

Green Clay-Based Functional Fillers Empowering Particleboards: A Synergistic Antibacterial–VOC Regulation Strategy for Healthy Indoor Living

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Abstract—Particleboards are central to furniture and interior fit-out systems, yet their contribution to healthy indoor living is limited by two coupled material-level challenges: colonisation of moisture-exposed surfaces and the release of volatile organic compounds (VOCs) from wood, adhesive, and finishing constituents. This evidence-integrated design study develops a green clay-based functional-filler strategy that treats antimicrobial performance and VOC mitigation as coupled but independently verifiable outcomes. The strategy uses organo-modified montmorillonite as a carrier for Cu²⁺ and ZnO antibacterial sites while proposing the clay microenvironment as a potential adsorption domain for formaldehyde and broader VOCs. Published particleboard evidence demonstrates that a Cu²⁺/ZnO@MMT-O filler achieved a 99% antibacterial rate against both *Escherichia coli* and *Staphylococcus aureus* at 1.25 wt% loading, while retaining a modulus of rupture of 10.65 MPa, a modulus of elasticity of 2304.40 MPa, an internal bond strength of 0.29 MPa, and 24 h thickness swelling of 16.31% [1]. These published values establish antimicrobial feasibility and illuminate an interfacial trade-off, but they do not establish VOC reduction. Accordingly, the present manuscript makes no claim of measured VOC mitigation. It outlines an accessible preliminary comparison using a small laboratory-built enclosure and basic descriptive statistics; formal ISO 16000-9 chamber testing remains a subsequent validation step. X-ray diffraction and infrared spectroscopy suffice for the initial filler assessment, while advanced imaging and precise surface-area measurements are optional follow-up analyses. The contribution is a transparent material-design and evaluation framework: mineral-supported antimicrobial action is evidenced, whereas a defensible healthy-indoor claim requires controlled VOC kinetics, mechanical retention, and release safety. This framing converts a single-function additive into a testable platform for healthier wood composites.

Keywords—particleboard, montmorillonite, inorganic antibacterial filler, volatile organic compounds, healthy indoor

I. INTRODUCTION

Particleboard is a resource-efficient composite that converts small wood particles into panels for furniture, cabinetry, partitions, and interior fit-out. Its sustainability case, however, is judged increasingly through indoor exposure rather than embodied carbon alone. Occupants interact with the same panel through touch, cleaning cycles, humidity excursions, and air exchange. A panel that retains structural

integrity but supports microbial transfer or releases odorous and irritant VOCs does not fully meet the contemporary design objective of healthy residential environments. This objective is especially relevant where wood composites are installed at high surface-area-to-room-volume ratios [2][3].

The two exposure pathways have often been handled separately. Antimicrobial boards typically rely on organic biocides, metal salts, metal oxides, or nanoscale surface treatments. Formaldehyde and VOC interventions, by contrast, focus on adhesive selection, scavengers, ventilation, coatings, or post-treatment. This separation is materialistically inefficient. A filler that changes adhesive curing, particle–resin contact, porosity, and moisture uptake can influence both microbial susceptibility and emission behaviour. A robust strategy must therefore resolve performance across multiple scales: active-site chemistry at the filler surface, filler dispersion in the particle network, structural transfer through the cured resin, and chemical exchange with indoor air [4][5][6][7][8].

Montmorillonite is a promising bridge material because its layered mineral structure supports ion exchange, organic modification, nanoparticle anchoring, and adsorptive interactions. Cu²⁺ and ZnO provide complementary antibacterial modes. Copper can perturb bacterial envelopes and metabolic functions, whereas ZnO is widely associated with contact-mediated damage and oxidative stress [9][10][11][12]. In the supplied reference study, Cu²⁺/ZnO co-loading on organo-modified montmorillonite generated stronger antimicrobial activity than singly loaded systems and retained practical board performance at an identified 1.25 wt% loading. The study, however, did not measure VOC emissions. It therefore cannot be read as evidence that an antimicrobial filler has reduced indoor chemical exposure.

This paper addresses that evidence boundary directly. Its research question is: how can green clay-based functional fillers be designed and evaluated so that antibacterial efficacy and VOC mitigation are treated as coupled, auditable outcomes in particleboard? The aim is not to retrofit a VOC claim onto published antibacterial data. Rather, the aim is to formulate a dual-function architecture, extract the transferable evidence for the antibacterial branch, and identify feasible preliminary tests followed by formal experiments to verify the emission branch. The scope is limited to dry-condition particleboard with mineral-

supported Cu²⁺/ZnO active sites and a small laboratory enclosure for exploratory comparison. It does not establish long-term human exposure, life-cycle impacts, fungal resistance, or commercial certification.

The remainder of the manuscript reviews the relevant material and testing literature, defines a dual-function experimental strategy, synthesises the published evidence using source-linked figures and tables, and discusses the conditions under which a healthy-indoor claim becomes scientifically defensible. The paper concludes with an implementation pathway that keeps observed results, design hypotheses, preliminary measurements, and future formal validation distinct.

II. RELATED WORK

A. Antibacterial particleboards require stable active-site presentation

Organic antibacterial agents can exhibit strong initial activity but may degrade during hot pressing, migrate during service, or create concerns about persistence and resistance. Inorganic systems offer higher thermal tolerance and can remain active when the metal component is immobilised rather than dispersed as a freely mobile phase. Recent wood-composite studies have explored essential-oil microcapsules, in situ metal-oxide growth, and bio-based antifungal approaches. These approaches confirm a need for hygienic materials, but their transferability depends on thermal stability, compatibility with adhesive chemistry, and the ability to minimise release of active species.

Clay-supported metal systems address part of this challenge. Montmorillonite offers a high specific surface area, ion-exchange capacity, and a layered host lattice that may distribute active species more uniformly than unbound particles. Studies of copper- or zinc-containing montmorillonite and bentonite report enhanced antimicrobial activity when the active components are immobilised within or on the clay structure. The central design variable is not simply metal content. It is the accessibility of active sites after hot pressing, balanced against the degree to which the filler disrupts resin continuity or creates water-accessible interfaces.

B. Indoor VOC performance is an emission-kinetics problem

VOCs released by composite wood products arise from multiple sources, including residual formaldehyde, reaction products, wood extractives, solvents, and additives. Consequently, an emission claim cannot be inferred from adsorption capacity measured on loose powder. Exploratory measurements can compare time-dependent headspace concentrations from manufactured boards in a small, reproducible laboratory enclosure under matched conditions; they cannot yield ISO-compliant area-specific emission rates without controlled ventilation and validated mass-balance conditions. ISO 16000-9 specifies a general laboratory method for determining area-specific emission rates of VOCs from construction products; EN 16516 similarly provides a horizontal reference framework for regulated dangerous substances from construction products. ASTM D6007 provides a small-chamber route for formaldehyde concentrations emitted by wood products under defined conditions.

The adsorption literature supports the plausibility of an organoclay contribution but not a board-level conclusion. Modification changes montmorillonite interlayer environments, polarity, accessible pores, and the affinity for organic compounds [13][14][15]. Related sorption and composite studies likewise indicate that accessible clay surfaces, moisture, and resin interfaces can alter pollutant interactions [16][17]. Yet humidity can compete with organic uptake and the cured resin can seal, expose, or transform the available clay surface. The effective response must therefore be measured after board manufacture and conditioning, not projected from sorbent characterisation alone.

C. The unresolved coupling is structural, chemical, and evaluative

Nanofillers can affect cure progression, resin viscosity, stress transfer, and water transport. Published particleboard studies have shown that filler use can improve a targeted functionality while changing bending strength, internal bonding, or swelling. Such trade-offs are neither incidental nor necessarily disqualifying; they are the mechanism by which an interface-level modification becomes a panel-level property [18][19][20][21]. The literature gap is a test architecture that considers bacterial reduction, exploratory VOC behaviour, release safety, and structural retention within the same formulation space. Figure 1 defines that architecture. It distinguishes literature-supported antibacterial mechanisms from the proposed VOC-mitigation pathway, which requires formal chamber testing before any performance claim may be made.

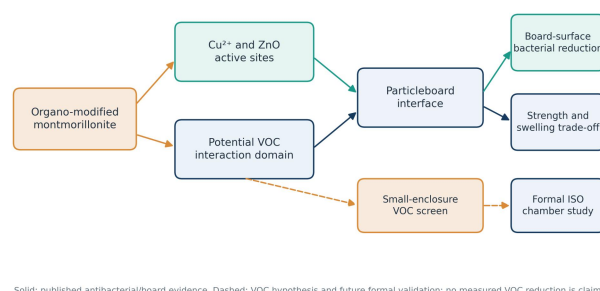


Fig. 1. Evidence-integrated design pathway for the clay-based multifunctional filler. The antibacterial branch and board-property trade-off are supported by published evidence; the VOC branch is a hypothesis screened in a laboratory-built enclosure and reserved for subsequent formal chamber validation.

III. MATERIALS AND METHODS

A. Study design and evidence boundary

The study was structured as an evidence-integrated design analysis with a laboratory-feasible preliminary scheme and a separate formal-validation pathway. Published values were curated from Pang et al. only when stated in the article text or tables. No unreported values were digitised, interpolated, or treated as new observations. The antibacterial branch therefore reports source-linked evidence. The VOC branch remains a hypothesis: a small laboratory enclosure can screen relative trends, whereas formal standard-chamber work is needed before a dual-function performance conclusion is drawn. This distinction prevents an adsorption rationale or preliminary headspace comparison from being mistaken for a certified emission result.

B. Filler concept and panel formulations

The proposed filler is organo-modified montmorillonite bearing Cu^{2+} and ZnO , denoted $\text{Cu}^{2+}/\text{ZnO}@\text{MMT-O}$. An organo-modified clay is used to improve compatibility with the organic panel matrix and to create a microenvironment capable of interacting with non-polar and moderately polar volatiles. Cu^{2+} and ZnO are selected as complementary antibacterial components. An initial panel comparison can prioritise an unfilled board (0 wt%) and co-loaded $\text{Cu}^{2+}/\text{ZnO}@\text{MMT-O}$ at 1.25 and 1.50 wt% based on dry wood-particle mass. An MMT-O-only comparison can be included when resources permit; singly loaded carriers and intermediate 0.50, 0.75, and 1.00 wt% gradients belong to a later expanded study. The same adhesive mass fraction, pressing schedule, target density, wood furnish, and conditioning protocol should be applied across treatments.

The preliminary scheme can use a limited number of separately mixed boards at the three priority loadings and take multiple specimens for mechanical, microbiological, and exploratory VOC comparisons. Cuts from one board must be identified as subsamples, not independent production replicates. The number of boards and valid observations should be stated explicitly; uncertainty intervals require genuinely independent boards and are omitted when replication is insufficient. An enclosure blank and an unfilled-board control identify background contamination and inherent panel emissions. An MMT-O-only control, when available, further separates clay effects from the metal-loaded surface in follow-up comparisons.

C. Characterisation and performance measurements

The initial filler assessment can use X-ray diffraction (XRD) to check clay-layer changes and Fourier-transform infrared spectroscopy (FT-IR) to examine characteristic functional groups. Simple inspection of blend uniformity and recorded processing conditions complements these tests without claiming nanoscale dispersion. Nitrogen adsorption-desorption surface-area measurements and electron microscopy with elemental mapping may be performed as supplementary characterisation in later work; neither is a required experiment in the present framework. Particleboard properties should be measured after conditioning using the applicable procedures of GB/T 17657-2022, including modulus of rupture (MOR), modulus of elasticity (MOE), internal bond strength (IB), and thickness swelling (TS). The operational benchmark is a formulation that meets a stated performance class while retaining sufficient interfacial integrity for its intended dry-use application.

Antibacterial evaluation should combine a screening assay on filler suspensions with a film-covering assay on board surfaces where microbiological facilities are available. The latter measures activity after active sites have been processed into the composite. Following LY/T 1926-2020, bacterial reduction can be expressed as $R = (B - C)/B \times 100\%$, where B and C are mean colony counts for control and treated specimens, respectively. *Escherichia coli* and *Staphylococcus aureus* provide Gram-negative and Gram-positive challenge organisms. A strong-performance threshold should be identified before testing and accompanied by an assessment of potential release; follow-up wet-extraction or ageing tests can establish whether efficacy depends on uncontrolled metal migration [22].

D. VOC chamber-testing protocol

VOC behaviour can first be screened in a laboratory-built small enclosure using matched, conditioned board specimens, the same exposed area-to-volume ratio, a documented temperature and relative humidity, fixed equilibration periods, and enclosure blanks. The preliminary device should be checked for leakage and background contamination; sampling at a practical early and later time point can indicate relative headspace trends. DNPH derivatisation followed by high-performance liquid chromatography may be retained for formaldehyde, and thermal desorption gas chromatography-mass spectrometry may be retained for TVOC and compound-resolved VOCs when those routine analytical services are available. The simplified enclosure does not reproduce the controlled airflow, loading, and quality assurance of ISO 16000-9:2024; its concentration comparisons must not be described as standard area-specific emission rates. A formal ISO chamber study can subsequently measure day 1, 3, 7, 14, and 28 emission trajectories at specified temperature, humidity, loading, and air-exchange conditions. Such formal kinetics are necessary for board-level interpretation; humidity should be recorded because it can change formaldehyde emission parameters.

For each exploratory endpoint, the analysis should report the observed values, blank-corrected group means and standard deviations where repeated boards exist, and 95% confidence intervals only when independent replication supports their calculation. Relative concentrations can be compared at matched sampling times, without inferring certified emission rates or treating subsamples as independent boards. The priority comparison is co-loaded $\text{Cu}^{2+}/\text{ZnO}@\text{MMT-O}$ against the unfilled control; a subsequent MMT-O-only control can help distinguish carrier effects from the metal-loaded surface. Repeated-measures linear mixed models may be considered only in a later, larger independently replicated chamber study, not as a required part of this preliminary analysis.

E. Data handling and statistical transparency

All sample exclusions should be declared before analysis. Instrument faults, enclosure leaks, and microbial plate-count failures should be logged with reasons rather than silently replaced. Preliminary results should be described with sample counts, means, standard deviations, and, where justified by independent replication, 95% confidence intervals. Limited replication does not support detailed distributional modelling or multiple pairwise significance claims. Robust models and false-discovery-rate correction are possible advanced tools for later expanded studies, not requirements of the present framework. Table I summarises the design elements and the published numerical evidence is reproduced in the subsequent manuscript tables; no VOC emission dataset is implied or fabricated.

TABLE I. FUNCTIONAL DESIGN MATRIX FOR THE DUAL-OUTCOME PARTICLEBOARD STRATEGY

Design element	Primary material role	Required observation	Evidence status
Organo-modified MMT	Carrier compatibility and adsorption microenvironment	XRD and FT-IR; recorded formulation and blend conditions	Supported as a carrier concept
Cu^{2+} / ZnO active sites	Multi-site bacterial inhibition	Published MIC/MBC; board-surface	Supported for antibacterial

Design element	Primary material role	Required observation	Evidence status
		bacterial reduction; follow-up release screen	action
Particleboard interface	Load transfer and moisture response	MOR, MOE, IB, thickness swelling	Supported as a trade-off requirement
Staged VOC evaluation	Exploratory headspace comparison; formal emission validation	Small-enclosure relative concentrations; later ISO chamber emission rates	Hypothesis; no measured board VOC outcome

IV. RESULTS AND EVIDENCE INTEGRATION

A. Published clay structure and antimicrobial potency support the antibacterial branch

The published filler data show why a mineral carrier is useful for active-site organisation. Relative to MMT-O, Cu²⁺/ZnO@MMT-O had the largest reported specific surface area (50.870 m² g⁻¹) and pore volume (0.169 cm³ g⁻¹) among the four compared materials. These are previously published measurements, not required nitrogen-sorption tests in the proposed preliminary study. They do not prove VOC capture in a board, because gas uptake depends on the cured composite and exposure conditions. They nevertheless motivate later examination of whether accessible mineral domains remain after pressing. The texture result is material-specific and should not be generalised to all organoclays without direct evidence.

The antimicrobial comparison was more direct. In the reported broth-dilution assay, the co-loaded filler had a minimum inhibitory concentration of 0.125 mg mL⁻¹ for both *E. coli* and *S. aureus*. That value was lower than the corresponding 0.500 mg mL⁻¹ for Cu²⁺@MMT-O and 0.250 mg mL⁻¹ for ZnO@MMT-O. The paired decrease is consistent with complementary action in the tested system but does not alone quantify interaction synergy. Figure 2 summarises only the reported values; Table II presents the published texture values and Table III presents the published antimicrobial assay values. The unmodified carrier was reported as having MIC greater than 5 mg mL⁻¹ and is shown as a threshold rather than an exact numerical value.

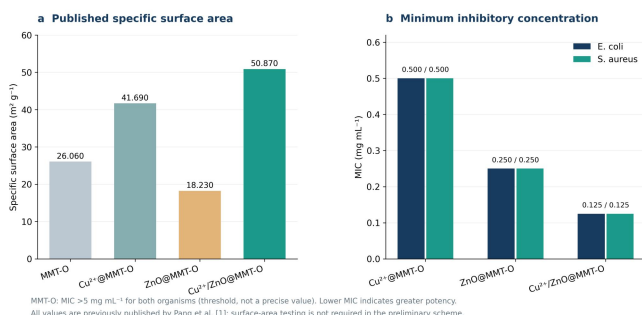


Fig. 2. Published filler evidence from Pang et al. Previously reported surface areas and minimum inhibitory concentrations are shown as source-linked values; the MMT-O MIC exceeds 5 mg mL⁻¹ and is not an exact measurement. Nitrogen-sorption characterisation is not required for the proposed preliminary scheme.

TABLE II. PUBLISHED CLAY TEXTURAL PROPERTIES

Sample	Specific surface area (m ² g ⁻¹)	Pore volume (cm ³ g ⁻¹)	Mean pore size (nm)
MMT-O	26.060	0.109	12.640
Cu ²⁺ @MMT-O	41.690	0.145	13.340
ZnO@MMT-O	18.230	0.064	11.420
Cu ²⁺ /ZnO@MMT-O	50.870	0.169	10.200

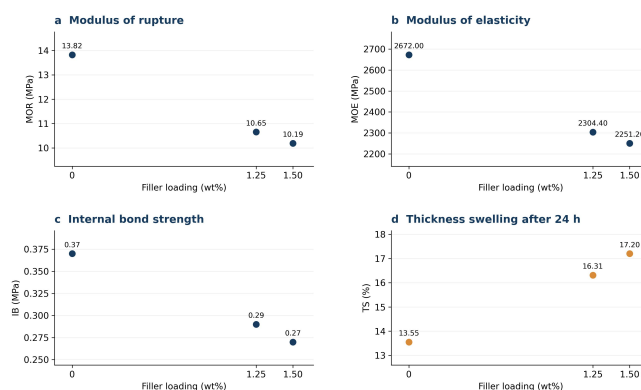
TABLE III. PUBLISHED ANTIMICROBIAL POTENCY OF CLAY-SUPPORTED SYSTEMS

Sample	MIC, <i>E. coli</i> (mg mL ⁻¹)	MIC, <i>S. aureus</i> (mg mL ⁻¹)	MBC, <i>E. coli</i> (mg mL ⁻¹)	MBC, <i>S. aureus</i> (mg mL ⁻¹)
MMT-O	>5.000	>5.000	>5	>5
Cu ²⁺ @MMT-O	0.5	0.5	4.0	3.0
ZnO@MMT-O	0.25	0.25	3.0	3.0
Cu ²⁺ /ZnO@MMT-O	0.125	0.125	1.0	1.0

B. Published board-level data locate a feasible, but not cost-free, loading window

Board-level evidence is needed because loose-filler potency does not ensure performance after incorporation. At 1.25 wt% Cu²⁺/ZnO@MMT-O, the published particleboard achieved antibacterial rates of at least 99% against both organisms. Its reported MOR, MOE, and IB were 10.65 MPa, 2304.40 MPa, and 0.29 MPa, respectively, with 24 h TS of 16.31%. In the same report, an unfilled board had higher MOR, MOE, and IB values, while the 1.50 wt% formulation exhibited lower strength metrics and higher swelling. The result identifies 1.25 wt% as a constrained compromise in that specific process, rather than as a universal optimum.

Figure 3 makes the trade-off visible, and Table IV gives the exact reported board-property values. The reference limits are shown only as contextual guide lines and do not replace specification checks for the intended product class. The decline in strength is consistent with a filler changing adhesive continuity, cure kinetics, or particle-resin contact. The rise in thickness swelling suggests that filler introduction may create accessible hydrophilic pathways or local discontinuities. A next-stage dual-function study can screen whether features that make clay accessible to VOCs also affect water response and mechanical retention. Formal emission kinetics are required before antibacterial rate, chemical exposure, and board durability can be evaluated jointly.



At 1.25 wt%, published bacterial reduction was ≥99% for *E. coli* and *S. aureus*. Points denote reported loadings only. Data source: Pang et al. [1]. No VOC outcomes or intermediate loading values were inferred.

Fig. 3. Published particleboard property trade-offs at explicitly reported filler loadings. MOR, MOE, IB, and 24 h TS values are transcribed from the source; selected GB/T 4897-2015 limits provide context only. No intermediate values or VOC outcomes are inferred.

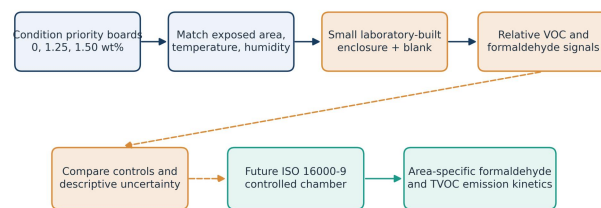
TABLE IV. PUBLISHED PARTICLEBOARD PERFORMANCE AT REPORTED FILLER LOADINGS

Filler loading (wt%)	MOR (MPa)	MOE (MPa)	IB (MPa)	24 h TS (%)	Antibacterial rate
0.00	13.82	2672.00	0.37	13.55	Not reported in selected text
1.25	10.65	2304.40	0.29	16.31	≥99% for both organisms
1.50	10.19	2251.20	0.27	17.20	Not reported in selected text

C. VOC mitigation remains a hypothesis until chamber measurements are made

No VOC-emission measurements were reported in the supplied antimicrobial particleboard article. Therefore, the present evidence cannot quantify a formaldehyde reduction, a TVOC reduction, an adsorption capacity in the cured board, or a human-exposure benefit. The co-loaded organoclay architecture is plausible enough to warrant testing, but the direction and magnitude of any emission change are unknown. Previous reports on organoclay interaction with formaldehyde in resins and wood composites provide a material rationale without establishing this board's emissions [23][24][25][26][27]. Recent particleboard chamber and commercial wood-panel studies indicate compound-specific dynamics, humidity sensitivity, and differences among panel profiles [28][29][30]. A mineral filler could lower emissions through adsorption, increase them through altered cure chemistry, or shift the compound distribution without changing TVOC. Simple enclosure screening can identify candidate trends; formal controlled-chamber work is needed to quantify the alternatives.

Figure 4 converts this uncertainty into a staged test sequence, and Table V specifies its measurements and decision constraints. Exploratory enclosure sampling compares formaldehyde and TVOC concentrations from the priority formulations under matched conditions. Compound-resolved fingerprints are a useful secondary endpoint if analytical capacity permits, because unchanged TVOC mass can conceal shifts in individual compounds. A later formal chamber study should pre-specify whether the key comparison is a day-28 area-specific rate, the entire 28-day profile, or both. The unfilled control and, when available, an MMT-O-only control help avoid attributing every observed change to Cu²⁺/ZnO. This architecture keeps a preliminary screening observation separate from a validated material claim.



Preliminary enclosure concentrations are not ISO-compliant area-specific emission rates. No emission reduction is claimed.

Fig. 4. Staged VOC validation architecture for the proposed dual-function particleboard. A laboratory-built enclosure permits preliminary relative concentration screening; ISO 16000-9 controlled-chamber testing is reserved for formal area-specific emission-rate validation. This is a protocol schematic, not an emissions result.

TABLE V. CHAMBER-TEST MEASUREMENT AND DECISION PLAN

Endpoint	Sampling schedule	Method	Primary comparison	Interpretation constraint
Formaldehyde concentration; later area-specific rate	Early and later screening; formal days 1, 3, 7, 14, 28	Small-enclosure screen; DNPH-HPLC if available; later ISO chamber	Co-loaded filler vs. unfilled board	Screening concentrations are not ISO emission rates
TVOC concentration; later area-specific rate	Early and later screening; formal days 1, 3, 7, 14, 28	Small-enclosure screen; TD-GC-MS if available; later ISO chamber	Co-loaded filler vs. unfilled board	Matched conditions and blanks; no certified rate from screen
VOC composition	Selected screening times; formal days 7 and 28	Optional TD-GC-MS compound identification	Relative profiles and blank-corrected signals	TVOC equality does not establish compound equality
Antibacterial rate and mechanical retention	Conditioned matched specimens	LY/T 1926-2020; GB/T 17657-2022	Priority 0, 1.25, 1.50 wt% formulations	Do not count repeated cuts as independent boards

V. DISCUSSION

A. Why a clay platform is a reasonable, but incomplete, indoor-health strategy

The value of the clay platform lies in its ability to organise functions rather than merely add ingredients. In the antibacterial branch, the carrier can anchor active components and increase their effective interfacial presentation. The published low MIC of the co-loaded system and the high board-surface antibacterial rate support this role. Related clay-supported copper and zinc antibacterial studies offer additional mechanistic context without substituting for board-level results [31][32][33]. In the VOC branch, organoclay chemistry offers a plausible route to alter volatile sorption and diffusion, but a loose-powder adsorption mechanism or an exploratory sealed-enclosure concentration is not equivalent to a lower emission rate from a cured board under controlled airflow. Resin encapsulation, humidity, temperature, and ventilation can all change the apparent response.

This distinction has practical consequences for design research. A visual or material narrative that shows clay pores, metal sites, and a healthy home is not evidence of reduced indoor exposure. The evidence must be anchored to the use condition and exposure pathway. The recommended response is not to abandon the multifunctional idea; it is to attach the correct test method to each claim. In this sense, the present framework integrates materials science with interior-system design: health performance is verified at the interface between a panel and occupied air, not only at the scale of powder morphology.

B. The optimal formulation is a Pareto frontier, not a single maximum

The published 1.25 wt% formulation illustrates a constrained optimum. It yielded a strong antibacterial outcome while maintaining reported board values compatible with selected dry-use thresholds, but its strength and swelling outcomes were less favourable than those of the unfilled control. Once formal VOC data become available, optimisation becomes multidimensional. A formulation could be excellent for bacterial reduction yet induce an adverse emission profile through altered resin cure. Another could reduce early VOC emissions but lose adsorption capacity after humidity cycling. A Pareto comparison should retain formulations for which no alternative is simultaneously better in antibacterial rate, formaldehyde/TVOC emissions, MOR, IB, and dimensional stability; without VOC measurements, the emission dimension remains explicitly unresolved.

A useful analysis should not collapse all outcomes into an arbitrary single score before readers can inspect the pattern. First, report each observed endpoint and its descriptive uncertainty where the sample size permits. Second, identify formulations that satisfy stated safety and structural constraints. Third, after formal emission data are available, compare the remaining formulations with a transparent multi-criteria decision rule whose weights reflect the use case. A bedside furniture panel, a school partition, and a dry-service cabinetry core may require different weighting because their touch frequency, surface area, moisture exposure, and ventilation contexts differ.

C. Release, ageing, and humidity are decisive boundary conditions

Metal-bearing antibacterial fillers should be assessed not only for efficacy but also for release control. Migration from antimicrobial products is an established concern in other product categories, and in an indoor board the relevant question is whether active ions or particulates become available during wet wiping, abrasion, or humid ageing. The clay carrier may improve immobilisation, but this cannot be assumed. Simple recorded wet-wiping or extraction screens can guide preliminary assessment; standardised abrasion, cyclic-humidity, elemental analysis, and repeat bacterial testing are follow-up validation tasks. Subsequent VOC comparisons should also account for humidity because it can change both clay sorption and organic emission pathways.

The VOC branch likewise needs careful chemical interpretation. Formaldehyde has a specific analytical and regulatory history, but lower formaldehyde alone does not prove lower overall chemical burden. Where routine analytical access permits, thermal-desorption GC-MS can screen whether the filler shifts other relevant carbonyls,

aromatics, terpenes, or residual processing compounds. Odour perception and health relevance cannot be inferred from TVOC alone. Compound-resolved analysis remains an optional exploratory endpoint and an important component of later formal validation, rather than a prerequisite for initial board preparation.

D. Limitations

The main limitation is evidentiary rather than rhetorical. The supplied study establishes a credible antibacterial foundation but does not provide a VOC chamber dataset. This manuscript consequently makes a strategy claim and a staged protocol claim, not a measured VOC-reduction claim. The proposed laboratory enclosure is useful for preliminary within-setup comparisons but lacks the controlled airflow and quality assurance needed for ISO-compliant area-specific rates. Published numerical values were available for selected loading levels and endpoints; no missing values were reconstructed. External validity is limited by the cited board's particular furnish, adhesive, density, pressing schedule, and conditioning regime. Different resins, decorative overlays, and use conditions may change both antibacterial accessibility and emission behaviour.

These limitations indicate a feasible sequence: prepare a small priority set of boards; use XRD and FT-IR for initial filler checks; assess board-surface bacterial reduction and mechanical and moisture properties; and screen relative VOC headspace behaviour in a documented small enclosure. Subsequent formal work should expand independent board replication, verify dispersion and metal retention if warranted, perform controlled ISO chamber testing with chemical analysis, assess ageing and release, and disclose deviations and exclusions. Until formal data are available, the manuscript remains an evidence synthesis and design framework rather than an original VOC-emissions report.

VI. CONCLUSION

Green clay-based functional fillers offer a coherent route to healthier particleboards when they are evaluated as integrated material systems. Published evidence shows that Cu²⁺/ZnO@MMT-O can deliver strong antibacterial performance in particleboard at a loading that retains practical dry-use board properties. The same clay platform has a chemically plausible but unverified role in VOC mitigation. This study separates the established antibacterial result from the proposed emission function and provides a feasible preliminary screening sequence followed by the formal controlled-chamber validation needed to connect them responsibly.

The next empirical study can begin with the three priority loading levels and report board-surface bacterial reduction, structural metrics, dimensional stability, and exploratory VOC concentration trends. A subsequent expanded programme should establish controlled emission trajectories, compound-specific profiles, and active-species release with adequate independent replication. Only then can a genuine Pareto-optimal formulation be assessed across all endpoints. If validated, the approach could shift particleboard functionalisation from a single-purpose additive strategy toward an evidence-based indoor-health material platform. If not validated, the staged protocol can still identify how the antibacterial filler modifies emissions.

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COMPETING INTERESTS

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