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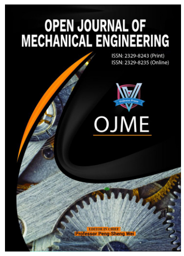

ARTICLE

VOC REMOVAL TECHNOLOGY FOR WOOD MATERIALS

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ABSTRACT

When used indoors, wood-based panels release volatile organic compounds (VOCs) such as olefins, aromatics, and esters, posing risks to human health. VOCs are key pollutants affecting indoor air quality and are closely linked to human health and quality of life. VOC emissions from wood-based panels primarily originate from adhesives, chemical formulations, and wood components, and their release characteristics are influenced by material properties and processing conditions. Gas chromatography-mass spectrometry is commonly used to determine total volatile organic compound (TVOC) content. Effective control strategies include the degradation and mineralization of wood extracts, the use of water-based additives and adhesives, and the modification or substitution of coatings and adhesive systems. This paper systematically reviews the sources and volatilization characteristics of VOCs in wood-based panels, as well as current technologies for reducing VOC emissions. The aim is to identify suitable testing methods and emission control approaches to improve indoor air quality and provide a safer and healthier indoor environment for users.

KEYWORDS

Wood, VOCs, coatings, adhesives.

1. INTRODUCTION

Indoor air quality is a significant public health concern. Volatile organic compounds (VOCs) degrade indoor air quality and are closely associated with adverse effects on human health and well-being [1, 2]. VOCs typically originate from adhesives, chemical formulations, and wood components [3]. Gas chromatography-mass spectrometry can be used to determine the content of total VOCs [3]. The degradation and mineralization of wood extracts can reduce VOC emissions, while the use of water-based additives and adhesives can also minimize the release of VOCs. Modifying and substituting coatings and adhesives can effectively reduce indoor VOC levels. This article focuses on the sources and volatilization characteristics of VOCs, as well as technologies for reducing VOCs, to identify suitable testing methods in advance for assessing the total volatile organic compound (TVOC) levels of several types of panels.

2. SOURCES OF VOCS

Both natural wood itself and adhesives can release detectable levels of formaldehyde, and wood species significantly influence volatile organic compound (VOC) emission levels. This study investigated variations in formaldehyde content across different wood species after drying and pelletization, while also analyzing the effects of wood grade and age (young vs. mature wood) on formaldehyde levels. Results indicated that softwoods generally exhibit higher formaldehyde content than hardwoods, wood grade has no significant impact, and mature wood contains higher formaldehyde levels than young wood [4]. Cork exhibited the highest VOC emission concentration, primarily composed of terpenes (70%-90%), with relatively low levels of hexene and acetic acid (10%-25%). Hardwood VOC emissions were significantly lower (approximately 50 times lower), mainly containing degradation products such as hexanal, pentanal, and acetic acid, and lacking terpenes [5]. Thermally modified wood is increasingly used as a decorative material, as this treatment enhances dimensional stability and inhibits decay and fungal growth. Despite its rapidly growing production, research on VOC emissions from thermally modified wood and its impact on indoor air quality remains limited [6]. After heat treatment, TVOC emissions decreased in softwoods but increased in hardwoods. In softwoods, releases of terpenes and hexene decreased significantly, while acetic acid and furfural increased. Hardwoods exhibited reduced emissions of hexanal and pentanal, while acetic acid and furfural increased. Formaldehyde emissions were generally present at low concentrations but increased after heat treatment, with VOC release rising as the heat treatment temperature increased [5]. Different wood-based materials exhibit varying levels of VOC emissions. This study measured formaldehyde emission (FE) from commercially available particleboard, medium-density fiberboard (MDF), and plywood in the Czech Republic using the EN 717-2 gas analysis method and the EN 717-1 small chamber method. Gas analysis results indicated that plywood has lower FE than particleboard and MDF [7]. Coriander board exhibited formaldehyde emission levels 300-600 times lower (< 0.2 μg/m^2·h), demonstrating superior environmental performance compared to MDF and particleboard [1].

Different adhesive types exhibit varying levels of VOC emissions. This study investigated the effects of adhesive type and pressing parameters on VOC emissions from thermally pressed mixed hardwood particleboard, evaluating three adhesives: urea-formaldehyde (UF) resin, phenol-formaldehyde (PF) resin, and polymeric methyl diisocyanate (pMDI) resin. Results indicated that formaldehyde and methanol emissions from UF particleboard and methanol emissions from PF particleboard accounted for the highest proportions of total VOCs at 92% and 72%, respectively. PF particleboard exhibited lower formaldehyde and acetic acid release during hot pressing, while pMDI particleboard primarily emitted acetic acid and high molecular weight VOCs. Furthermore, pMDI significantly reduced methanol emissions from the boards [8].

The model can effectively predict VOC content and sources. This study measured and compared the types and concentrations of formaldehyde and VOCs in UF resin, wood chips, resin-treated wood fiber, MDF, and PF resin at different production stages. Results indicated that formaldehyde in wood-based panels primarily originated from UF resin, with resin formaldehyde content exhibiting a linear correlation with panel formaldehyde release rates. VOC emissions in panels primarily originated from wood chips, and drying and hot-pressing processes could effectively reduce both formaldehyde and VOC emissions [9].

3. VOCS ELIMINATION TECHNOLOGIES

Wood modification is an effective method for enhancing the inherent properties of wood, primarily encompassing three aspects: green processes, renewable modifiers, and non-toxic, biodegradable products. VOC emissions peak during the hot-pressing process, followed by veneer drying, adhesive application, and cold pressing. After water treatment of the veneer drying exhaust, formaldehyde and acetaldehyde emission levels decrease. Among carbonyl compounds, acetaldehyde emissions from veneer drying exceed those from other processes, while formaldehyde is the primary emission from hot pressing. Continuous monitoring revealed differing emission patterns between VOCs associated with adhesive application and those from the hot-pressing process [10]. This study investigated the effectiveness of three formaldehyde scavengers in wood-based panels. Sodium sulfite, ammonium sulfite, and urea were added during particleboard preparation, with comparisons made of their physical and mechanical properties (internal bond strength, thickness swelling rates, density, moisture content) and formaldehyde emission levels. Formaldehyde content was measured using the perforation method, while release rates were assessed via the dryer method and gas analysis. The corresponding reaction mechanisms for each scavenger were analyzed and discussed. Significant performance differences among the scavengers in emission testing could be explained by the stability of the formaldehyde capture products. Sodium bisulfite demonstrated the best performance and could be used to produce particleboard with near-zero formaldehyde emissions [11]. VOC emissions from wooden furniture significantly impact indoor air quality. This study treated radiata pine (Pinus radiata D. Don) with sodium bicarbonate and ozone aqueous solutions to reduce VOC content without compromising mechanical properties, as shown in Figure 1 (a). As depicted in Figure 1 (b)-(d), the surface color of samples treated with either method exhibited minimal difference compared to untreated samples. Scanning electron microscope (SEM) images of sodium bicarbonate-treated samples (Figure 1 (e)–(g)) revealed inward contraction of some striations and altered fiber structure. This indicates that sodium bicarbonate disrupts the internal structure, reduces cellulose crystallinity, and damages the binding layer between lignin/hemicellulose and cellulose. In contrast, SEM images of ozone-treated Radiata pine samples revealed expansion and fracture of stripe pores at their midpoints. Ozone reacted with double bonds in Radiata pine VOCs, producing a bleaching effect [12]. This study investigates the potential reuse of steam condensate from high-frequency/vacuum drying of hardwoods. Oak, beech, and walnut condensate replaced 5% deionized water in laboratory synthesis of UF resin and production of MDF. VOC emissions were tested using the microchamber method, and bonding properties were evaluated according to European standards. Results indicated that MDF modified with UF resin using condensate exhibited lower emissions of primary VOCs—α-pinene, β-pinene, limonene, and acetic acid—compared to the control group, except for acetic acid in the oak condensate group [13]. This study employed simple and

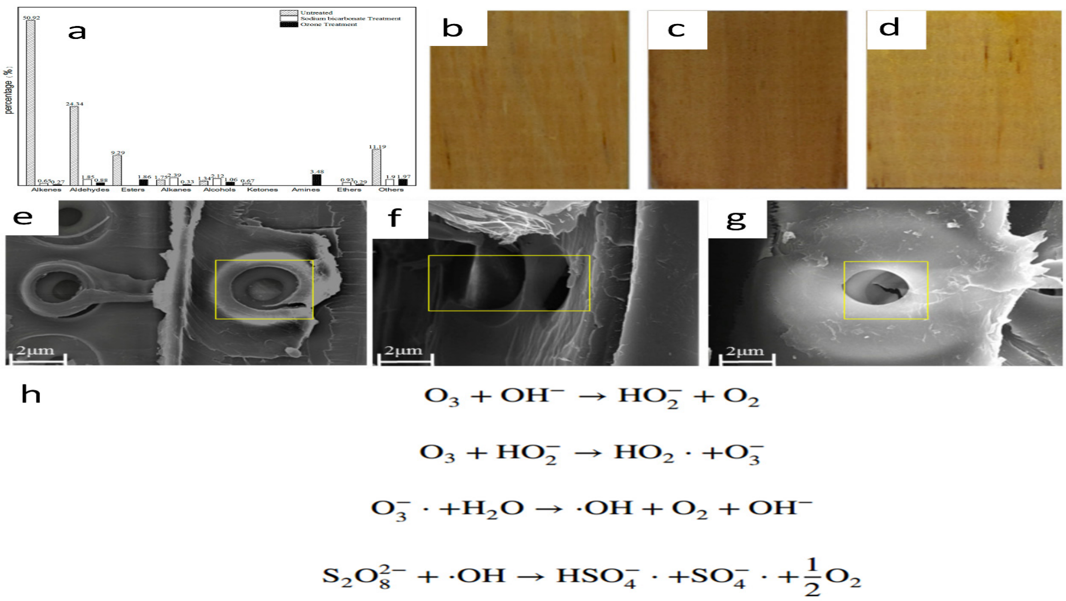

Figure 1: (a) VOC content in RP before and after different treatments; RP surface images: (b) untreated sample; (c) sodium bicarbonate-treated sample; (d) ozone-treated sample; RP SEM images: (e) untreated sample; (f) sodium bicarbonate-treated sample; (g) ozone-treated sample [12]. Copyright 2020 from MDPI (Basel, Switzerland)

efficient chemical treatments such as tartaric acid, citric acid, and sodium bicarbonate to reduce VOC emissions. Volatile emissions were analyzed using Headspace Solid-Phase Microextraction (HS-SPME)/ Gas Chromatography-Mass Spectrometry (GC-MS) to monitor changes in characteristic VOCs, including acetic acid, benzaldehyde, α-pinene, β-pinene, limonene, and borneol. Non-targeted screening identified key biomarkers. Results indicated that untreated spruce samples exhibited the highest TVOC content, while hemp samples showed the lowest. Hemp underwent significant chemical modification of lignocellulosic components (hemicellulose, lignin, extractives), leading to pronounced changes in key VOCs and increased total emissions [2].

Wood and coatings are extensively used in indoor furniture and large-area surfaces such as walls, floors, and ceilings. Wood-based panels manufactured from wood particles, fibers, sawdust, and formaldehyde-based resins emit formaldehyde and TVOC. This study employed the Field and Laboratory Emission Cell (FLEC) method and the 20L chamber method to investigate the formaldehyde and TVOC emission characteristics of MDF panels coated with three unfinished wood-based materials (oak veneer, low-pressure/high-pressure melamine impregnated paper) and four finishing materials (coated paper (CP), two decorative foils, polyvinyl chloride (PVC)). Results indicated that uncoated wood-based materials exhibit lower formaldehyde and TVOC emissions. Coating materials did not reduce TVOC emissions but decrease formaldehyde release in the 20L chamber test. In the FLEC test, both types of coating materials reduced TVOC and formaldehyde emissions from MDF [14]. This study investigated the emission characteristics of VOCs and their components in sealed environments using PVC-plywood (PVC-P), melamine-impregnated paper plywood (MI-P), water-based paint laminated plywood (WP-P), and unfinished plywood (UF-P) as research subjects. VOCs were sampled at 2, 4, 6, 8, 12, 18, 24, and 30 hours post-sealing under three loading ratios (1, 2, and 2.5 m^2/m^3), followed by analysis via GC-MS. Results indicated that VOC concentrations gradually increased and approached saturation with prolonged sealing duration. Decorated plywood reached saturation faster than unfinished plywood, with contamination levels ranking as PVC-P > MI-P > WP-P. Aromatic hydrocarbons accounted for over half of the VOC concentrations and were most significantly affected by the loading ratio. Surface treatment reduced aromatic hydrocarbon emissions but increased the release of other compounds [15]. This study employed a 20L small chamber method to investigate the effects of surface treatments on the release of formaldehyde, toluene, and TVOCs from particleboard and MDF. Panels with different formaldehyde emission grades (E0, E1, E2) were selected and subjected to five surface treatments: low-pressure laminate (LPL), PVC film, polyurethane-coated paper, direct coating (DC), and ultraviolet-cured coating (UVC). Results indicated that the FE grade of the board significantly influences its FE. All surface finishes substantially reduced formaldehyde emissions while significantly decreasing TVOCs and toluene emissions. However, DC and UVC coatings notably increased TVOCs and toluene emissions: styrene accounted for approximately 87% of TVOCs in DC samples, and toluene constituted about 73% in UVC samples. Formaldehyde emissions from MDF was influenced by the surface exposure method of the samples, while TVOCs and toluene emissions were independent of the FE rating and sample preparation method [16]. Finished wood-based panels require surface treatments such as LPL, PVC, CP, DC, or veneer overlay/ultraviolet coating (VO-UVC). This study compared formaldehyde emissions and combustion performance across five processes, measuring formaldehyde release using the Korean KSM1998 dryer method and analyzing combustion behavior with a cone calorimeter. Results indicated that VO-UVC exhibited the lowest formaldehyde emissions, while DC-treated panels demonstrated higher heat release rates and mass loss rates than other finishes [17]. The packaging method of furniture significantly impacted post-unboxing VOC emissions: samples wrapped in stretch film exhibited the highest VOC concentrations, while those packaged in corrugated cardboard showed the lowest levels. This trend remained consistent regardless of coating type [18].

Modified adhesives can reduce VOC emissions. Latent catalysts such as ammonium sulfate generate hexamethylenetetramine during curing, whose hydrolysis is believed to promote formaldehyde release throughout the board's lifecycle. In contrast, orthophosphate-catalyzed curing produces no byproducts. Orthophosphoric acid was used as a catalyst replacement for ammonium sulfate in curing UF resin. Results showed that under high-temperature and high-humidity conditions, the internal bond strength of orthophosphoric acid-cured particleboard was comparable to that of the ammonium sulfate group, while it exhibited lower formaldehyde content [19]. To reduce formaldehyde and VOC emissions from composite flooring, this study employed cashew nut shell liquid-based cardanol-formaldehyde (CF) resin and CF/polyvinyl acetate (PVAc) resin for maple plywood veneers. Both UV-cured CF and CF/PVAc systems met Korean standard E(1) and E(0) grades; PVAc addition resulted in a slight increase in TVOC emissions [20]. Adding bio-oil as a phenol substitute can reduce both the cost and FE from plywood in radiant floor heating systems. Temperature increases elevated the equilibrium FE value and shortened the equilibration time. FE primarily originated from residual formaldehyde in plywood manufacturing, subsequently released through the breaking of C-O-C and CH_2 bonds in the resin [21]. Bark is a severely undervalued material. Due to issues such as color, morphology, composition, and mechanical properties, bark is unsuitable for particleboard production. Given its chemical composition, particularly phenolic compounds, bark can serve as a formaldehyde scavenger. This study investigated the feasibility of using bark as a formaldehyde scavenger in particleboard. Single-layer particleboard was prepared using a mixture of birch, spruce (Picea abies), and pine (Pinus sp.) bark. UF and melamine-urea-formaldehyde resins were employed. Formaldehyde release was measured via the perforation method (EN 12460-5), gas analysis (EN 12460-3), and the bottle test (EN 717-3). Results indicated that bark addition significantly reduces formaldehyde emissions [22]. This study aimed to investigate the feasibility of producing low-density particleboard while reducing formaldehyde emissions without significantly compromising the physical and mechanical properties of the boards. These properties include thickness swelling rate, surface water absorption rate, bending strength, modulus of elasticity, internal bond strength, and surface stability. Adjusting the hardwood-softwood ratio revealed that increasing hardwood chips significantly reduced formaldehyde emissions but elevated thickness swelling and surface water absorption. Simply lowering density severely degraded all properties and proved unfeasible. Adding 0.25% and 0.4% isocyanate-based additives to the low-density formulation markedly improved all performance metrics [23].

Nano-modified adhesives can reduce VOC emissions. This study prepared low-emission boards coated with nano-modified melamine-impregnated paper, incorporating 0.5% and 1% nano-TiO_2 and nano-nano-montmorillonite to reinforce melamine

Table 1: TVOC emission rates of five wood-based panels

Test Item	Test Method	Test Result
Toona sinensis	1 m^3 Chamber Method	0.09 $mg/m^2 \cdot h$
Broussonetia papyrifera	1 m^3 Chamber Method	0.04 $mg/m^2 \cdot h$
Platanus × acerifolia	1 m^3 Chamber Method	0.05 $mg/m^2 \cdot h$
Paulownia spp.	1 m^3 Chamber Method	0.05 $mg/m^2 \cdot h$
Populus tomentosa	GC690	5962.2950 $\mu g/m^3$

resin, investigating their effects on formaldehyde and VOC emissions. Results indicated that nano-materials significantly reduce emissions. Formaldehyde emissions showed a slight decrease at 0.5% nanoparticle loading. As loading increased, formaldehyde emissions decreased by 22.2% to 36.6% compared to the control group. Aromatic hydrocarbons and alkanes, the primary VOCs, exhibited marked reductions in content with nanoparticle addition. At 1% nanoparticle loading, TVOC decreased by 22.6% to 25.6% [24]. This study investigated VOC emissions from particleboard coated with nano-modified water-based polyurethane varnish. Surface modification of nanoparticles using the KH550 silane coupling agent was employed to enhance their dispersion in water-based polyurethane. VOC emissions were measured via the chamber method, and the VOC degradation effects of nano-TiO_2, montmorillonite, and their composite systems were compared. Results indicated that KH550 modification improved nanoparticle dispersion, and the modified varnish enhanced VOC degradation performance in panels. After UV irradiation, the equilibrium TVOC concentration of panels coated with nano-modified varnish was 21.05%-41.57% lower than that of the control group, with significant reductions also observed in aldehyde and ketone compounds [25].

This study selected five types of fresh wood panels and tested them using the 1 m^3 climate chamber method, as shown in Table 1. The panels of *Toona sinensis*, *Broussonetia papyrifera*, *Platanus × acerifolia*, and *Paulownia spp.* all met the requirements of the HJ 571-2010 standard for TVOC emission rates. The VOC concentration of the *Populus tomentosa* panel measured in this test was 5962.2950 μg/m^3, which far exceeded the limit specified in indoor air quality standards and did not meet the standard requirements. Therefore, it was necessary to explore suitable methods for TVOC removal. The following was an investigation of TVOC elimination methods, providing a basis for future TVOC control. Based on the above analysis, this study first employed thermal desorption to remove TVOCs from *Populus tomentosa* panels, or alternatively used sodium bicarbonate and ozone aqueous solutions for treatment. If the panels were to be fabricated into plywood, decorative materials such as CP could be applied, or cashew nut shell liquid combined with nano-modified adhesives could be used to reduce VOC emissions.

4. CONCLUSION

Wood panels used indoors release VOCs such as olefins, aromatics, and esters, posing risks to human health. Research on VOC sources and elimination technologies can reduce indoor pollution. Wood material grade, wood age (e.g., young vs. mature), and treatment methods influence VOC content, as does adhesive type. Wood modification effectively enhances inherent properties through green processes (thermal/cold treatment and coating), renewable modifiers (bio-oils and nanomaterials), and non-toxic biodegradable products (biofiltration). In summary, among our five types of panels, this study first employed thermal desorption to remove TVOCs from *Populus tomentosa* panels, or alternatively used sodium bicarbonate and ozone aqueous solutions for treatment. If the panels were to be fabricated into plywood, decorative materials such as CP could be applied, or cashew nut shell liquid combined with nano-modified adhesives could be used to reduce VOC emissions.

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