

## Letter to editor

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# Advancing Formaldehyde Emission Regulation in Wood-Based Panels: Standardization Gaps, Technical Challenges, and Future Prospects for Sustainable Panel Manufacturing

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## Abstract

Formaldehyde emission from wood-based panels remains a critical issue at the interface of material engineering, indoor air quality, and regulatory science. International standards and regulations have progressively lowered permissible emission limits. However, these frameworks rely predominantly on static chamber measurement and short-term evaluation, which limits their predictive capacity for long-term performance under dynamic environmental conditions. Modern adhesive technologies including ultra-low molar ratio resins, hybrid bio-based systems, and nano-enabled mitigation strategies introduce emission-related behavior that existing tests do not fully capture. This Letter critically examines current emission standards, identifies technical limitations, and outlines prospects for performance-based, durability-integrated regulation.

**Keywords** Formaldehyde emission; Standardization; Panel manufacturing

## 1. Introduction

Wood-based panels such as particleboard, MDF, OSB, and plywood are indispensable materials in construction and furniture manufacturing. However, formaldehyde emission associated with thermosetting resins has long been a regulatory and health concern due to its acute and chronic effects on indoor air quality, including irritation and potential carcinogenicity [1].

Regulatory frameworks have progressively tightened limits on formaldehyde release, exemplified by chamber-based classification in EN 717-1 [2] and the environmental chamber methods of ISO 16000 [3]. In North America, ASTM E1333 [4] serves as the technical reference for large chamber emission measurement and un-

derlies regulatory frameworks such as CARB Phase 2 [5] and EPA TSCA Title VI [6]. While these standards have significantly reduced emission levels, advances in adhesive chemistry and panel microstructure engineering necessitate critical analysis of the adequacy of current testing paradigms.

## 2. Existing Emission Standards and Their Technical Basis

Current formaldehyde emission standards are grounded in environmental chamber testing designed to quantify steady-state emission concentrations under controlled conditions. EN 717-1 specifies chamber dimensions and environmental parameters for emission measurement



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[2]. The ISO 16000 series defines procedures for indoor air pollutant measurement [3]. ASTM E1333 outlines a large-scale chamber method recognized in North America [4] and forms the basis for CARB Phase 2 [5] and EPA TSCA Title VI thresholds [6]. Although harmonized, these standards focus on short-term equilibrium emission at defined chamber conditions, limiting long-term predictive capability.

### 3. Technical and Methodological Challenges

Formaldehyde emission originates from residual free formaldehyde, incomplete curing reactions, and hydrolytic degradation of methylene linkages over time; hydrolysis is influenced by moisture and temperature variations [1]. Physically, emission is governed by diffusion through heterogeneous composite structures. However, static chamber tests [2, 4] do not replicate real environmental fluctuations. Existing standards generally assess emissions within 7–28 days after production, potentially overlooking long-term durability. Modern adhesive systems such as ultra-low molar ratio resins and bio-based hybrid adhesives exhibit altered hydrolysis and diffusion behavior [7]. Nano-engineered additives modify diffusion pathways and structural integrity [8], yet current standards do not explicitly evaluate these mitigation mechanisms.

### 4. Emerging Technologies and Their Regulatory Implications

Innovations in adhesive chemistry and nano-enabled mitigation strategies provide promising solutions. Nanocellulose incorporation enhances crosslink density and may reduce free formaldehyde reservoirs [7]. Nano-clay additives increase diffusion path tortuosity [8]. Bio-based hybrid systems partially substituting lignin, tannin, or soy components reduce synthetic formaldehyde dependency [7]. Despite these advances, current emission standards [2, 4] evaluate modified systems using identical static chamber methods, without structural performance metrics or long-term durability assessment under cyclic environmental conditions [5, 6].

### 5. Future Prospects for Performance-Based Standardization

Future standards should incorporate cyclic humidity exposure and extended monitoring to simulate real service conditions. Emission kinetics modeling and diffusion-based predictive approaches would complement chamber testing. A life-cycle assessment perspective aligned with indoor air quality guidelines [1] would better integrate sustainability considerations. Greater harmonization among EN 717-1 [2], ISO 16000 [3], ASTM

E1333 [4], CARB Phase 2 [5], and EPA TSCA Title VI [6] is essential for global regulatory coherence.

### Conclusion

Formaldehyde emission standards have achieved substantial progress in reducing allowable emission levels and improving indoor air quality. However, contemporary advances in adhesive technology, micro-biostructural engineering, and mitigation strategies require further evolution of testing and regulatory methodologies. Transitioning from static short-term chamber compliance to predictive, durability-oriented, and performance-based standardization better aligns regulatory frameworks with modern material science and sustainability objectives.

### Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

### Declarations

#### Ethics approval and consent to participate

Not applicable.

#### Consent for publication

Not applicable.

### Competing interests

The authors declare that they have no competing interests.

Received: May. 2026 Accepted: May. 2026

Published online: May. 2026

DOI: 10.22034/ASAS.2026.580632.1101

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