Research Article

Effect of Free Formaldehyde on Chemical Structure and Thermal Properties of Nano-Titanium Dioxide Resin

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In order to understand and improve the degradation rate of formaldehyde, the study on the chemical structure and thermal properties of nano-titanium dioxide resin by free formaldehyde was proposed. In this research, nano-titanium dioxide was prepared by the low temperature hydrolysis method and characterized by using the scanning electron microscope (SEM) and X-ray diffraction (XRD). The degradation behavior of formaldehyde was studied by using the degradation rate of formaldehyde in the container as the evaluation index. The influence of the photocatalytic coating on the degradation rate of formaldehyde under different loading conditions, different temperatures, and different humidity was investigated. The experimental results show that the formaldehyde degradation rate of the photocatalytic coating prepared by loading 5 g nano-TiO_2 into a 200 g emulsion system can reach 93% under the conditions of room temperature of 25°C, humidity of 50%, and UV lamp irradiation of 120 min. *Conclusion.* This study is obviously better than the commercial P25 nano-titanium dioxide degradation effect of formaldehyde.

1. Introduction

With the development of social economy, people's requirements for the environment are also increasing day by day, and the problem of air pollution has attracted people's extensive attention. Our country's population spends most of its time in enclosed spaces such as indoors or in cars. The problem of indoor air pollution needs to be solved urgently. The quality of indoor or car environment is related to people's physical and mental health [1]. In recent years, people's living standards have also been greatly improved, but indoor decoration and decoration, cleaning agents, pesticides, disinfectants, and other chemical agents are full of life in all aspects, which produce formaldehyde-based organic matter, causing environmental pollution. It has seriously affected people's quality of life and health, so it is very necessary to eliminate formaldehyde using efficient and simple methods. Long-term exposure to formaldehyde will cause oral cancer, skin cancer, lung cancer, leukemia, and other diseases, causing serious harm to the human body. On October 27, 2017, formaldehyde was included in the list of class I carcinogens published by the WHO's International

Agency for Research on Cancer [2]. In order to improve the living environment and quality of life, it is a hot topic to seek an environmentally friendly and effective formaldehyde degradation treatment method. The traditional formaldehyde treatment methods are mainly the adsorption method, condensation precipitation method, and so on, which have certain limitations.

Often just finished decoration of the house formaldehyde concentration will exceed the standard, and too much high concentration of formaldehyde will cause great harm to the human body and make people have difficulty breathing, severe headache, sore throat, and other symptoms. Therefore, the effective reduction or control of formaldehyde concentration is an effective means to ensure health. China specified in 2005 that the concentration of formaldehyde in class 1 civil buildings must be less than 0.08 mg/m³. Therefore, the improvement of indoor air quality must receive extensive attention [3]. Among many methods, nano-Ti O2 photocatalytic technology has been widely concerned because of its unique advantages, but the visible light utilization rate is low due to the defects of nano-Ti O2 itself, so it is necessary to modify nano-Ti O2 to improve the visible

light utilization rate and photocatalytic performance, as shown in Figure 1.

2. Literature Review

Liu Y. prepared a photocatalytic coating with TiO_2, which could degrade 69% of formaldehyde under UV lamp irradiation for 30 min [4]. Some studies have proved that the photocatalytic degradation efficiency of TiO_2 photocatalytic coatings is closely related to the amount of nano-TiO_2 in them. The study of Zaer-Miri and S. showed that the photocatalytic degradation of formaldehyde gas by the photocatalytic coating containing modified nano-titanium dioxide could reach 70% [5]. Guo's study proved that under the lighting condition of 12 36 W fluorescent lamps, the removal rate of formaldehyde by photocatalytic coatings containing TiO_2 increased significantly [6]. Bai's study showed that in the visible light region, the degradation performance of organic pollutants by TiO_2 photocatalytic coatings mixed with Ag was significantly improved, and the removal rates of benzene and formaldehyde reached 69.1% and 71.1% within 24 h, respectively [7]. Qian applies the TiO_2/VACF photocatalytic layer on the surface of the purification layer of the air purifier and finds that different UV lamp powers have different photocatalytic degradation efficiency of formaldehyde in the air purifier. Studies show that when the power of UV lamp changes from 20 W to 61 W, the photocatalytic efficiency of the TiO_2/ACF photocatalytic layer on formaldehyde increases significantly [8]. The reaction time of gaseous pollutants on the surface of a photocatalyst of the air purifier is also an important factor to be considered in design. Wang's study showed that when the surface area of the photocatalytic film at the core of the air purifier reached half of the surface area of the whole purifier, its reaction was larger than the film area, and the photocatalytic efficiency was also higher [9]. Kao reduced the air circulation velocity in the reactor through the slow airflow, increased the contact time between the gas and the photocatalytic film in the air purifier, and increased the degradation rate of air pollutants in the reactor from 5% to 44% [10]. The photocatalytic film area in the core area of the air purifier is also related to the pollution density in the air environment, which will also affect the degradation efficiency of the purifier. And, with a glass plate as the carrier and titanium dioxide as the reaction subject, toluene was used as the simulated pollutant to study the influence of humidity on toluene degradation efficiency and byproducts on the experiment. The results show that humidity not only has a great influence on the photocatalytic degradation of toluene but also produces different byproducts, but when humidity is high, the byproducts produce the least damage to the human body [11]. Makarevich studied the photocatalytic effect of air purifiers with honeycomb structure, tubular static mixer structure, and spiral structure under the two factors of the dynamic conduction rate and external mass conduction rate. Different structures had little influence on the external mass conduction rate but had an important influence on the dynamic conduction rate [12].

At present, the methods to remove formaldehyde include the physical adsorption method, plant absorption purification method, ventilation purification air method, and catalytic degradation technology, among which the study of using photocatalytic coating to degrade formaldehyde has become the focus. The degradation rate of formaldehyde of nano-TiO_2 and photocatalytic coatings prepared in this study reached 93% under the irradiation of an ULTRAVIOLET lamp, and the degradation rate of formaldehyde was still good after the saturation experiment.

3. The Research Methods

3.1. Titanium Dioxide. Titanium dioxide is a kind of polycrystalline substance, commonly known as titanium dioxide, with the chemical formula TiO_2, used in photocatalysts, cosmetics, disinfection, sterilization, photocatalysis, and other fields. Nano-TiO_2 has a good photocatalytic effect, stable property, and no secondary pollution. It is used in photocatalytic reaction. Iron dioxide is stable in nature, and there are three crystal types: plate titanium, anatase, and rutile, which can be converted under certain conditions. Among them, plate titanium has the worst stability, and rutile has the highest stability. The ti-Ti bond length of the anatase type is longer than that of rutile, while the Ti-O bond length is shorter than that of rutile.

In the crystal structure of titanium dioxide, titanium ions are located in the center of the octahedron formed by six adjacent ions. Three titanium atoms are connected around the oxygen atom, and three titanium atoms are located in three different octahedron centers. Of the three crystal types of titanium dioxide, only anatase and rutile have photocatalytic properties. The anatase type has better photocatalytic ability than the rutile type. This is mainly because the gap width of the anatase type is 3.2 eV, and the conduction potential is −0.5 eV. O2 can easily obtain conduction band electrons, thus leading to electron-hole separation and thus improving the catalytic performance [13]. The rutile band gap width is 3.0 eV, and the conduction potential is −0.3 eV, while the standard potential of O2/O2- is −0.33 eV. Therefore, the conduction electrons cannot be captured by O2 on the surface of TiO_2, so the catalytic activity is not good.

Up to now, most of the semiconductor photocatalysts studied are n-type semiconductor compounds with a wide band gap. Among these semiconductors, TiO_2, CdS, and ZnO have the highest photocatalytic activity, but CdS and ZnO are prone to photocorrosion under light, resulting in Cd2+ and Zn2+, secondary pollution to the environment, toxicity to organisms, and harm to the environment. TiO_2 photocatalytic materials do not have these disadvantages. It has many unique advantages, such as stable chemical properties, no photocorrosion after illumination, no toxicity to organisms, abundant sources, high potential of photogenerated electrons and holes, and strong oxidation and reducibility. Therefore, TiO_2 photocatalytic materials have broad application prospects in air purification, sewage treatment, organic matter degradation, and antibacterial and antivirus applications. The band gap of TiO_2 is 3.0–3.2 eV,

| Pretreatment of titanium dioxide nanoparticles, TiO2 | Preparation of titanium dioxide nanorods, NR | The surface of titanium dioxide nanorods is loaded with Fe,Fe/NR |

FIGURE 1: Chemical structure of free formaldehyde on nano-titanium dioxide resin.

TABLE 1: Reference formulation of nano-TiO$_2$ photocatalytic coating.

The raw material	m/g
Hydroxyethyl cellulose	1
Film-forming agent	1.5
Heavy calcium carbonate	95
The styrene-acrylic emulsion	80
Dispersant	3
Flow ping agent	2
Thickener	Moderate amount
Distilled water	100
Nano-titanium dioxide	Moderate amount

and the electron-hole generated under photoexcitation is easy to recombine, which leads to the low photocatalytic efficiency of nano-TiO$_2$.

3.2. Preparation of Nano-TiO$_2$ and Photocatalytic Coatings.

Nano-titanium dioxide is a kind of a semiconductor particle. Under certain light intensities, the electrons will change from the ground state to the excited state, thus forming electron-hole pairs. Due to the small size of nano-TiO$_2$ particles, it can effectively prevent electron-hole pair recombination, so its catalytic activity is improved from the other hand. There are many methods to prepare nanometer titanium dioxide [14, 15]. Commonly used ones are hydrolysis, hydrothermal, sol-gel, and so on. Here, the hydrothermal reaction is used to prepare nano-titanium dioxide. It has the advantages of simple process conditions, low temperature, uniform nanoparticles, and so on and is favored by many laboratories and factories. There are many ways to prepare TiO$_2$, but physical methods are difficult to control, and chemical methods are usually used to prepare TiO$_2$. The chemical methods commonly used in the laboratory are the gas phase method, liquid phase method, and solid phase method. The liquid phase method has the advantages of simple equipment, easy production, uniformity, and high purity. Commonly used liquid phase methods are sol-gel, hydrothermal, liquid precipitation, and so on. The hydrothermal process is usually at a certain temperature and pressure with water as a solvent in a closed container reaction. The temperature in this process is lower than the calcination temperature, but good crystals can still be obtained. This method is not very complicated to operate and is feasible in the laboratory. At the same time, the reaction conditions are easy to control, and the energy consumption is relatively less. In addition, the specific surface area of TiO$_2$

can be increased, and it is widely used in laboratory and industrial production.

Solution A was prepared by mixing 20 mL anhydrous ethanol and 10 mL isopropyl titanate (TTIP) evenly. Add 20 mL anhydrous ethanol to 48.5 mL distilled water and adjust the solution pH = 2. After repeated experiments, the average yield of nano-titanium dioxide under this condition is about 92%. After being mixed evenly, it is poured into a beaker to prepare solution B. Put the beaker into the magnetic stirrer of constant temperature water bath. During the stirring process, drop solution A into solution B, and stir the reaction at 60°C for 1 h. After the reaction, the reaction solution was sonicated for 40 min and transferred to the Petri dish and placed in the oven for drying. After being removed, the nano-TiO$_2$ sample was prepared by grinding [16].

First, hydroxyethyl cellulose, a film-forming agent, heavy calcium carbonate, styrene-acrylic emulsion, and a dispersant were added to a beaker filled with 100 mL distilled water according to the formula, and they were stirred evenly on the magnetic stirrer. Then, the levelling agent and thickening agent were added to continue to stir evenly to prepare the emulsion dispersion system. The self-made nano-titanium dioxide (3 g, 5 g, 10 g, and 15 g) was added to 200 g of the prepared emulsion dispersion system and stirred evenly to prepare photocatalytic coatings with different nano-titanium dioxide contents (the reference formula is shown in Table 1).

The prepared photorush coating was evenly coated on a nonwoven cloth of 400 mm × 400 mm, dried naturally in a dark and ventilated place, and hung in the center of a closed reactor for later use.

3.3. Photocatalytic Efficiency Test.

The naturally dried nonwoven fabric is suspended and fixed in the experimental airtight container, and a certain amount of formaldehyde gas is passed so that its concentration reaches 1 mg/m3 (10 times the indoor formaldehyde concentration required by GB/T 1883-2002 "Indoor Air Quality Standard"), and the fan and ultraviolet lamp are opened. One sample was taken every 30 min, and seven samples were taken. According to GB/T 18204.26–2000 "Determination Method of formaldehyde in Air in Public Places," formaldehyde in samples was determined by phenol reagent spectrophotometry, and its degradation rate was calculated according to the following formula [17]:

$$\text{degradation rate} = \frac{c_0 - c}{c_0} \times 100\%. \tag{1}$$

Here, c_0 is the formaldehyde initial concentration and c is the formaldehyde concentration measured at different degradation times.

4. Results Analysis

4.1. Characterization Analysis of Nano-TiO$_2$. Figure 2 shows the XRD patterns of nano-TiO$_2$ prepared by low-temperature hydrolysis.

It can be seen from Figure 2 that diffraction peaks appear at $2\theta = 25.60°$, $37.69°$, and $47.80°$, which are consistent with the characteristic peaks of the anatase phase. As anatase is the most active form among the three crystal forms of titanium dioxide, it provides a guarantee for photocatalytic degradation of formaldehyde. A large number of small burr peaks also appeared in Figure 2, but there was no characteristic peak of the rutile phase. This indicates that the sample contains amorphous titanium dioxide. Amorphous titanium dioxide has no periodic structure and cannot produce a diffraction effect on X-ray but can promote the separation of hole charge and photogenerated electron in the anatase crystal, thus improving the photocatalytic activity of nano-TiO$_2$. The enlarged peak width indicates that the titanium dioxide sample has a small average grain size, which is 11.39 nm calculated according to the Scherrer formula [18].

A small number of large round clusters can be seen from the scanning electron microscope, indicating that there is an agglomeration phenomenon, which may be caused by the uneven dripping rate of reactants in the preparation process or the instability of centrifugal separation, drying, and other conditions. The diameter of sample TiO$_2$ is mostly distributed in the range of dozens to 100 nanometers, and the morphology is mostly spherical with good uniformity.

4.2. Influence Factors of Formaldehyde Degradation by Nano-TiO$_2$ Photocatalytic Coatings

4.2.1. Influence of Nano-TiO$_2$ Loading on the Formaldehyde Degradation Rate of Photocatalytic Coating. Figure 3 shows the influence of different nano-TiO$_2$ loadings on the formaldehyde degradation rate of photocatalytic coatings.

It can be seen from Figure 3 that in the degradation process of photocatalytic coatings with different nano-TiO$_2$ contents, the degradation rate of formaldehyde is faster when nano-TiO$_2$ content is higher before 90 min. After 90 min, the degradation rate of formaldehyde tended to be stable, and the degradation curve tended to be gentle. After 120 min, the change of the degradation rate was not obvious. The reason is that the concentration of formaldehyde is low after 90 min, and the probability of contact with the active site on the catalyst surface decreases, thus hindering the photocatalytic reaction, so the degradation efficiency slows down, and the curve tends to flatten [19]. It can also be seen from Figure 3 that loading 5 g nano-titanium dioxide can achieve a better formaldehyde degradation effect and save cost.
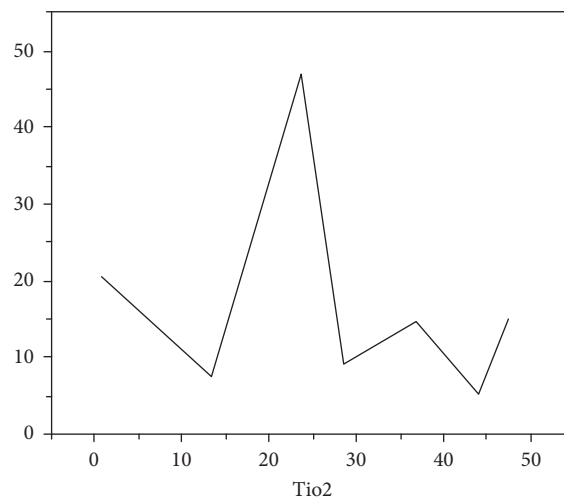

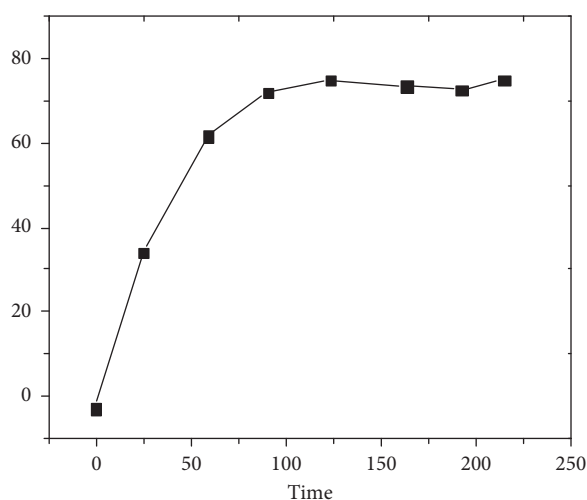FIGURE 2: X-ray diffraction pattern of the nano-TiO$_2$ sample.

FIGURE 3: Influence of different loadings on formaldehyde degradation rate of photocatalytic coatings.

4.2.2. Effect of Temperature and Humidity on the Formaldehyde Degradation Rate of Photocatalytic Coatings. Figure 4 shows the influence of temperature on the formaldehyde degradation rate of coatings under a sampling time of 120 min.

As can be seen from Figure 4, the degradation rate of formaldehyde by coating gradually increases with the increase of temperature, which is mainly due to the increase of temperature, the acceleration of the molecular movement rate, and the increase of the number of collisions between the catalyst and formaldehyde molecules, thus increasing the degradation rate. The degradation rate tends to be stable after 25°C because at room temperature, the heat energy is far less than the energy required for the electron transition in the valence band of the catalyst [20]. Therefore, the influence of temperature on the formaldehyde degradation efficiency of coating is limited [21].
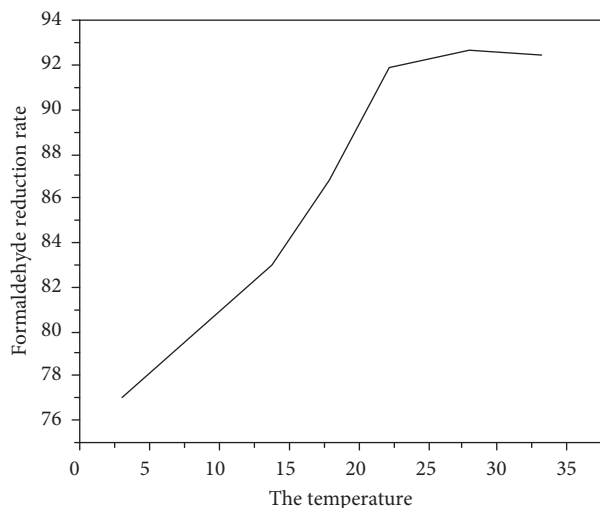
FIGURE 4: Influence of temperature on the formaldehyde degradation rate of photocatalytic coatings.

FIGURE 5: Influence of humidity on the formaldehyde degradation rate of photocatalytic coatings.

Figure 5 shows the influence of humidity on the formaldehyde degradation rate of coatings under a sampling time of 120 min.

Figure 5 shows that the formaldehyde degradation rate increases first and then decreases with the increase of humidity. As can be seen from the photocatalytic reaction mechanism, water molecules under certain humidity conditions can act as the trapping agent of the holes on the catalyst and are necessary conditions for hydroxyl radicals generated in the photocatalytic process [22, 23]. However, because the surface of nano-TiO_2 is hydrophilic, when the humidity is too high, the adsorption competition between water and formaldehyde molecules occurs on the surface of the catalyst, thus hindering the reaction between formaldehyde molecules and the photocatalyst, resulting in a decrease in the degradation rate. Therefore, appropriate humidity is favorable for photocatalytic reaction. A humidity of about 50% is appropriate [24].

FIGURE 6: Influence of different nano-TiO_2 on the formaldehyde degradation rate of photocatalytic coatings.

4.3. Comparison of the Formaldehyde Degradation Effect between Self-Made Nano-TiO_2 and P25 TiO_2. According to the above preparation method of photocatalytic coating, the photocatalytic coating containing 5 g P25 nano-TiO_2 was prepared, and the photocatalytic coating containing 5 g self-made nano-TiO_2 was compared in the formaldehyde degradation effect. The results are shown in Figure 6.

As can be seen from Figure 6, the formaldehyde degradation rates of self-made TiO_2 and P25 TiO_2 photocatalytic coatings are 84% and 63%, respectively, at 90 min, and the formaldehyde degradation rate of the former is significantly higher than that of the latter within the first 90 min [25]. The formaldehyde degradation rate of self-made TiO_2 tended to be stable after 120 min, while that of P25 TiO_2 tended to be stable after 180 min, and the degradation rate was significantly lower than that of self-made TiO_2. Therefore, the degradation effect and degradation stability time of self-made nano-TiO_2 are obviously better than P25 nano-TiO_2.
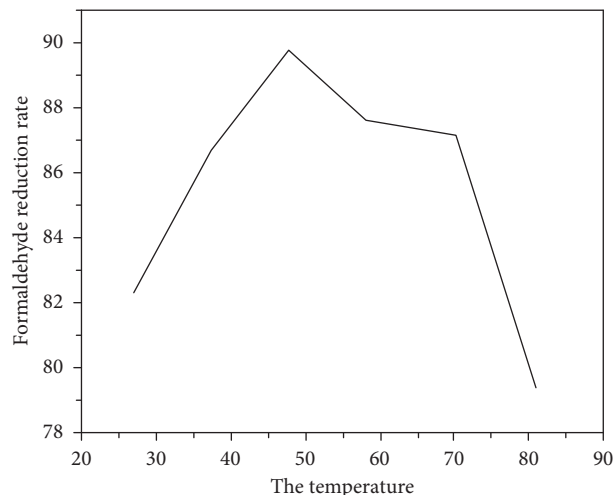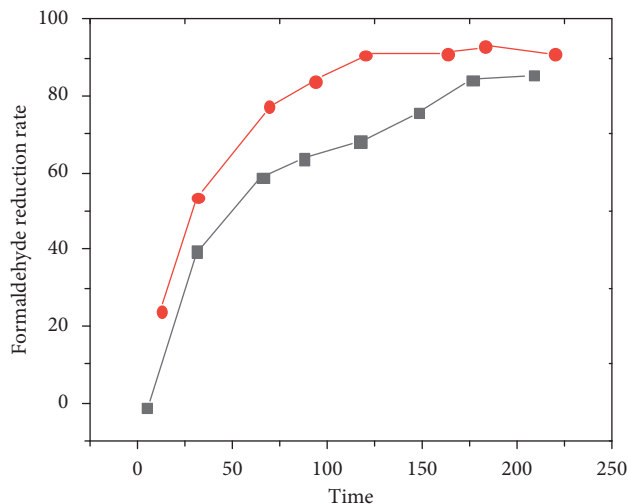
5. Conclusion

(1) The experimental results show that under the same conditions, the photocatalytic coatings loaded with 3 g, 5 g, 10 g, and 15 g TiO_2 nanoparticles had a better formaldehyde degradation effect when the TiO_2 nanoparticles were loaded with 5 g TiO_2. In the room temperature range, the degradation rate of formaldehyde increases with the increase of temperature. When the temperature is higher than 25°C, the temperature has little influence on the degradation effect of formaldehyde, and the degradation curve tends to be flat. With the increase of humidity, formaldehyde degradation first increased and then decreased, and the formaldehyde degradation rate reached the maximum at about 50% humidity.

(2) The photocatalytic coating was prepared by nano-TiO_2 prepared by the low temperature hydrolysis

method. Its formaldehyde degradation rate and degradation effect are obviously better than the commercial P25 nano-TiO$_2$.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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