苯、乙苯和甲苯为低风险($HI < 1$)。

(4)综合污染指数结果表明,室内多种低浓度污染物之间存在叠加作用,加权平均和沈氏模式两种方法均得到污染物超标率明显增大,毒性作用大大增加,因此必须重视多重污染物的协同效应。

参考文献:

[1] Gong Y, Wei Y J, Cheng J H, *et al.* Health risk assessment and personal exposure to volatile organic compounds (VOCs) in metro carriages—a case study in Shanghai, China[J]. *Science of the Total Environment*, 2017, **574**: 1432-1438.

[2] Ghaffari H R, Kamari Z, Hassanvand M S, *et al.* Level of air BTEX in urban, rural and industrial regions of Bandar Abbas,

Iran; indoor-outdoor relationships and probabilistic health risk assessment[J]. *Environmental Research*, 2021, **200**, doi: 10.1016/j.envres.2021.111745.

[3] Zhao J J, You X Y. Probabilistic health risk assessment of exposure to carcinogens of Chinese family cooking and influence analysis of cooking factors[J]. *Science of the Total Environment*, 2021, **779**, doi: 10.1016/j.scitotenv.2021.146493.

[4] Golkhorshidi F, Sorooshian A, Jafari A J, *et al.* On the nature and health impacts of BTEX in a populated middle eastern city: Tehran, Iran[J]. *Atmospheric Pollution Research*, 2019, **10** (3): 921-930.

[5] Ceron-Breton J G, Cerón Bretón R M, Kahl J D W, *et al.* Concentrations, sources, and health risk associated with exposure to BTEX at ten sites located in an urban-industrial area in the Bajío Region, Mexico[J]. *Air Quality, Atmosphere & Health*, 2021, **14**(5): 741-761.

[6] Liang L W, Wang Z B, Li J X. The effect of urbanization on environmental pollution in rapidly developing urban agglomerations[J]. *Journal of Cleaner Production*, 2019, **237**, doi: 10.1016/j.jclepro.2019.117649.

[7] Zhang X L, Li X F, Wang Z C, *et al.* Exposure level and influential factors of HCHO, BTX and TVOC from the interior redecoration of residences[J]. *Building and Environment*, 2020, **168**, doi: 10.1016/j.buildenv.2019.106494.

[8] Chang T, Wang J H, Lu J Q *et al.* Evaluation of indoor air pollution during decorating process and inhalation health risks in Xi'an, China: a case study[J]. *Aerosol and Air Quality Research*, 2019, **19**(4): 854-864.

[9] Huang Y, Su T, Wang L Q, *et al.* Evaluation and characterization of volatile air toxics indoors in a heavy polluted city of northwestern China in wintertime[J]. *Science of the Total Environment*, 2019, **662**: 470-480.

[10] Garg A, Gupta N C. A comprehensive study on Spatio-temporal distribution, health risk assessment and ozone formation potential of BTEX emissions in ambient air of Delhi, India[J]. *Science of the Total Environment*, 2019, **659**: 1090-1099.

[11] Goodman N B, Steinemann A, Wheeler A J, *et al.* Volatile organic compounds within indoor environments in Australia[J]. *Building and Environment*, 2017, **122**: 116-125.

[12] Clark N A, Demers P A, Karr C J, *et al.* Effect of early life exposure to air pollution on development of childhood asthma[J]. *Environmental Health Perspectives*, 2010, **118**(2): 284-290.

[13] Baghani A N, Sorooshian A, Heydari M, *et al.* A case study of BTEX characteristics and health effects by major point sources of pollution during winter in Iran[J]. *Environmental Pollution*, 2019, **247**: 607-617.

[14] Hajizadeh Y, Mokhtari M, Faraji M, *et al.* Trends of BTEX in the central urban area of Iran: a preliminary study of photochemical ozone pollution and health risk assessment[J]. *Atmospheric Pollution Research*, 2018, **9**(2): 220-229.

[15] Huang L H, Mo J H, Sundell J, *et al.* Health risk assessment of inhalation exposure to formaldehyde and benzene in newly remodeled buildings, Beijing[J]. *PLoS One*, 2013, **8**(11), doi: 10.1371/journal.pone.0079553.

[16] Li F, Zhang J D, Jiang W, *et al.* Spatial health risk assessment and hierarchical risk management for mercury in soils from a typical contaminated site, China[J]. *Environmental Geochemistry and Health*, 2017, **39**(4): 923-934.

[17] Winner D A. Exposure factors handbook: 2011 edition; release of final report[J]. *Federal Register*, 2011, **76**(191): 61098.

[18] Duan X L, Zhao X G, Wang B B, *et al.* Highlights of the

- Chinese exposure factors handbook (Adults) [M]. Amsterdam: Academic Press, 2015.
- [19] United States Environmental Protection Agency. Integrated Risk Information System[EB/OL]. <http://www.epa.gov/iris>, 2003-04-17.
- [20] 舒爱霞, 李孜军, 邓艳星, 等. 综合指数评价法在室内空气质量评价中的应用[J]. 化工装备技术, 2010, **31**(2): 60-62.
- Shu A X, Li Z J, Deng Y X, *et al.* Application of aggregative index number to indoor air quality determination[J]. Chemical Equipment Technology, 2010, **31**(2): 60-62.
- [21] 沈晋明. 室内空气品质的评价[J]. 暖通空调, 1997, **27**(4): 22-25.
- Shen J M. Indoor air quality evaluation[J]. Heating Ventilating & Air Conditioning, 1997, **27**(4): 22-25.
- [22] Du Z J, Mo J H, Zhang Y P, *et al.* Benzene, toluene and xylenes in newly renovated homes and associated health risk in Guangzhou, China[J]. Building and Environment, 2014, **72**: 75-81.
- [23] Chang T, Ren D X, Shen Z X, *et al.* Indoor air pollution levels in decorated residences and public places over Xi'an, China[J]. Aerosol and Air Quality Research, 2017, **17**(9): 2197-2205.
- [24] GB 50325-2020, 民用建筑工程室内环境污染控制标准[S].
- [25] Gilbert N L, Guay M, Gauvin D, *et al.* Air change rate and concentration of formaldehyde in residential indoor air[J]. Atmospheric Environment, 2008, **42**(10): 2424-2428.
- [26] Bari M A, Kindziarski W B, Wheeler A J, *et al.* Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada[J]. Building and Environment, 2015, **90**: 114-124.
- [27] Hadei M, Hopke P K, Rafiee M, *et al.* Indoor and outdoor concentrations of BTEX and formaldehyde in Tehran, Iran: effects of building characteristics and health risk assessment[J]. Environmental Science and Pollution Research, 2018, **25**(27): 27423-27437.
- [28] Steinemann A. Volatile emissions from common consumer products[J]. Air Quality, Atmosphere & Health, 2015, **8**(3): 273-281.
- [29] Costa S, Costa C, García-Léston J, *et al.* Human exposure to formaldehyde, a risk evaluation of occupational health effects[J]. Toxicology Letters, 2014, **229**, doi: 10.1016/j.toxlet.2014.06.419.
- [30] Madureira J, Paciência I, Rufo J, *et al.* Source apportionment of CO₂, PM₁₀ and VOCs levels and health risk assessment in naturally ventilated primary schools in Porto, Portugal[J]. Building and Environment, 2016, **96**: 198-205.
- [31] Yu C W F, Kim J T. Building pathology, investigation of sick buildings—VOC emissions[J]. Indoor and Built Environment, 2010, **19**(1): 30-39.
- [32] Dingle P, Franklin P. Formaldehyde levels and the factors affecting these levels in homes in Perth, Western Australia[J]. Indoor and Built Environment, 2002, **11**(2): 111-116.
- [33] Cincinelli A, Martellini T, Amore A, *et al.* Measurement of volatile organic compounds (VOCs) in libraries and archives in Florence (Italy)[J]. Science of the Total Environment, 2016, **572**: 333-339.
- [34] Gibson L T, Ewlad-Ahmed A, Knight B, *et al.* Measurement of volatile organic compounds emitted in libraries and archives: an inferential indicator of paper decay? [J]. Chemistry Central Journal, 2012, **6**(1), doi: 10.1186/1752-153X-6-42.
- [35] Han T T, Ma Z Q, Li Y R, *et al.* Real-time measurements of aromatic hydrocarbons at a regional background station in North China: seasonal variations, meteorological effects, and source implications[J]. Atmospheric Research, 2021, **250**, doi: 10.1016/j.atmosres.2020.105371.
- [36] Ye W, Zhang X, Gao J, *et al.* Indoor air pollutants, ventilation rate determinants and potential control strategies in Chinese dwellings: a literature review [J]. Science of the Total Environment, 2017, **586**: 696-729.
- [37] Liang W H, Lv M Q, Yang X D. The combined effects of temperature and humidity on initial emittable formaldehyde concentration of a medium-density fiberboard[J]. Building and Environment, 2016, **98**: 80-88.
- [38] Liang W H, Lv M Q, Yang X D. The effect of humidity on formaldehyde emission parameters of a medium-density fiberboard: experimental observations and correlations [J]. Building and Environment, 2016, **101**: 110-115.
- [39] Liang W H, Yang S, Yang X D. Long-term formaldehyde emissions from medium-density fiberboard in a full-scale experimental room: emission characteristics and the effects of temperature and humidity [J]. Environmental Science & Technology, 2015, **49**(17): 10349-10356.
- [40] Huangfu Y B, Lima N M, O'Keeffe P T, *et al.* Diel variation of formaldehyde levels and other VOCs in homes driven by temperature dependent infiltration and emission rates [J]. Building and Environment, 2019, **159**, doi: 10.1016/j.buildenv.2019.05.031.
- [41] Masih A, Lall A S, Taneja A, *et al.* Exposure profiles, seasonal variation and health risk assessment of BTEX in indoor air of homes at different microenvironments of a Terai province of northern India[J]. Chemosphere, 2017, **176**: 8-17.
- [42] Alsoub E M, Omari K W. BTEX indoor air characteristic values in rural areas of Jordan: heaters and health risk assessment consequences in winter season [J]. Environmental Pollution, 2020, **267**, doi: 10.1016/j.envpol.2020.115464.
- [43] Chen X Y, Li F, Liu C Y, *et al.* Monitoring, human health risk assessment and optimized management for typical pollutants in indoor air from random families of university staff, Wuhan City, China [J]. Sustainability, 2017, **9**(7), doi: 10.3390/su9071115.
- [44] 范洁, 樊灏, 沈振兴, 等. 西安市新装修公共场所空气污染物浓度分析及健康风险评价[J]. 环境科学, 2021, **42**(5): 2153-2158.
- Fan J, Fan H, Shen Z X, *et al.* Concentration analysis and health risk assessment of air pollutants in newly decorated public places in Xi'an [J]. Environmental Science, 2021, **42**(5): 2153-2158.
- [45] Zhang Z F, Zhang X, Zhang X M, *et al.* Indoor occurrence and health risk of formaldehyde, toluene, xylene and total volatile organic compounds derived from an extensive monitoring campaign in Harbin, a megacity of China[J]. Chemosphere, 2020, **250**, doi: 10.1016/j.chemosphere.2020.126324.
- [46] Rösch C, Kohajda T, Röder S, *et al.* Relationship between sources and patterns of VOCs in indoor air[J]. Atmospheric Pollution Research, 2014, **5**(1): 129-137.

CONTENTS

Analysis on Spatial-temporal Characteristics and Driving Factors of PM _{2.5} in Henan Province from 2015 to 2019	GE Qi-xu, LIU Yan, YANG Hong, <i>et al.</i>	(1697)
Pollution Characterization, Source Identification, and Health Risks of Atmospheric Particle-Bound Heavy Metals in PM _{2.5} in Zhengzhou City: Based on High-resolution Data	QU Guang-hui, SUN Jun-ping, WANG Shen-bo, <i>et al.</i>	(1706)
Source Analysis and Composition Characteristics of Water-soluble Ions During Spring Festival in Ningbo	YANG Meng-rong, PAN Yong, HUANG Zhong-wen, <i>et al.</i>	(1716)
Characteristics of Nitroaromatic Compounds in PM _{2.5} in Urban Area of Shanghai	ZHUANG Min, MA Ying-ge, CHENG Yu-huang, <i>et al.</i>	(1725)
Characteristics and Sources of Nitrated Phenols in Atmospheric Fine Particles of Northern Suburban Nanjing	CHEN Mei-juan, QIAN Zi-he, GU Chen-juan, <i>et al.</i>	(1738)
Variety of the Composition and Sources of VOCs During the Spring Festival and Epidemic Prevention in the Pearl River Delta	JIANG Ming, YUAN Luan, WEN Li-rong, <i>et al.</i>	(1747)
Speciated Emission Inventory of VOCs from Industrial Sources and Their Ozone Formation Potential in Chongqing	LI Ling, LI Zhen-liang, FANG Wei-kai, <i>et al.</i>	(1756)
Volatile Organic Compound Emission Characteristics and Influences Assessment of a Petrochemical Industrial Park in the Pearl River Delta Region	ZHANG Xue-chi, SHA Qing-e, LU Meng-hua, <i>et al.</i>	(1766)
Characteristics and Source Apportionment of Vehicular VOCs Emissions in a Tunnel Study	LIU Xin-hui, ZHU Ren-cheng, JIN Bo-qiang, <i>et al.</i>	(1777)
Accurate Identification of Pollution Sources in a Chemical Enterprise Based on a Distributed Multi-channel VOCs Online Monitoring Mass Spectrometry System	WEI Xiao, ZHANG Yong-jie, WANG Pei-tao, <i>et al.</i>	(1788)
Coordinated Control of PM _{2.5} and O ₃ in Hangzhou Based on SOA and O ₃ Formation Potential	LIN Xu, YAN Ren-chang, JIN Jia-jia, <i>et al.</i>	(1799)
Effect of WESP on Emission Characteristics of Condensable Particulate Matter from Ultra-low Emission Coal-fired Power Plants	WANG Peng-cheng, YUAN Chang, LIANG Sheng-wen, <i>et al.</i>	(1808)
Measurement Analysis and Superposed Effect of Residential Indoor Air Pollutants in Xi'an	WANG Xiu-ru, FAN Hao, FAN Jie, <i>et al.</i>	(1814)
Occurrence of Atmospheric (Micro)plastics and the Characteristics of the Plastic Associated Biofilms in the Coastal Zone of Dalian in Summer and Autumn	TU Chen, TIAN Yuan, LIU Ying, <i>et al.</i>	(1821)
Spatiotemporal Distribution of Ammonia Emissions from Poultry Farming in the Yangtze River Delta Based on Online Monitoring Derived Local Emission Factors	GAO Zong-yuan, XU Chang, NI Yuan-zhi, <i>et al.</i>	(1829)
Agricultural Ammonia Emission Inventory and Its Distribution in Xining City	YANG Yi, JI Ya-qin, GAO Yu-zong, <i>et al.</i>	(1844)
Analysis of the Urban Water Eco-environment Protection Strategy in the Beijing-Tianjin-Hebei Region from "Three Waters" Overall Planning	LIAO Ya, HOU Xiao-shu, REN Xiao-hong	(1853)
Non-carcinogenic Risk Assessment of Cadmium Exposure Through Drinking Water in Chinese Residents Based on Age-stratification Weight	QIN Ning, Ayibota Tuexunbieke, LIU Yun-wei, <i>et al.</i>	(1863)
Hydrochemical Characteristics and Transformation Relationship of Surface Water and Groundwater in the Plain Area of Bortala River Basin, Xinjiang	LEI Mi, ZHOU Jin-long, ZHANG Jie, <i>et al.</i>	(1873)
Hydrochemical Composition Characteristics and Control Factors of Xiaohuangni River Basin in the Upper Pearl River	TU Chun-lin, YIN Lin-hu, HE Cheng-zhong, <i>et al.</i>	(1885)
Temporal and Spatial Variation Characteristics and Driving Factors of Nitrogen of Shallow Groundwater in Hetao Irrigation District	YUAN Hong-ying, YANG Shu-qing, ZHANG Wan-feng, <i>et al.</i>	(1898)
Provenance of Groundwater Solute and Its Controlling Factors in Yancheng Area	WANG Jian, ZHANG Hua-bing, XU Jun-li, <i>et al.</i>	(1908)
Hydrogen and Oxygen Isotopic Characteristics of Different Water and Indicative Significance in Baiyangdian Lake	WANG Yu-shan, YIN De-chao, QI Xiao-fan, <i>et al.</i>	(1920)
Optical Composition and Potential Driving Factors of Chromophoric Dissolved Organic Matter in Large Lakes and Reservoirs in the Eastern Region of China	CHEN Li-li, XIAO Qi-tao, YU Xiao-qin, <i>et al.</i>	(1930)
Fluorescence Spectral Characteristics of Dissolved Organic Matter in Songhua Lake Sediment	CHENG Yun-xuan, ZHAO Ke, ZHANG Yue, <i>et al.</i>	(1941)
Abundance and Fluorescent Components of Dissolved Organic Matter Affected by Land Use in a Drinking Water Source	GAO Jing, PU Xiao, ZHANG Yu-hu, <i>et al.</i>	(1950)
Emission of Methane from a Key Lake in the Eastern Route of the South-to-North Water Transfer Project and the Corresponding Driving Factors	ZHU Jun-yu, PENG Kai, LI Yu-yang, <i>et al.</i>	(1958)
Distribution Characteristics and Ecological and Health Risk Assessment of Phthalic Acid Esters in Surface Water of Qiandao Lake, China	MI Qi-xin, GUO Xiao-chun, LU Shao-yong, <i>et al.</i>	(1966)
Phosphorus Adsorption Characteristics and Loss Risk in Sediments of Lake Bay During the Overwinter Period of Cyanobacteria	JIN Zheng-hai, TU Cheng-qi, WANG Shu-hang, <i>et al.</i>	(1976)
Ecological Quality Assessment of the Wetlands in Beijing: Based on Plant Diversity	LI Guo, SUN Guang, ZHAO Zi-yi, <i>et al.</i>	(1988)
Effects of Pollution Control of Xiaqing River on Environment Factors and Phytoplankton Community in the Laizhou Bay	ZHANG Jing-jing, WANG Yu-jue, LI Fan, <i>et al.</i>	(1997)
Effects of Different Aeration Treatments on Bacterial Diversity, Metabolic Activity, and Function in Constructed Wetlands	WANG Fei-peng, HUANG Ya-ling, ZHANG Rui-rui, <i>et al.</i>	(2007)
Analysis on the Source Tracing and Pollution Characteristics of Rainfall Runoff in the Old Urban Area of Nanning City	YUE Zhen-wu, LI Yi-ping, ZHOU Yu-xuan, <i>et al.</i>	(2018)
Effects of Aging on the Cd Adsorption by Microplastics and the Relevant Mechanisms	WANG Jun-jie, CHEN Xiao-chen, LI Qian-da, <i>et al.</i>	(2030)
Carbonized Foam Supported Co ₃ O ₄ Activated Peroxymonosulfate Towards Rhodamine B Degradation	WANG Yuan-yuan, YAN Xin, AI Tao, <i>et al.</i>	(2039)
Promoting Nitrogen Removal in ANAMMOX Biofilm Reactor by Fe ²⁺ Under Low Nitrogen Concentration	ZHENG Xu-wen, QIN Jia-fu, WANG Xiao-jun, <i>et al.</i>	(2047)
Investigation on Oxygen Gas-liquid Mass Transfer in Sewage Pipelines Under Enhanced Ventilation	YANG Zhou, ZHANG Zhi-qiang, YANG Jing, <i>et al.</i>	(2055)
Characteristics and Assessment of Heavy Metal Contamination in Soils of Industrial Regions in the Yangtze River Economic Belt	ZHANG Yi, ZHOU Xin-quan, ZENG Xian-min, <i>et al.</i>	(2062)
Distribution and Environmental Significance of Rare Earth Elements in Typical Protected Vegetable Soil, Northern China	WANG Zu-wei, LIU Ya-ming, WANG Zi-lu, <i>et al.</i>	(2071)
Sources Identification, Ecological Risk Assessment, and Controlling Factors of Potentially Toxic Elements in Typical Lead-Zinc Mine Area, Guizhou Province, Southwest China	ZHANG Fu-gui, PENG Min, HE Ling, <i>et al.</i>	(2081)
Distribution Characteristics of Heavy Metals in Soils Affected by Different Land Use Types in a Superimposed Pollution Area with High Geological Background	WANG Xue-wen, LIU Hong-yan, GU Xiao-feng, <i>et al.</i>	(2094)
Distribution Characteristics of Heavy Metals in Farmland Soils Around Mining Areas and Pollution Assessment	WANG Hai-yang, HAN Ling, XIE Dan-ni, <i>et al.</i>	(2104)
Concentration Characteristics of Heavy Metals in Farmland-Sphagnum System and Ecological Risk Assessment	ZHU Di, ZHANG Zhao-hui, WANG Zhi-hui	(2115)
Spatial Variation and Influencing Factors of Soil pH in Anshun City	CHEN Qing-xia, LU Xiao-hui, TU Cheng-long	(2124)
Synergistic Repair Effect of Calcite-Based Passivator and Low-Accumulation Maize	REN Chao, REN Yu-zhong, LI Jing-tian, <i>et al.</i>	(2133)
Effects of <i>Burkholderia</i> sp. Y4 on Cadmium Damage and Uptake in Rice Seedlings	ZHANG Ya-hui, LIU Yue-min, WANG Chang-rong, <i>et al.</i>	(2142)
Changing Characteristics of Carbon-Based Greenhouse Gas Fluxes in Paddy Field in the Middle-Lower Yangtze Plain in China	LIU Shuo, ZHEN Xiao-jie, LIU Gang, <i>et al.</i>	(2151)
Effects of Plastic Film Mulching and Biochar Application on N ₂ O Emission from a Vegetable Field	HU Jian, JIANG Chang-sheng, CHEN Xin-tong, <i>et al.</i>	(2163)
Effects of Nitrogen Fertilizer Management on CH ₄ and N ₂ O Emissions in Paddy Field	ZHENG Mei-qun, LIU Juan, JIANG Pei-kun, <i>et al.</i>	(2171)
Structure and Functional Diversity of Bacterial Community in Rhizosphere Soil of Typical Vegetation in the Riparian Zone Along the Downstream of Songhua River	WANG Lu-ying, SUN Hui-zhen, YANG Xue	(2182)
Effects of Cotton Stalk Returning on Soil Enzyme Activity and Bacterial Community Structure Diversity in Cotton Field with Long-term Saline Water Irrigation	ZHOU Yong-xue, CHEN Jing, LI Yuan, <i>et al.</i>	(2192)
Effect of pH on the Abundance and Community Structure of Comammox <i>Nitrospira</i> in Paddy Soils	MA Rui, ZHAO Yong-peng, WANG Zhi-hui, <i>et al.</i>	(2204)
Effects of Biochar on Soil Organic Carbon of Eroded Cultivated Layer of Slope Farmland in Purple Hilly Area	ZHANG Jian-le, ZENG Xiao-ying, SHI Dong-mei, <i>et al.</i>	(2209)
Effects of Organic Fertilizer Replacing Chemical Fertilizer on Organic Carbon Mineralization and Active Organic Carbon in Dryland Yellow Soil	LIN Shi-fang, WANG Xiao-li, DUAN Jian-jun, <i>et al.</i>	(2219)
Soil Organic Carbon Storage, Active Component Contents, and Stability Along a Flooding Gradient in the Tidal Wetland of the Jiulong River Estuary	HUANG Xiao-qing, TONG Chuan, LUO Min, <i>et al.</i>	(2226)
System Construction and the Function Improvement of Ecological Carbon Sink in Coal Mining Areas Under the Carbon Neutral Strategy	LIU Xiang-hong, YAN Yong-jun, LIU Wei, <i>et al.</i>	(2237)