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Indoor Formaldehyde Removal Techniques through Paints: Review

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Abstract

Due to its ability to cause illnesses and discomfort even at low concentrations, formaldehyde pollution of indoor air poses a significant risk to human health. Sources of formaldehyde in indoor environments include textiles, paints, wallpapers, glues, adhesives, varnishes, and lacquers; furniture and wooden products like particleboard, plywood, and medium-density fiberboard that contain formaldehyde-based resins; shoe products; cosmetics; electronic devices; and other consumer goods like paper products and insecticides. According to the World Health Organisation, indoor formaldehyde concentrations shouldn't exceed 0.1 mg/m^3. The methods include membrane separation, plasma, photocatalytic decomposition, physisorption, chemisorption, biological and botanical filtration, and catalytic oxidation. Materials based on metal oxides and supported noble metals work as oxidation catalysts. Consequently, a paint that passively eliminates aldehydes from buildings can be developed by adding absorbents and formaldehyde scavengers to the latex composition. It will be crucial to develop techniques for the careful detection and removal of formaldehyde in the future. Additionally, microbial decomposition is less expensive and produces fewer pollutants. The main goal of future research will be to develop a biological air quality control system that will boost the effectiveness of formaldehyde elimination. The various methods of removing formaldehyde through paints have been reviewed here, including the use of mixed metal oxides, formaldehyde-absorbing emulsions, nano titanium dioxide, catalytic oxidation, and aromatic formaldehyde abating materials that can improve indoor air quality.

Keywords

Formaldehyde, Absorption, Paints, Catalytic Oxidation, Nanofillers

1. Introduction

These days, maintaining interior air quality and minimizing the negative impacts of air pollutants on human health and air quality requires minimizing exposure levels. Most indoor living spaces release aerobes, particulate matter, and organic or inorganic contaminants. Given that people spend over 90% of their time indoors in modern culture, the indoor environment has a substantial influence on respiratory health [1]. Indoor air quality (IAQ) of commercial and residential spaces is a growing concern as more ailments are linked to indoor air pollution [2]. All indoor environments contain carbonyl compounds, such as aldehydes, which are a common kind of moderately toxic volatile organic compound (VOC). These substances can greatly exacerbate IAQ, causing nausea, vomiting, dizziness, exhaustion, and headaches upon exposure. Even while these air pollutants are present in indoor air at sub-ppb levels, their concentrations can rise to ppm levels, particularly in industrial settings, therefore substantial abatement is required. IAQ can be effectively achieved by improving the ventilation rate to remove indoor VOCs; however, doing so comes with a higher energy cost. Therefore, to reduce ultra-dilute indoor pollutants in smart buildings without requiring extreme ventilation, more energy-efficient alternatives are needed [3] [4].

Formaldehyde is the most commonly encountered VOC and is the primary indoor air contaminant with mild to chronic impacts on individuals. This class of compounds, characterized by their carbon-based structures that readily evaporate at ambient temperatures, was identified as human carcinogens in 2004. [5]. On the other hand, formaldehyde-based chemistry has several uses, either on its own or in conjunction with other substances. It is used to make resins such as urea-formaldehyde, indigo, and para-rosaline dyes, to process the anti-polio vaccine, to decolorize vat dyes, and to make formalin, a 30% - 50% aqueous solution of formaldehyde stabilised in a specific percentage of methanol that is used as a fungicide, disinfectant, and historically, to give clothing a permanent set, such as pleats in wool skirts [6] [7] [8]. Formaldehyde infiltration into indoor spaces arises from a broad spectrum of sources, posing significant indoor air quality concerns. These origins encompass furniture and wooden products like particleboard, plywood, and medium-density fiberboard employing formaldehyde-based resins, as well as insulating materials. Textiles, do-it-yourself materials, household cleaning products, cosmetics, electronic devices, and various consumer goods also contribute to formaldehyde emissions. Awareness of these diverse sources is crucial for mitigating health risks "**Table 1**." and enhancing indoor air quality, emphasizing the need to address formaldehyde exposure at its numerous entry points [9] [10] [11].

Table 1. Effect of formaldehyde on health.

Range	Effects
0.1 to 4 ppm	Slight eye irritation, upper breathing tracks—nose and throat,
5 to 20 ppm	Coughing, breathing trouble, tearing, risk of pulmonary edema
21 to 100 ppm	Chest pain lung irritation, irregular heartbeat, lethal within minute

The maximum formaldehyde exposure levels occur in newly manufactured products as well as in extremely high indoor temperatures and humidity levels [12]. Formaldehyde can be found in coatings like the woodenware in the family room, floorboards, furniture, and walls. What is scarier is that formaldehyde typically has a three-to-fifteen-year release period. World Health Organisation communiqué identifier No. 153, published in 2004: Formaldehyde produces distorted materials and is hazardous [13]. Paint has a long history and has been widely used in the construction sector since it was introduced to China. Three factors can sum up the effect of the coating: decoration, protection, and unique functionality. The production and processing of building materials frequently generate formaldehyde, and even more importantly, painting furniture constructed on these panels produces formaldehyde [14]. The symptoms of chronic formaldehyde poisoning include weakness, loss of appetite, palpitations, weight loss, headaches that don't go away, and sleeplessness. Most significantly, though, formaldehyde H_2-C=O is categorized by the International Agency for Research on Cancer (IARC) as a recognized carcinogen that can cause acute myeloid leukemia, lung cancer, and nasopharyngeal cancer [15] [16] [17].

Increasing the room's ventilation rate would be the best course of action in these situations to immediately lower formaldehyde emissions; however, Opening windows and ventilation in a room, on the other hand, is not an option in a filthy metropolis [18], manage humidity, keep a reasonable temperature using dehumidifiers and air conditioning systems, or build an intelligent dwelling construction with off-gassed wood or goods. The Agency for Toxic Substances and Disease Registry states that formaldehyde concentrations between 0.4 and 3 ppm can cause symptoms of mild to moderate irritation of the eyes, nose, throat, and many other diseases. The World Health Organisation states that indoor formaldehyde should not surpass 0.1 mg/m^3. Elevated levels have been associated with a higher risk of some types of cancer. Furthermore, as people spend 80% - 90% of their time indoors—in their homes, offices, cars, or shopping centers—it is critical to create solutions for both low-temperature indoor formaldehyde emission rates and clean indoor air [9]. Various methods have been explored thus far to enhance indoor air quality and reduce formaldehyde concentrations. Adsorption, thermal oxidation, photocatalytic oxidation, plasma breakdown with or without catalyst help, biological/botanical filtration, such as phytoremediation and microbial elimination, and thermal oxidation are examples of these approaches [19]-[25]. In addition to these primary formaldehyde removal techniques, membrane technology combines one or more of the above-mentioned techniques into a single membrane, which aids in the abatement of volatile organic compounds (VOCs). These formaldehyde elimination techniques can be divided into two main categories: 1) destruction and 2) recovery. Techniques for membrane separation, condensation, adsorption, and absorption are all included in recovery methods which are shown in **Figure 1**. The destructive method, on the other hand, includes processes such as plasma decomposition, thermal and non-thermal catalytic oxidation, photocatalytic oxidation,

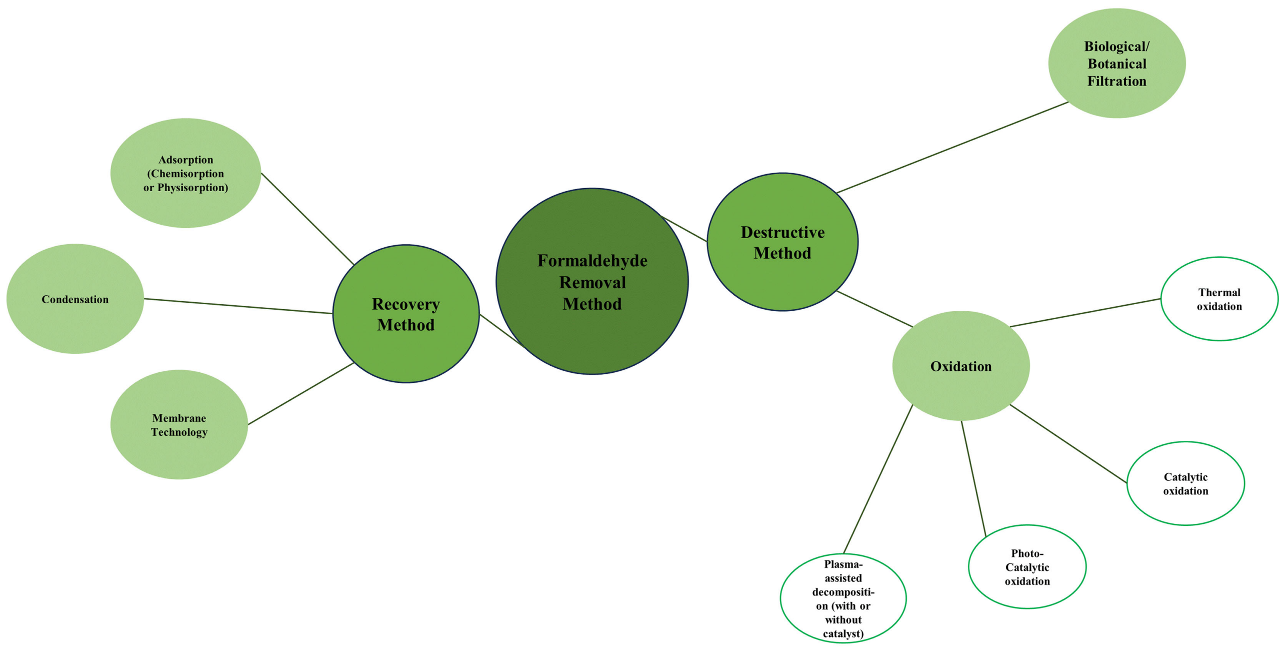

Figure 1. Technique for removing formaldehyde from the air.

biological/botanical filtration, and incineration, which convert formaldehyde into harmless, odourless, and environmentally friendly components such as CO_2 and H_2O [26] [27] [28].

Adsorption, biofiltration, catalytic oxidation, and photocatalysis are a few of the IAQ techniques used to reduce indoor pollution. Among these, adsorption-based passive management of aldehydes seems to be a viable remediation method for effectively removing indoor volatile organic compounds [29]-[33]. Adsorption employing filtration media is the conventional method for eliminating volatile organic compounds (VOCs) from interior spaces. This technique works through weak physisorption processes or substantial chemisorption interactions with contaminants. Adsorption of indoor aldehydes necessitates extremely effective sorbents with adjustable surface chemistry and pore structure for long-term sequestration. Porous adsorbents that have been tested for this purpose include activated carbon, molecular sieves, silica gel, zeolites, metal-organic frameworks, and amine-functionalized mesoporous sorbents [34]-[44]. Since amine-based sorbents have a strong affinity for aldehydes even in the presence of moisture, they have drawn a lot of interest to their use in the adsorptive removal of airborne aldehydes, particularly formaldehyde [45]. Some of the processes employed include absorption, physisorption, chemisorption, biological and botanical filtration, membrane separation, photocatalytic breakdown, plasma, and catalytic oxidation [46].

Adsorbents added to the latex composition can, therefore, provide a paint that removes aldehydes from buildings passively. Nevertheless, despite their many benefits, the management of indoor VOCs has yet to be studied for such latex coatings. Aminosilicas were added to polyacrylic-based latex paints by Nomura and Jones [47]. They found that while the adsorption rate was marginally lower, the dried paintings were able to efficiently compete with powdered aminosilicas for the capture of gaseous formaldehyde. Most recently, by including silica-supported amino polymers into polyacrylic-based latex, our research also looked into the possibility of sorbent-incorporated latex coatings for IAQ management. After that, the latex coatings were utilised for passive indoor CO_2 management, and the outcomes showed how well this buffering strategy worked to counterbalance high indoor CO_2 levels in commercial buildings [48]. Decreased adsorption kinetics due to possible latex pore blockage is one of the major issues with this "smart paints" development strategy. In order to reduce these kinetic barriers, latex formulation should be optimized [49] [50] [51].

The utilisation of mixed metal oxides, formaldehyde-absorbing emulsions, nano titanium dioxide, catalytic oxidation, and aromatic formaldehyde abating compounds that can enhance indoor air quality are some of the techniques for eliminating formaldehyde from paints that have been reviewed here.

2. Removal of Formaldehyde through Paints: Research Treads

2.1. Incorporation of Mixed-Metal Oxides (MMO's)

This study discusses the use of mixed-metal oxides (MMOs) such as Si/Ti and Si/Zr in latex paints in the form of thin layers to permanently capture indoor formaldehyde. The effectiveness of surface coatings to remove formaldehyde was tested in a lab-scale indoor air chamber, and the results were compared to powder equivalents [52]. This study developed several mixed-metal oxides (MMOs) with different ZrO_2 and TiO_2 loadings, including Zirconium dioxide (ZrO_2)/Silicon dioxide (SiO_2) and TiO_2/SiO_2. It then examined the formaldehyde adsorption capability of these MMOs. The ZrO_2/SiO_2 combination with a weight percentage of 25/75 was found to have the maximum adsorption capacity, approximately 250% higher than that of the parent SiO_2. Researchers attempted to passively remove the low quantities of the formaldehyde from indoor air by combining our zirconia and titania-based MMOs, which had demonstrated effectiveness in gaseous formaldehyde adsorption, with latex paint [53]. Mechanism of formaldehyde Adsorptive Removal from Air using Mixed-Metal Oxides is shown in **Figure 2**.

2.2. Incorporation of Formaldehyde Absorbing Emulsions

Coating formulation models based on PRIMAL™ SF-208 ER acrylic copolymer dispersion have been developed; these models have the potential to lower the formaldehyde content in addition to meeting other necessary operational and quality requirements [54]. Coalescent and container preservatives were not used in the creation of the basic formulation models for matte and semi-gloss coatings. Based on the testing results, the developed coatings can neutralise and absorb formaldehyde from the surrounding air. The test findings match the DOW

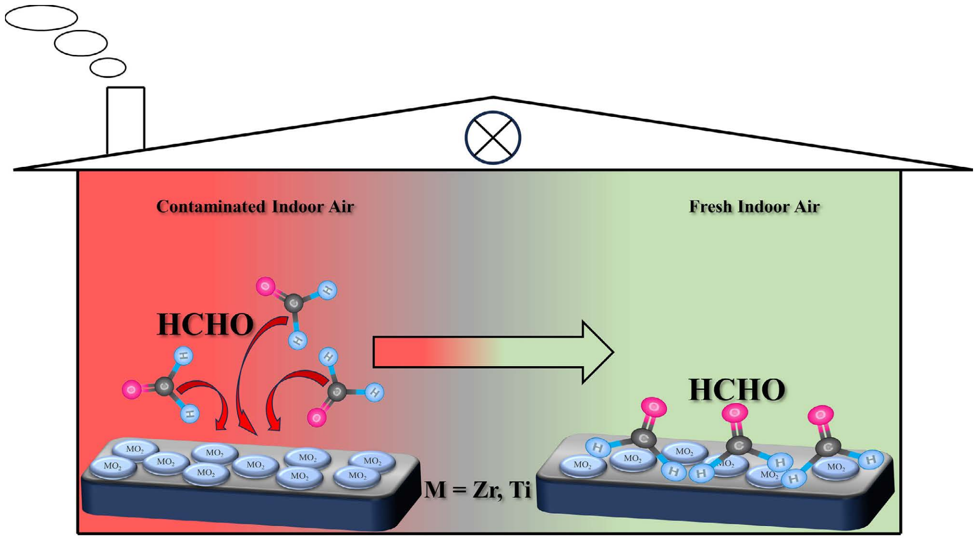

Figure 2. Formaldehyde adsorptive removal from air using mixed-metal oxides.

Chemical experimental data. Their data lays the foundation for additional paint coating application of the Primal TM SF-208 ER dispersion as well as additional investigation and research into the potential for formaldehyde reduction in paints and coatings for both interior and outdoor use [55].

2.3. Incorporation of Nano Titanium Dioxide

The inside wall paint was mixed with a unique nano-titanium dioxide (TiO_2) composite, which served as a photocatalyst. Nano-TiO_2 had an average diameter of roughly 20 nm. The sample's primary crystal component was anatase, with a considerable shift in its optical absorption edge from 387 nm - 520 nm. To learn more about the characteristics of formaldehyde breakdown in the air, researchers looked at nano-composite paint that contained varying doses of nano-TiO_2. According to test results, the formaldehyde decomposition ratio of the nano-paint can almost reach above 80%, particularly for the paint that contains 3% (w/w) nano TiO_2, which is evaluated at over 90%. According to the main analysis of the photocatalytic formaldehyde breakdown reaction kinetics, the findings from the experiment suited the first-order reaction kinetics model fairly well. In the end, the process caused small molecular organic molecules to oxidise to CO_2 and H_2O, effectively removing pollutants from the atmosphere [56] [57].

Nanomaterials have been utilised extensively in many fields to enhance air quality and decompose formaldehyde. They can produce negative ions and have been the subject of numerous domestic invention and technology reports. Of these, the nano-TiO_2 effect has been shown to be the most effective. As shown in the Chinese Patent, an eco-friendly variety of photochemical catalysis interior wall coating [58]. In order to develop a type of environmental protective water paint for ambient curing, it uses inorganic and organic composite emulsion and scattered photocatalyst in an area with functional stuffing form. This is assisted by additional auxiliary agents and other functional-type additives. The feed composition and weight percent proportioning of this coating are as follows: silicone sol, a mixed liquid of one or both in organosilicon acrylic acid latex and polyacrylate dispersion, mixed phase titanium dioxide granule of nano-level Anatase or Anatase and Rutile Type, or surface treated titanium dioxide composite particle, which can contain photocatalyst, pigment, filler, and other additives, as well as water solvent but this class coating of prior art only adds titanium dioxide optical catalyst, need to lean on photochemical catalysis, but unglazed or that light is faint is indoor, the effect of decomposing formaldehyde is undesirable. The present invention utilises a technical solution to achieve the goal. It involves applying an interior wall coating that is a kind of decomposing formaldehyde that absorbs a certain weight percentage of the described interior wall coating by film-forming base material, filler, and activity charcoal powder [59]. Formaldehyde-absorbing building coating demonstrated by the invention and its preparation method, which includes quartz sand, methyl α-naphthyl acetate, diatomite, titanium dioxide, tuber fern, nano-silver ionic, defoamer, plasticizer, and dispersant, can effectively remove a range of hazardous heavy metals, including formaldehyde adsorption and harmful gas [60].

2.4. Catalytic Oxidation

Given that VOCs have a negative impact on human health, several solutions have been developed to address and eliminate indoor air pollution. In this paper, we examined the many approaches that are currently in use, focusing on the removal of air pollutants by catalytic oxidation, adsorption, and the usage of the nanofibrous membrane. Adsorption is one of these technologies with the most significant potential for adsorbing VOCs from the air into the solid phase. The main reasons for its dominance are its accessibility, ease of use, and cost. However, it has encountered difficulties such as saturation and pore blockage, necessitating the regular synthesis of adsorbents and raising the system's cost. Like this, frequent catalyst replacement may be necessary even with photocatalytic processes due to the catalyst's limited lifetime caused by the loss of active sites. Despite the fact that photocatalytic oxidation is an effective technique because it operates at room temperature and removes a wide range of air pollutants, primarily by converting harmful formaldehyde into benign, odourless, and environmentally friendly components like H_2O and CO_2, the commonly used ultraviolet light source is expensive. Therefore, more research should be done to improve the removal capability when exposed to visible light. In contrast, the most effective method for removing volatile organic compounds at low temperatures is catalytic oxidation. It is also not cost-effective because noble metals are needed as catalysts. Furthermore, adopting a nanofibrous membrane-like shape has advantages since it inhibits catalyst nanoparticles or adsorbents from overflowing out of the filter medium and increases the density of active sites accessible for pollutant interactions [61].

When a catalyst particle absorbs light or photons with energy hv (where h is

Planck's constant and ν is frequency), photocatalysis occurs. Electron (e^-) ejection from valence band to conduction band occurs only when hν is greater than or equal to the photocatalyst's band gap energy. Hydroxyl radicals (OH•) can be produced by reacting with water molecules through the holes (h^+) that remain in the photocatalyst's valence band. Because these radicals have a great oxidising power, they are the ones that cause organic contaminants to degrade into carbon dioxide (CO_2) and water (H_2O). Conduction band electrons can simultaneously combine with oxygen molecules to generate the superoxide radical anion ($O_2\bullet^-$), a highly reactive intermediate species with high standard redox potentials. Organic substrates can then be mineralized to produce CO_2 and H_2O. Figure 3 depicts the mechanism of photocatalytic oxidation.

2.5. Formaldehyde Abating-Fragrant

Green-labelled, low-VOC interior paints that reduce formaldehyde are formaldehyde scavengers. Nevertheless, the formaldehyde-absorbing paints lose around 20% of their ability to absorb formaldehyde when aromatic ingredients are added. Consequently, an emulsion that may add scent to formaldehyde-absorbing paints without sacrificing their ability to absorb formaldehyde must be developed. The process involves adding monomers and functional additives to a reaction vessel, emulsifying the monomers and functional additives with demineralized water and surfactants to create a pre-emulsion, heating a

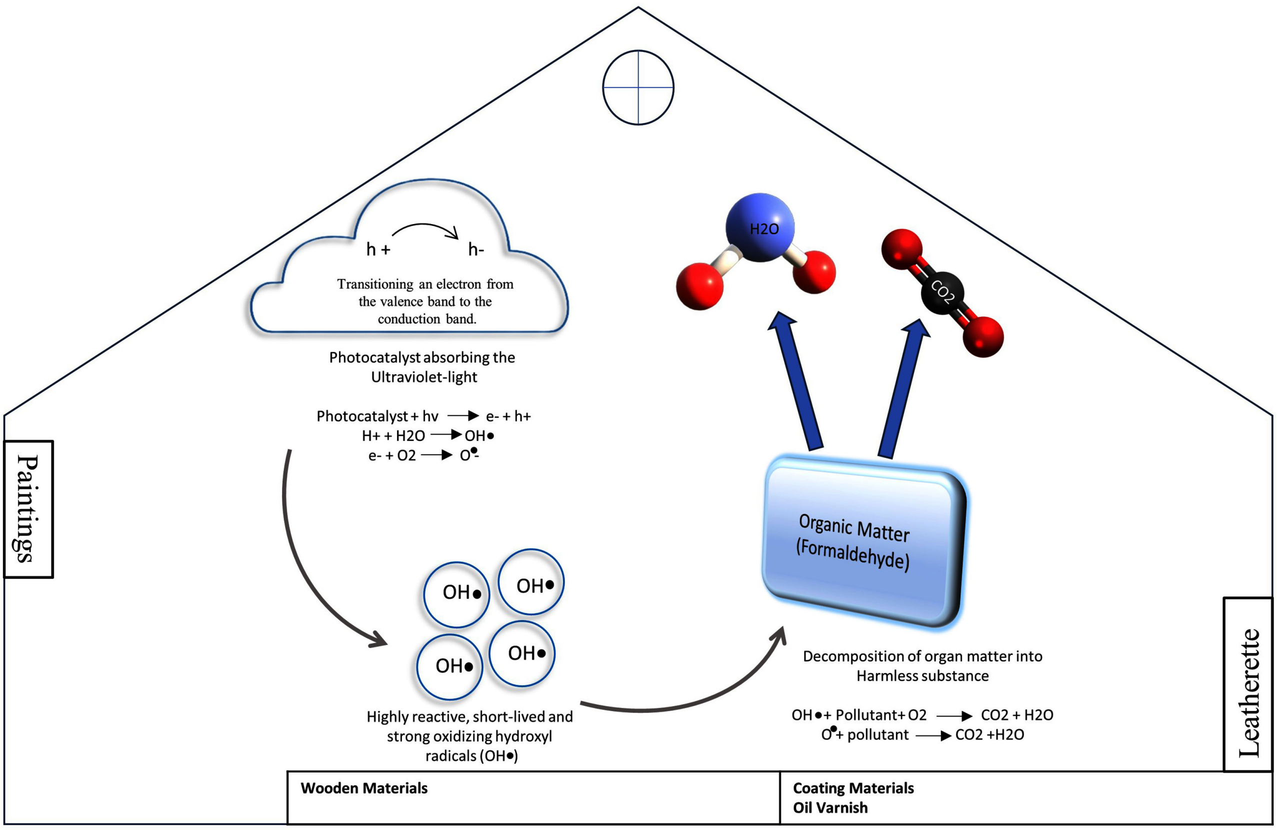

Figure 3. Mechanism of photocatalytic oxidation.

portion of the pre-emulsion and an initiator solution to create latex seed particles, mixing the latex seed particles and pre-emulsion together to develop a mixture, adding 2-acetoacetoxyethyl methacrylate monomer to the mixture, and cooling the mixture to room temperature. Methacrylic acid, butyl methacrylate, methyl methacrylate, and 1,4-butanediol dimethacrylate make up the monomers. Compounds with at least one functional group chosen from isocyanate, diazonium, aldehyde, or amine make up the functional additive. In addition to adding scent to paints, functional additives like those mentioned above particularly those containing organic compounds with aldehyde, amine, diazonium, and isocyanate functional groups are likely to react with the active methylene hydrogen groups that are typically present in interior paints. These methylene hydrogen groups are primarily the paints' sources of formaldehyde absorption. The formaldehyde absorbing source may scavenge internally as a result of this [62].

3. Conclusion

Several technologies have been developed in response to the harmful effects of indoor air pollutants like formaldehyde on human health. To remove indoor formaldehyde from the air, we reviewed a variety of current techniques in this research, with a focus on membrane separation, plasma, photocatalytic decomposition, physisorption, chemisorption, biological and botanical filtration, and catalytic oxidation. The most promising of these technologies for adsorbing VOCs from the air into the solid phase is adsorption. Similarly, even in the case of a photocatalytic process, the limited lifetime of the catalyst resulting from the loss of active sites can necessitate regular catalyst replacement. However, the most viable approach is thought to be catalytic oxidation, which effectively removes VOCs at moderate temperatures. Using morphology similar to a nanofibrous membrane has certain advantages as well, as it inhibits catalyst nanoparticles or adsorbents from leaking out of the filter medium and increases the density of active sites accessible for pollutant interactions. The paint industry has also commercialised the use of acrylic dispersion and formaldehyde scavengers, as well as the decrease of formaldehyde released in paints for both internal and external use. In conclusion, the different approaches to formaldehyde removal that have been covered here, such as the employment of aromatic formaldehyde abating materials, nano titanium dioxide, formaldehyde-absorbing emulsions, mixed metal oxides, and catalytic oxidation, could all help to enhance indoor air quality.

4. Futuristic Approach

There will be an increasing number of issues soon that endanger people's lives and health. Although we cannot always be protected from harmful influences, we can nevertheless escape risk thanks to the advancement of modern science and production technology. According to scientific research, the coatings that develop have the ability to neutralize and absorb formaldehyde from the surrounding air. Due to its high toxicity, broad diffusion, and prolonged release period, formaldehyde is a dangerous indoor air pollutant that can seriously harm human health. Thus, it will be essential to develop techniques in the future for the sensitive detection and removal of formaldehyde. For visual formaldehyde detection and removal, an aerogel based on biopolymers such as cotton cellulose and chitosan with high sensitivity towards formaldehyde will be developed. The variety of natural microorganisms capable of removing formaldehyde is currently rather high. The breakdown of formaldehyde by microorganisms is going to be the preferred method going forward due to its advantages over adsorption and chemical oxidation. Microbial degradation is also more economical and results in less pollution. Future research efforts will primarily focus on developing a "microorganism-based active coating" that will increase formaldehyde removal efficiency. This will lead to an improvement in the system's ability to remove formaldehyde inside when it is implemented in homes and offices.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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