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Comprehensive Analysis of Indoor Formaldehyde Removal Techniques: Exploring Physical, Chemical, and Biological Methods

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Abstract: This research focuses on the evaluation of diverse approaches for removing formaldehyde from indoor environments, which is a significant concern for indoor air quality. The study systematically examines physical, chemical, and biological methods to ascertain their effectiveness in formaldehyde mitigation. Physical methods, including air circulation and adsorption, particularly with activated carbon and molecular sieves, are assessed for their efficiency in various concentration scenarios. Chemical methods, such as photocatalytic oxidation using titanium dioxide and plasma technology, are analyzed for their ability to decompose formaldehyde into non-toxic substances. Additionally, biological methods involving plant purification and microbial transformation are explored for their eco-friendly and sustainable removal capabilities. The paper concludes that while each method has its merits, a combined approach may offer the most effective solution for reducing indoor formaldehyde levels. The study underscores the need for further research to integrate these methods in a practical, cost-effective, and environmentally sustainable manner, highlighting their potential to improve indoor air quality significantly.

Keywords: Indoor air quality; Formaldehyde removal; Photocatalytic oxidation; Activated carbon; Biological purification

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1. Introduction

As the quality of life improves, people are paying increasing attention to the quality of their living environment. Before moving into a new house, they want to know whether the indoor air quality meets the standards and if it poses any health risks. They also seek information on how to measure air quality, and what measures to take if the standards are exceeded. The primary pollutant in newly renovated houses is formaldehyde, which mainly comes from furniture, decorative materials, and paints used during the renovation process. Formaldehyde is embedded within these materials, and naturally, it is released slowly over a long period, with a release cycle that can last up to 15 years. Direct skin contact with formaldehyde can cause allergic dermatitis, pigmentation, and necrosis. Long-term inhalation of low doses can lead to symptoms like memory decline, sleepiness, and neurasthenia. High-concentration inhalation can induce respiratory diseases and even cancer; high levels of formaldehyde are also genotoxic substances that can cause mutations in genetic material, making it an "invisible killer" in homes [1].

2. The harm of indoor formaldehyde

Individuals' sensitivity to formaldehyde varies greatly, with the eyes being the most sensitive, followed by the sense of smell and respiratory irritation. Studies [2] show that a reduction in olfactory function is characterized by an increased threshold and decreased sensitivity. The human olfactory threshold for formaldehyde is 0.06–0.07 mg/m^3. At concentrations below 1.2 mg/m^3, the irritation is mild; above 3.6 mg/m^3, irritation increases; at 4.8–6.0 mg/m^3, 30 minutes of exposure can cause teary and itchy eyes and throat dryness; 12–24 mg/m^3 can lead to difficulty breathing, coughing, and headache; at ≥ 60 mg/m^3, it can cause pneumonia, pulmonary edema, and even death. Furthermore, exposure to a concentration of 5 mg/m^3 of formaldehyde can immediately cause a drop in blood pressure and an increase in neutrophils (21%), accompanied by a left shift in neutrophilic toxic granules, and a significant increase in eosinophils on the second day of poisoning.

3. Physical methods for removing indoor formaldehyde

3.1. Physical adsorption method

Physical adsorption is the result of van der Waals forces between the adsorbate and adsorbent molecules, generally more effective at lower pollutant concentrations. Commonly used adsorbents for physical adsorption include materials with a large specific surface area, like activated carbon and molecular sieves. Activated carbon, as a widely used adsorbent, is extensively applied in the removal of atmospheric pollutants. Research teams [3] have studied the influence of the specific surface area and pore structure of activated carbon on formaldehyde adsorption. The results show that microporous materials with a larger specific surface area are conducive to enhancing the adsorption effect of formaldehyde. Compared to micropores, mesopores can promote the adsorption process of formaldehyde more rapidly, making molecular sieves more effective than activated carbon in removing formaldehyde. Several molecular sieves were used for static adsorption of formaldehyde, and the impact of specific surface area and structure on adsorption efficiency was examined. The results indicate that pore sizes in the mesoporous range are beneficial for enhancing formaldehyde removal. Although the article points out that the physical properties of activated carbon and molecular sieves can effectively adsorb formaldehyde, it does not provide experimental evidence for low-concentration formaldehyde environments. Additionally, new types of filter materials, such as high-efficiency particulate air filtering materials, are also used for the removal of indoor formaldehyde. By improving the material itself and its resistance to environmental impacts, the efficiency and effectiveness of formaldehyde filtration are enhanced.

3.2. Air circulation method

The air circulation method leverages the volatile nature of formaldehyde to reduce its indoor concentration through natural or mechanical ventilation. Researchers have developed air quality models to simulate the process of ventilating and exchanging air for the migration and removal of indoor formaldehyde. A research team [4] used natural ventilation simulations to study the diffusion of indoor formaldehyde, finding that a starting mass concentration of 0.16 mg/m^3 of formaldehyde could be reduced to meet health standards (≤0.10 mg/m) after 150 seconds of ventilation. The simulation under natural ventilation conditions showed that it could decrease indoor formaldehyde levels. Natural ventilation effectively and quickly purifies low concentrations of indoor formaldehyde, but when the concentration is high, this method is slow and may not achieve the desired results. Mechanical ventilation can increase the rate of indoor airflow, thereby effectively enhancing the efficiency of removing formaldehyde. However, the release of formaldehyde indoors is a continuous process, and both natural and mechanical ventilation can only temporarily reduce its concentration without fundamentally solving the problem of indoor formaldehyde pollution. Additionally, this method is greatly affected by seasons. For example, in some northern areas of China, where winters are cold and outdoor pollution is more severe than indoors, this method is not applicable. Although this method has many limitations, it is still widely used due to its characteristics of low cost, simple operation, and effective short-term removal, and it can be combined with other methods to improve the removal rate of indoor formaldehyde.

4. Chemical methods for removing indoor formaldehyde

4.1. Photocatalytic oxidation

Photocatalytic oxidation involves treating the surface of photocatalytic materials with light, generating photoelectrons and holes on the surface. These electrons and holes produce highly active free radicals through their redox properties, ultimately achieving the removal of pollutants. Titanium dioxide is the primary material used in photocatalytic oxidation. This method is not only effective in removing pollutants but also safe and pollution-free.

Using titanium dioxide (TiO_2) as a photocatalyst and ultraviolet (UV) light irradiation to remove low concentrations of formaldehyde, studies have shown [5] that the photocatalytic oxidation method with TiO_2 is effective in eliminating formaldehyde. Further research [6] indicates that Cerium/TiO_2 photocatalytic oxidation is the most efficient, although the rate of formaldehyde removal decreases as the initial concentration increases. However, the limited reaction space somewhat restricts the application of such catalysts. To address this issue, materials with a larger specific surface area, such as activated carbon, are commonly used as carriers. Under illumination, using TiO_2-supported activated carbon fibers (ACF) to remove formaldehyde has shown [7] that increasing the intensity of light can effectively purify low concentrations of formaldehyde without causing secondary pollution. The use of TiO_2-loaded activated carbon fibers for formaldehyde removal [8] demonstrated that under visible light, the removal efficiency of activated carbon fiber material is significantly higher than that of activated carbon fiber alone. The effect of different wavelengths of UV light on formaldehyde removal using TiO_2-loaded activated carbon was also studied. The results show that composite UV light achieves the best formaldehyde removal effect.

The continuous development and improvement of photocatalytic oxidation have made it highly efficient in removing indoor formaldehyde. However, this method requires light irradiation and can be affected by humidity, wavelength, and other factors, which might prevent it from achieving the desired removal effect. Additionally, the investment cost for this method is relatively high, making it less suitable for solving formaldehyde pollution in everyday life.

4.2. Plasma technology

Plasma technology is generally divided into low-temperature and high-temperature plasma, with low-temperature plasma being more commonly used for purifying polluted gases. Low-temperature plasma technology treats polluted gases by using high-energy electrons to collide inelastically with gas molecules, causing excitation, dissociation, ionization, and other activation reactions, thereby achieving the removal of pollutants. This method is characterized by good removal efficiency and fast reaction speed, making it effective in removing indoor formaldehyde. However, plasma technology alone has poor selectivity in removing formaldehyde, so it is often used in conjunction with other methods.

Combining plasma technology with photocatalytic oxidation for formaldehyde removal has shown [9] that the synergistic purification effect is significantly higher than either method alone. Research teams [10] using plasma-catalytic oxidation with direct current corona discharge and MnO_x/Al_2O_3 (manganese oxide/alumina) as a catalyst found that the formaldehyde removal rate greatly increased when combined with catalytic oxidation. However, this method produces by-products like ozone (O_3) and intermediate products like formic acid (HCOOH), which can decrease the degradation rate of formaldehyde.

Plasma technology for purifying formaldehyde has the advantages of fast degradation rate and good effectiveness. However, the high voltage discharge used in reactors produces by-products like O_3, which not only hinders the degradation of formaldehyde but also causes secondary pollution to the surrounding environment.

5. Biological methods for removing indoor formaldehyde

Biological methods are a natural approach to purifying pollution, primarily using the absorption, oxidation, and complexation functions of plants or microorganisms to remove pollutants. Compared to physical methods, biological methods can effectively purify indoor formaldehyde in a safe, environmentally friendly manner without secondary pollution. This approach is economical and eco-friendly, mainly including plant purification and microbial transformation methods.

5.1. Plant purification method

The plant purification method uses potted plants to absorb indoor polluted air, which is then decomposed into harmless substances through various reactions within the plant. To identify plants effective at removing formaldehyde, researchers [11] have studied the purification capabilities of different plants. A research team selected 21 types of plants with different leaf types for formaldehyde purification experiments under certain light conditions. The results showed that succulents and lanceolate plants were less efficient, while spider plants were the most effective at removing formaldehyde. It was suggested that the shape of the plant leaves affects the absorption of formaldehyde, providing direction and a theoretical basis for future research. Another team [12] used the smoke purification method in a closed environment to study the effect of plants and soil surface microorganisms on the purification of low concentrations of formaldehyde. The results indicated that potted plants achieved a 33% purification rate of formaldehyde, with the soil microorganisms in devil's ivy having the most significant effect. The research also further refined the study of plant purification effects on high concentrations of formaldehyde, proposing that soil microorganisms play an important role in purifying formaldehyde, offering a new direction and theory for biological purification.

Plant purification methods can continuously absorb formaldehyde in the air and have a stable removal effect without secondary pollution, making them safe and environmentally friendly. However, this method has limitations like slow purification rates, long duration, and significant environmental impact, which restrict its use in indoor formaldehyde purification.

5.2. Microbial transformation method

Microorganisms have certain capabilities to purify formaldehyde, hence microbial transformation purification is also used for indoor formaldehyde removal. This method involves the metabolic activity of microorganisms, which degrades indoor formaldehyde into non-toxic and harmless CO_2 and H_2O, thus achieving pollution removal. However, not all microorganisms are effective in purifying formaldehyde. Research teams [13] found that biological filters based on methylotrophic bacteria could purify both low and high concentrations of formaldehyde effectively. Using microorganisms' formaldehyde oxidase can also remove indoor formaldehyde effectively, but the mechanism of microbial degradation of formaldehyde is not yet fully understood and requires further exploration.

Currently, microbial purification of formaldehyde is often used in conjunction with plant purification, achieving both effectiveness and environmental friendliness. Biological methods for purifying indoor formaldehyde are highly effective and risk-free in terms of secondary pollution. However, the biological entities used in this method have stringent environmental requirements, limiting its widespread application in daily life and production processes.

6. Conclusion

This paper comprehensively explored various methods for the removal of indoor formaldehyde, a significant environmental pollutant that poses health risks in residential and occupational settings. The methods examined ranged from physical and chemical to biological approaches, each with its unique mechanisms and effectiveness. The physical methods, including air circulation and adsorption techniques, provide practical solutions for reducing indoor formaldehyde levels. Notably, the use of activated carbon and molecular sieves demonstrates considerable potential. However, these methods have limitations in terms of their effectiveness against high concentrations and continuous emission of formaldehyde.

Chemical methods, particularly photocatalytic oxidation using titanium dioxide and plasma technology, showed high efficiency in formaldehyde removal. These approaches benefit from their ability to decompose formaldehyde into harmless substances. However, factors like the need for light irradiation in photocatalytic oxidation and the production of secondary pollutants in plasma technology restrict their widespread application. Biological methods, involving plant purification and microbial transformation, emerge as environmentally friendly options with the added aesthetic and psychological benefits of green spaces. Plants and microorganisms can effectively degrade formaldehyde, transforming it into non-toxic substances. However, the practical application of these methods is constrained by their slower reaction rates and the environmental sensitivity of the biological agents.

In conclusion, while each method exhibits specific strengths and limitations, a combination of these strategies could potentially offer a more holistic and effective solution to indoor formaldehyde pollution. Future research should focus on integrating these methods in a cost-effective and environmentally sustainable manner, potentially leading to innovative solutions for improving indoor air quality and safeguarding public health.

Disclosure statement

The author declares no conflict of interest.

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