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Pollution Pattern of Formaldehyde and TVOC in Indoor Air and Its Control Measures

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ABSTRACT

As primary indoor air pollutants, formaldehyde and total volatile organic compounds (TVOC) are characterized by a wide range of pollution sources, large concentration range and long release periods exist. These pollutants are important indicators for monitoring indoor air pollution. This paper analyses the classification and sources of main pollutants in indoor air, focuses on the pollution patterns of formaldehyde and TVOC in interior environments, and measures the relationships among decoration time, functional rooms of different types, and indoor formaldehyde and TVOC pollution levels to further analyse their patterns and propose control measures for improving indoor air quality. Interior decoration pollution can be categorized into organic, inorganic and radioactive pollution. The detection rate of formaldehyde and TVOC in the tested air samples is 100%. The average values of indoor formaldehyde concentration with decoration periods of 3, 3-12 and 12 months are 0.21, 0.11, and 0.04 mg/m^3 respectively, whereas those of TVOC concentration are 0.92, 0.49 and 0.21 mg/m^3 respectively. Formaldehyde and TVOC concentrations decrease as decoration time increases. The highest average concentrations of formaldehyde and TVOC, maximum over-standard multiples and over-standard rates are observed during the decoration time of 3 months. One year after decorating, formaldehyde content decreases to a value lower than the national standard limit, indoor air quality improves, and the over-standard rate of TVOC concentration significantly decreases compared with that of formaldehyde. The contents of formaldehyde and TVOC in the children's room are significantly higher than those in the master bedroom, second bedroom and living room. The results of this research exhibit a great reference value for further improving the pollution characteristics database of typical indoor air pollution indicators (formaldehyde and TVOC), enriching the pollution characteristics and regularity of indoor air formaldehyde and TVOC, understanding the current situation of indoor air pollution, and solving the problems of indoor air pollution.

INTRODUCTION

Indoor air pollution is the accumulation and scattering of various indoor chemical, biological, and physical pollutants in an interior environment that reduces indoor air quality and endangers human life, work and health. Indoor mainly refers to the room environment. The characteristics of indoor air pollution mainly include a wide range of pollutants, a wide sphere of influence, a long acting time on the human body, a high concentration of short-term pollution, and a long release period of pollutants. Moreover, the environment and development have become major global concerns in the 21st century. In human living spaces, indoor environments are more polluted than outdoors. Furthermore, most people living in the city spend most of their time indoors. Thus, living room environments exert long-term, direct, and widespread effects on human psychological and physical health. Furthermore, indoor areas have become the most direct and frequently contacted environment for people. With the rapidly developing national economy and continuously improving living standards, various types of buildings have emerged. Moreover, people have increased demands on interior decoration, furniture and daily necessities, thereby worsening indoor pollution problems. Among the many types of indoor air pollutants, formaldehyde and total volatile organic compounds (TVOC) are the typical primary pollutants and have a wide range of pollution sources, large concentration range, and long release cycle. Furthermore, they are important indicators for indoor air pollution monitoring. Formaldehyde has a strong stimulating and allergic reaction on human vision, smell, and respiratory organs, has potential carcinogenicity, and is dangerous for children, pregnant women, and old people with low immunity. TVOCs have many types and complex composition, and the long-term inhalation can cause immune-level disorders and severe damage to the liver and the haematopoietic system. By analysing the concentration levels, current pollution situations, and change patterns of indoor formaldehyde and TVOC, this research can provide data and theoretical reference to elucidate the influencing mechanisms of decorations on residents' indoor air quality.

EARLIER STUDIES AND COMMENTS

Indoor air quality problems have been reported from as early as the 1960s. Since the 1980s, air pollutant research has shifted its focus from the outdoor atmosphere to the indoor. Numerous studies have investigated the patterns of indoor air pollution and methods of controlling pollution. Hollowell analysed the concentrations of benzene series and other organic pollutants in offices and discussed the characteristics of source pollution and release intensity (Hollowell et al. 1981). Daily proposed that nonoccupational indoor formaldehyde concentration exposure may exceed the level of occupational exposure standards and require attention (Daily et al. 1981). Seifert detected and compared the concentrations of benzene and other TVOCs in indoor air with those of outdoor pollutants (Seifert et al. 1982). Lebret tested the average concentrations of TVOC in living rooms of more than 1,000 households and found that most indoor concentrations are higher than those outdoors (Lebret et al. 1986). Cohen investigated the indoor and outdoor concentrations in 36 households near industrial areas and found that indoor concentrations are higher than outdoors; however, no significant difference was observed between the two groups (Cohen et al. 1989). Lee analysed the indoor and outdoor air qualities in schools in Hong Kong and proposed control measures (Lee et al. 2000). Daisey analysed the relationship between indoor air quality, ventilation, and health symptoms in primary schools in America and found that many American school districts experience significant indoor environmental problems (Daisey et al. 2003). Bernstein evaluated studies on indoor pollutants and health effects and proposed reasonable measures for environmental control and interventions (Bernstein et al. 2008). Yang analyzed the indoor TVOC and formaldehyde (HCHO) concentrations in 55 different schools in Korea and suggested that the indoor air pollution problems of schools are equated with the chemical substances emitted by building materials or furniture (Yang et al. 2009). Tsigonia analyzed the indoor VOC concentrations in different beauty salons in Greece and concluded that high VOC concentrations are significantly reduced through good ventilation (Tsigonia et al. 2010). Sofuoglu measured the indoor air of three primary schools in Izmir, Turkey during spring, winter and autumn and found that benzene, toluene and formaldehyde are the most significant pollutants, and that these schools are exposed to a high risk of chronic toxicity and carcinogenesis (Sofuoglu et al. 2011). Wolkoff analyzed the effects of VOC concentration on human health in office environments and proposed measures to mediate indoor air pollution (Wolkoff 2013). Jung explored the distribution of indoor air pollutants in hospitals in different regions and proposed ventilation-based measures to improve the indoor air quality of different working areas in hospitals (Jung et al. 2015). Šenitková analyzed the factors that influence indoor air quality and concluded that many of the materials in buildings are sources of indoor air pollution (Šenitková et al. 2016). Shang analyzed the air quality of a shopping mall in western China in summer and found that the TVOC and formaldehyde concentrations of the entire shopping mall are higher than those outdoor due to the lack of fresh air exchange (Shang et al. 2016). Chi collected data from TVOC concentrations of 3122 indoor air samples in China and concluded that decoration materials and human activities affect indoor air quality (Chi et al. 2016). Studies showed that formaldehyde and TVOC concentration levels in indoor air environments, pollution characteristics and patterns, and pollution sources and analysis are popular research topics regarding indoor air pollution. However, the reports on formaldehyde and TVOC concentration levels only focused on the pollution in certain regions for a particular period. The overall pollution level of a region and the entire region as a whole at different stages is difficult to describe. Moreover, many pollution source classification methods, pollution source analyses, and source release models have been established in the environmental cabin; however, most source analyses have been conducted under a single condition and their lease models have been greatly simplified. Various pollution sources often coexist in the actual indoor environments; therefore, a single pollution source analysis and a pollution source release model are difficult to use for explaining the pollution characteristics and patterns in actual environments. Therefore, based on existing research, this paper analyses the main air pollution types and sources and pollution patterns of indoor formaldehyde and TVOC concentrations through experiments and proposes control measures to reduce indoor air pollution.

MAIN INDOOR AIR POLLUTANTS AND THEIR SOURCES

Interior decoration pollution, which includes organic, inorganic and radioactive, mainly comes from decorative building materials, decoration processing, and new furniture and facilities. Large quantities of man-made boards and organic chemical fibre products are widely used in decoration materials. Moreover, the harmful substances in decoration materials are the main sources of decoration pollutants. The organic pollution caused by formaldehyde, benzene series, and TVOC; inorganic pollution, such as ammonia and heavy metals; and radon radioactive pollution are the three most severe and harmful types of pollution.

Formaldehyde: Formaldehyde mainly comes from plates

used for interior decorations, such as plywood, medium density fibreboard, blackboards, particleboards, veneers, laminated and composite floorings, and man-made boards; and from furniture made with man-made boards and formaldehyde-containing paints. Moreover, wall cloths, wallpapers, chemical fibre carpets, foam plastic, paints, insulation layers, adhesives and other types of decorative materials may contain formaldehyde that might diffuse into indoor areas. Formaldehyde has a strong adhesive capacity, anti-pest effects, and can increase the hardness of plates. Urea-formaldehyde resin glue, which has formaldehyde as its main component, is widely used in various decoration materials and is the main cause of indoor formaldehyde pollution. Formaldehyde is mainly harmful to the respiratory system and has carcinogenic and teratogenic effects; moreover, it can be hidden in plates and furniture, with a release period exceeding 10 years.

Benzene series: The benzene series include benzene, toluene, ethyl benzene and xylene. Toluene and xylene are commonly used in interior decoration materials, such as various paints, adhesives, coating and waterproofing materials, and solvents or diluents. Benzene series can be released by wall packaging modelling and new furniture and floors that use paint and coating. Benzene series are severe carcinogens that cause blood toxicity, genotoxicity and carcinogenicity, inhibit and endanger haematopoietic functions of the human body, cause blood diseases, and exert stimulating effect on eyes, skin and the respiratory tract. Toluene might have huge effects on the fetus and trigger embryonic diseases.

Total volatile organic compound: TVOC, which is a total mass concentration that includes all VOCs in indoor air, has a highly complex composition and various categories, such as aldehydes, ketones, olefins, aromatics and alkanes. New TVOC species have been synthesized with the development of modern society and use of new decoration materials. TVOC can harm the human body and hundreds of VOCs are found in non-working indoor environments. TVOC is mainly derived from raw chemical materials, and many types of chemical raw materials, such as paint, glue and coatings, are used in house renovations. Many kinds of paints and additives are used for renovation, and paints have a complex composition, especially some solvent-based paints that inevitably contain TVOCs. Other interior decoration materials, such as wallpapers, contain TVOCs. Moreover, plastic sheets, foam insulation materials, man-made boards, and other building materials contain TVOCs as well. Used chemical fibre materials, tapestries, carpets and chemical fibre curtains, as well as daily office supplies, such as printers, copiers and ink, produce TVOCs.

Ammonia and heavy metal pollution: Most ammonia pollution types are caused by concrete additives used in the construction of buildings and are prevalent in the northern regions of China. Concrete antifreeze agents are added into the walls to improve the antifreeze effects during winter construction. Moreover, early strength and high-alkali concrete expansion agents are used to accelerate concrete coagulation. These additives contain substantial ammonia substances. However, as temperature and humidity change, ammonia is released from the walls and might last more than 10 years. Furthermore, building insulation and waterproof layers contain ammonia. In southern regions, ammonia pollution mainly comes from brighteners and supplements used in decoration materials, plates and furniture. Ammonia exerts strong stimulating and corrosive effects on the human respiratory tract and skin, and long-term exposure causes headache, sore throat, cough, chest tightness, tears, skin pigmentation, decreased immunity, severe pulmonary oedema, and even lung cancer. Heavy metal pollution in decorations is caused by lead, cadmium, chromium, mercury and arsenic that mainly come from paints, paintings, adhesives and furniture. The current national standard "Indoor Decorating and Refurbishing Materials - Limit of Harmful Substances of Interior Architectural Coatings" specifies the lead, chromium, cadmium and mercury limits of decoration materials.

EMPIRICAL STUDY ON THE POLLUTION PATTERNS OF INDOOR FORMALDEHYDE AND TVOC

Survey Object and Sample Source

In this paper, 593 urban dwellings in five different districts in Beijing City (Dong Cheng District, Xicheng District, Haidian District, Chaoyang District, and Fengtai District) with different social backgrounds and decoration ages are randomly selected from January 2016 to December 2016. The formaldehyde and TVOC concentrations were tracked in the indoor environments of different rooms (bedroom, living room, second bedroom and study). Before sampling, the doors and windows of test rooms were in their daily state, and then appropriately closed for 1-12 hours for sampling. The sampler is placed in the centre of the room and 1.5 meters above the ground. The indoor environmental conditions (such as temperature, humidity and atmospheric pressure) and sampling point conditions (such as room area, decoration status, human activity and ventilation conditions) were recorded during sampling. According to the national standard Code for Indoor Environmental Pollution Control of Civil Building Engineering (GB 50325-2010 (2013 version)), sampling points should be evenly distributed, avoid air ducts and vents, at least 5 m away from the

inner wall, and 0.8-1.5 m above the floor; moreover, the doors and windows should be closed for 1 h before testing. A large bubble absorption tube was used to collect formaldehyde and a first-stage soap film flow meter was used for calibration before sample data collection, with an error of ≤5%. TVOC was collected using a Tenax-TA adsorption tube and activated by N_2 at 300°C before use.

Main Instruments and Methods

The main instruments were a visible spectrophotometer (7230G, Shanghai Precision & Scientific Instrument Co., Ltd., Shanghai, China), a gas chromatograph (GC112A, Shanghai Precision & Scientific Instrument Co. Ltd., Shanghai, China), a thermal analyser (RJ-III, Guangdong Medical Devices Factory, Guangdong, China), and a Tenax-TA sampling tube (Beijing Municipal Labour Protection Science Research Institute, Beijing Sanhuan Huarao Electronics Trading Co. Ltd., Beijing, China). The detection methods were taken from literature. Formaldehyde detection referred to the second part of Health Inspection Method for Public Places (GB/T 18204.2-2014). Chemical pollutants and the phenol reagent spectrophotometric method was adopted for determination. TVOC detection adopted thermal analysis/capillary gas chromatography and the determination was conducted according to the Code for Indoor Environmental Pollution Control of Civil Building Engineering (GB 50325-2010).

TEST RESULTS AND DISCUSSION

Relationship between decoration time and indoor formaldehyde and TVOC concentrations: To explore the impact of different decoration times on indoor formaldehyde and TVOC concentrations, the measured data were divided into three groups according to decoration time: Group A was within 3 months after decoration, Group B was 3-12 months after decoration and Group C was 12 months after decoration. Table 1 shows that Group A exhibits the largest average formaldehyde content, maximum over-standard multiple, and over-standard rate, indicating that the formaldehyde release amount peaked 3 months after decoration; therefore, the rooms were not suitable for living during this period. The average formaldehyde content of Group B was 0.11 mg/m3 and was significantly lower than that of Group A (0.21 mg/m^3). One year after decoration, the average formaldehyde content of Group C decreased to a value below the national standard limit, and the indoor air quality had improved. This finding indicated that the formaldehyde emission gradually decreased overtime. This phenomenon is related to the pollution source and formaldehyde release pattern. Moreover, formaldehyde mainly comes from various man-made boards with urea-formaldehyde resin as the binder (such as plywood, fibreboard and particle board) and water-soluble paints that contain aldehyde preservatives; thus, formaldehyde has various sources, high toxicity and long pollution release time. In this survey, the formaldehyde content of Group C remained above 14.56% 1 year after decoration. This phenomenon occurred due to the high formaldehyde content and long release time of decoration materials. The TVOC concentration had a change pattern similar to that of formaldehyde, and its concentration decreased with prolonged duration. After 3 months, the over-standard rate of TVOC concentration was significantly reduced compared with that of formaldehyde, which occurred because TVOC has a short release cycle.

Formaldehyde and TVOC pollution situations in different types of functional rooms: As given in Table 2, the average formaldehyde content in different functional areas are in the order (descending) of: children's room > second bedroom > master bedroom > living room. The formaldehyde content over-standard rate of the most severely polluted children's room was 59.74%, which was significantly higher than those of the master bedroom, second bedroom, and living room. The average TVOC content in the living room has the minimum value; the content in the master bedroom was similar to that in the second bedroom, with the children's room having the highest content. These results are related to the functional partition and decoration features of the rooms. The living room is usually larger than the bedrooms and children's room and is well ventilated and thus conducive to the diffusion of pollutants. Therefore, the living room has low formaldehyde and TVOC contents. The children's room usually has complex decoration, uses more plates, has a small indoor space, and has concentrated sources of pollution. Hence, the diffusion of pollutants is affected and the formaldehyde and TVOC contents of the children's room are significantly higher than those of the other rooms.

COUNTERMEASURES AND MEASURES TO CONTROL INDOOR POLLUTANTS

Strengthen the prevention of interior decoration pollution and control the pollution sources: Interior decoration pollution should be prevented and controlled from the source. Effective measures should be considered to control the sources of main pollutants in decoration and avoid the introduction of various pollution sources to minimize the harm to the human body. People should promote the concept of ecofriendly house decoration and adopt healthy, simple, and reasonable decoration. People should not blindly follow trends, pursue luxury decoration, and exhibit large-scale use of the same or many decoration materials. For example, the ecofriendly E1-level plates in the cur-

Table 1: Relationship between decoration time and concentration of indoor formaldehyde and TVOC.

			Formaldehyde concentration			TVOC concentration		
	Decoration age (months)	Number of households detected	Average value (mg/m^3)	The maximum over-standard multiple	Over-standard rate (%)	Average value (mg/m^3)	The maximum over-standard multiple	Over-standard rate (%)
Group A	3	192	0.21	5.2	50.31	0.92	1.14	14.71
Group B	3-12	198	0.11	3.7	29.62	0.49	0.47	5.44
Group C	12	203	0.04	2.8	14.56	0.21	-	-

Table 2: Formaldehyde and TVOC pollution situations in different types of functional rooms.

		Formaldehyde concentration		TVOC concentration	
Functional room	Number of households detected	Average value (mg/m^3)	Over-standard rate(%)	Average value (mg/m^3)	Over-standard rate(%)
Living room	175	0.12	30.14	0.32	5.64
Master bedroom	196	0.16	29.62	0.42	9.35
Second bedroom	186	0.19	14.56	0.43	12.35
Children's room	194	0.25	59.74	0.59	16.54

rent market contain a small amount of formaldehyde. If a large number of E1-level plates are used in a certain area, harmful substances will accumulate and exceed the standard. Moreover, the overall decoration design should consider health perspectives and adopt enough effective ducts. Rooms should have good ventilation and lighting to facilitate the diffusion of harmful substances. Decoration materials are the main sources of pollution; thus, pollution control should focus on purchasing and selecting building materials. Branded building materials that have green logos and meet national standards should be considered. Furthermore, improved options include choosing natural materials or those that are close to nature, and paying attention to the ecofriendliness of products.

Strengthen pollution prevention during construction and avoid contact with indoor pollutants: The quality of decoration technology exerts important impact on decoration pollution. Using different decoration technologies to treat the same materials may lead to different pollution situations. A qualified formal decoration company should be employed for decoration, and people should pay attention to the construction and management level of the decoration team and ensure a scientific and ecofriendly construction technology. Pollution should be strictly controlled during construction, in that, the surfaces and edges of man-made boards should be wrapped and ecofriendly varnish applied to form a curing layer to inhibit formaldehyde diffusion. When installing floors, people should not use large core plates as liners to avoid excessive indoor formaldehyde. The partitions should adopt keels or other inorganic materials instead of boards. People should not use toluene or gasoline for large scale paint removal and degreasing during construction, and instead adopt mechanical grinding as much as possible. Diluents, adhesives and solvents should be timely sealed for storage after use, and decoration wastes should be timely removed. For wood products that need to be painted, such as doors, cabinets, and furniture, people should buy finished products from professional manufacturers, avoid indoor productions, and avoid painting to reduce pollution. The new furniture should be made from wood materials. When purchasing furniture made with man-made boards, people should pay attention to the edge sealing, place the furniture outside for a period of time after the purchase, and then move it inside the room. Furthermore, people should avoid using synthetic carpets that contain numerous harmful substances and those that may breed microorganisms that lead to secondary pollution.

Strengthen the governance over decoration pollution after construction and effectively reduce the concentration of pollutants: Newly renovated houses have the severest pollution; thus, people should not immediately move into such houses. Before moving in, they should open doors and windows for some time to expedite ventilation and diffuse pollution. Generally speaking, if the room decoration is completed in early summer, the formaldehyde and other substances can be reduced to a safe level, 2 months after the

decoration. If the room decoration is completed in spring, autumn and winter, the levels of formaldehyde and other substances are lowered to a safe level after 4 months to 6 months. Ventilation accelerates the release of benzene, formaldehyde, and other harmful substances. Moreover, ventilation should be speed up in high humidity and temperature because pollutants have the fastest emission under such conditions. Plants that purify indoor air should be placed inside houses to remove and adsorb dust, sterilize and reduce pollution, and improve the air quality. Some activated carbons and bamboo charcoal can be scattered in the living room, cabinets and toilets to remove ammonia, aldehydes, benzene, TVOC and other pollutants. Users with good economic conditions can install air purification devices to purify, adsorb and filter indoor air. Air purification and ventilation equipment purify indoor air through mechanical filtration, electrostatic dust removal and adsorbents. Activated carbon is the most commonly used adsorbent and its service life is determined by the flow rate of indoor gas, adsorption efficiency and amount of activated carbon.

Strengthen the market management of building materials and regulate market players legally: Indoor air pollution prevention and control is an integrated issue. Prevention, rather than governance, is the key to completely solving the problem. Administration of industry and commerce, quality supervision organizations, and other relevant departments should improve their efforts in strengthening the management of various materials. Material pollution should be tested regularly, substandard materials should be strictly prohibited from the market, toxic and harmful materials should be prevented from houses, and pollution should be controlled from the source. Moreover, administration of industry and commerce and quality supervision organizations should investigate false publicity and other deceitful behaviours and set strict market access to building materials to in turn strictly control the quality of building materials. Furthermore, administrations of industry and commerce at all levels should timely register or cancel building material enterprises with cancelled production. If any enterprise does not apply within the specified period, then its business license should be revoked according to the law. Ultrarange operations and unlicensed business behaviours should be investigated and punished according to the law to further regulate market players. Efforts in monitoring the quality of building materials should be improved. The test results of legal quality inspection agencies should be timely released to the public to provide consumer warnings and strengthen social supervision. If the inspection and monitoring results suggest that an enterprise sells substandard building materials, it should be severely punished according to relevant laws. If the products have unqualified monitoring results but is already in the market, consumers should promptly notify the relevant industrial and commercial authorities to implement fast and strict investigations. Case investigations and punishments should be strengthened. Right maintenance service networks should be expanded, the sources of clues should be expanded, and an improved reward system should be established. Office clerks should accept and deal with the complaints and reports regarding the quality of building materials in a timely manner, major cases should be timely exposed to the public, and suspected criminal cases should be promptly transferred to public security organizations.

CONCLUSION

In view of indoor formaldehyde and TVOC pollution, this paper selected 593 urban dwellings in different areas in Beijing with different social backgrounds and decoration times, to explore the formaldehyde and TVOC concentration levels, pollution status and change patterns in different functional rooms (bedroom, living room, second bedroom, and study). Research results indicated that interior decoration pollution can be categorized into organic, inorganic and radioactive pollution. The detection rate of formaldehyde and TVOC in the tested air samples was 100%. The formaldehyde and TVOC concentrations gradually decreased as decoration time increased. The average concentration, maximum over-standard multiple, and over-standard rate of formaldehyde and TVOC peaked within three months after decoration. After one year, the average formaldehyde content decreased to a value below the national standard limit and the indoor air quality was improved. The over-standard rate of TVOC concentration was significantly decreased compared with that of formaldehyde, three months after decoration. Moreover, the formaldehyde and TVOC contents in the children's room were significantly higher than those in the master bedroom, second bedroom and living room. This research focuses on the analysis of formaldehyde and TVOC pollution patterns in indoor air environments, proposes measures to improve indoor air quality, and provides a theoretical basis to elucidate indoor air pollution and choose a reasonable accommodation time. However, due to the restrictions of time and conditions, this research has limitations and many problems could be further explored. In the future, an in-depth research should quantify the source intensity and release patterns of formaldehyde and TVOCs in actual rooms, improve the concentration prediction model of indoor pollutants according to seasonal changes and other factors, enrich various tests about concentration levels and toxic effects of indoor pollutants, and ensure that the indoor pollutants released by various pollution sources meet the relevant standards.

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