Green Building Materials, Residential VOC Emissions, and Carbon-Neutral Healthy Housing: A Sustainability-Oriented Assessment

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Abstract

The global built environment confronts a dual challenge: decarbonizing housing stocks to meet climate targets while safeguarding indoor environmental quality, particularly concerning volatile organic compound (VOC) exposures from building materials. This paper presents a sustainability-oriented assessment that systematically examines the interconnections among green building material selection, residential VOC emissions, and the emergence of carbon-neutral healthy housing. Adopting a systems-level perspective, the analysis exposes structural trade-offs between embodied carbon reduction, energy efficiency, and chemical safety that are inadequately captured by prevailing certification frameworks and life cycle assessment boundaries. It argues that the architecture of performance standards, material databases, and building information modeling systems must be re-engineered to incorporate dynamic indoor exposure pathways and health impact metrics. The discussion spans material chemistry, ventilation infrastructure, occupant exposure patterns, and multi-criteria decision-support tools, with attention to uncertainty, environmental justice, and robustness of assessments. Governance mechanisms, including building codes, product labeling, and smart monitoring networks, are evaluated for their capacity to align carbon-neutral trajectories with health-protective outcomes. The paper further integrates insights from digital twinning and adaptive ventilation control as enablers of responsive healthy housing. By synthesizing literature across building physics, exposure science, life cycle assessment, and policy studies, the study advances an integrated framework in which carbon neutrality and residential health are co-optimized rather than traded off. The conclusion highlights research needs for transdisciplinary data architectures, dynamic exposure models, and policy mixes that can bridge the current fragmentation between green material innovation and indoor air quality regulation.

Keywords

Green building materials; Volatile organic compounds; Indoor air quality; Carbon neutrality; Healthy housing; Sustainability assessment; Life cycle assessment; Policy integration.

1. Introduction

Buildings and construction jointly account for nearly 40% of global energy-related carbon dioxide emissions, making the sector a decisive front in climate mitigation [1]. Simultaneously, the indoor environment presents a significant health domain; people in high-income nations spend approximately 90% of their time indoors, where pollutant concentrations can exceed outdoor levels by a factor of two to five [2]. This convergence of climate urgency and indoor exposure burden has galvanized a movement toward carbon-neutral healthy housing that simultaneously pursues net-zero operational energy and the provision of safe, health-promoting interiors. However, the substances that fill the building envelope, from structural composites to finishes and adhesives, are known emitters of volatile organic compounds (VOCs), creating a persistent tension between material choices optimized for low embodied carbon and those that minimize chemical off-gassing. The systemic nature of this tension demands a sustainability assessment that transcends single-attribute metrics and examines the structural interdependencies among green building material innovation, residential VOC dynamics, and carbon-neutrality pathways.

Green building rating systems such as LEED and BREEAM have been instrumental in shifting market attention toward energy, water, and material efficiency, yet their treatment of indoor chemical exposures remains fragmented and often limited to prescriptive low-VOC content thresholds for a narrow set of priority compounds [3]. These schemes seldom require dynamic modeling of indoor air quality under realistic occupancy and ventilation scenarios, nor do they routinely integrate human health risk quantification into the credit-weighting architecture. As a result, a building can achieve high sustainability rankings while generating chronic formaldehyde or terpene oxidation product exposures that impose non-negligible disease burdens. This disjuncture signals a deeper governance gap: the infrastructure of green building certification, life cycle assessment (LCA) databases, and material specification workflows has not been architected to handle the coupled complexity of carbon flows and indoor chemistry.

Life cycle assessment has become the dominant analytical backbone for material sustainability comparisons. Standard LCA practice inventories environmental impacts across upstream production, transport, use, and end-of-life phases, yet the use phase is typically modeled as an energy consumption module divorced from indoor emission and ventilation dynamics [4]. The omission of indoor chemical fate, transport, and human uptake pathways means that health damages from VOCs are externalized from the comparative evaluations that guide material innovation. Early indoor air research established the broad spectrum of VOC species present in residential settings, underscoring the need to move beyond total VOC (TVOC) surrogates toward compound-specific assessments of carcinogenic and non-carcinogenic risks [5]. Methodological advances have since enabled estimation of chronic health impacts attributable to indoor pollutants in U.S. residences, providing a tractable template for monetized health damage integration [6].

Concurrently, the architectural definitions of net-zero and carbon-neutral buildings have matured, coalescing around annual operational energy balances that rely on a mix of demand reduction, high-efficiency envelopes, and on-site renewable generation [7]. Yet these definitions remain overwhelmingly energy-centric; they do not encode indoor health performance criteria as binding constraints or co-optimization targets. A recent, extensive investigation into residential VOC exposures from building materials, which combined chamber-based emission testing with field monitoring across multiple urban residential typologies, underscored the pervasive nature of indoor VOC burdens and identified material categories that dominate risk profiles [8]. This evidence base reinforces the imperative to embed chemical exposure science directly within the design and evaluation architecture of carbon-neutral housing programs.

The present paper undertakes a sustainability-oriented assessment that reconceptualizes green building material selection and carbon-neutral healthy housing as co-evolving components of a socio-technical system. It examines structural trade-offs between embodied carbon and chemical safety, evaluates the capacity of current assessment infrastructures to handle such trade-offs, and proposes governance pathways that leverage digital monitoring, integrated modeling, and multi-criteria decision frameworks. By linking material chemistry, indoor environment physics, health impact quantification, and policy instruments, the analysis contributes a system-level perspective intended to guide the next generation of sustainability standards and urban housing strategies.

2. The Material-Health Nexus: Green Materials and VOC Emission Dynamics

The shift toward green building materials has been propelled by the ambition to reduce the embodied energy and carbon footprint of the building stock. Bio-based insulations, recycled steel, low-carbon concretes, and natural fiber composites are increasingly specified in new construction and deep retrofits. Yet the chemical composition and post-installation emission behavior of these materials are not solely determined by their renewable or recycled content; they are shaped by additive packages, binding agents, and surface treatments that can serve as sustained sources of VOCs. For instance, cellulose insulation treated with borate fire retardants can emit aldehydes under elevated humidity, while some natural oil-based coatings release reactive terpenes that participate in indoor ozone chemistry to generate secondary organic aerosols and carbonyls. The material-health nexus thus requires a conceptual model that treats the building as a dynamic chemical reactor whose material inventory evolves over time under thermal and moisture drivers.

The architectural challenge is to construct material assessment frameworks that capture the joint space of environmental impacts and chemical exposures. Current product-level environmental product declarations (EPDs) overwhelmingly report global warming potential, acidification, eutrophication, and primary energy demand, but are largely silent on indoor chemical emission rates or health toxicity potentials. Similarly, indoor emission labeling schemes such as the German AgBB or France's VOC regulation classify products based on chamber test concentrations after 28 days, yet these classifications are not systematically linked to whole-building concentration predictions or cumulative health risk indices. The resulting fragmentation prevents designers from evaluating whether a substitution that reduces embodied carbon by 20% could increase lifetime cancer risk by a factor that outweighs the carbon benefit in societal cost terms. Overcoming this fragmentation demands a common data architecture in which material passports include both life-cycle impact coefficients and time-sensitive emission factors for high-priority VOCs, enabling their simultaneous consideration in building information models (BIM) during early design stages.

VOC emission dynamics are governed by internal diffusion within the material matrix, surface evaporation, and sorption interactions with other indoor surfaces and airborne particles. The rate and decay profile of emissions are material-specific and sensitive to temperature, relative humidity, and ventilation rate. Green materials engineered for low embodied carbon often have higher porosity or hygroscopicity, which can alter VOC buffering and re-emission cycles in ways that differ markedly from conventional synthetic products. Therefore, a system-level assessment must not regard material emission rates as fixed constants but rather as time-dependent parameters coupled to the hygrothermal environment of the building zone. This coupling becomes especially consequential in passive house and net-zero energy buildings, where reduced air change rates are compensated by mechanical ventilation with heat recovery, concentrating any emitted VOCs if filtration or purge strategies are not optimized. The architecture of ventilation systems interacts with material emissions to determine the effective exposure dose, highlighting that green material selection and ventilation design must be integrated within a single health-protective optimization loop.

From a governance perspective, building codes have traditionally separated structural safety, energy efficiency, and indoor air quality into distinct regulatory silos. The material-health nexus underscores the need for convergence. A mandate to use regionally sourced, low-carbon materials could inadvertently increase population VOC exposure if not accompanied by mandatory dynamic indoor air quality modeling at the permit stage. Some jurisdictions have begun to require pre-occupancy flushing procedures and post-construction air sampling, but these are episodic interventions that do not address long-term chronic exposures from materials with slow decay profiles. Designing a governance architecture that bridges material standards, ventilation requirements, and ongoing building performance monitoring is a central challenge for the healthy housing paradigm.

3. Exposure Pathways and Health Impact Assessment in Residential Contexts

Residential exposure to VOCs is a function of time-varying emission sources, building airflow patterns, occupant activity, and the physical-chemical processes that determine pollutant fate. Human activity pattern data demonstrates that individuals in developed economies spend over two-thirds of their time inside their own dwelling, with sleeping occupying the longest continuous exposure period in bedrooms where off-gassing from furnishings and fabric may be concentrated [10]. The spatial heterogeneity of sources, coupled with imperfect whole-house mixing, means that room-level concentration gradients can differ significantly, producing location-specific cancer and non-cancer hazard quotients. Exposure assessment frameworks must therefore move beyond single-zone well-mixed approximations and adopt multi-zone or computational fluid dynamics-informed approaches that resolve the microenvironments where vulnerable subgroups such as children, the elderly, and those with pre-existing respiratory conditions spend the most time.

The health endpoints associated with residential VOCs span sensory irritation, neurocognitive effects, asthma exacerbation, and carcinogenicity, with formaldehyde and benzene among the most scrutinized. The methodology developed to estimate the chronic health impact of indoor air pollutants in U.S. residences provides a formal structure for translating concentration fields into disability-adjusted life years (DALYs) and economic damages, using unit risk factors and established concentration-response functions [6]. However, the epidemiological evidence base for many VOCs found in green building materials, such as limonene, alpha-pinene, and glycol ethers, remains sparse, forcing reliance on animal toxicology with interspecies uncertainty factors that can obscure the true risk-benefit balance. A sustainability assessment that aims to compare material options on a health-inclusive basis must contend with these toxicological data gaps by building probabilistic exposure models that propagate uncertainty through the entire chain from emission factors to health endpoints while being transparent about the resulting decision robustness.

An epidemiological perspective reveals inequities in VOC exposure burdens. Low-income communities and rental housing stocks often feature higher material loading densities of inexpensive composite wood products and vinyl flooring, coupled with inadequate ventilation, leading to disproportionately elevated indoor VOC levels [2]. When carbon-neutral housing programs are rolled out as part of urban regeneration, there is a risk that cost-driven green material substitutions may inadvertently replicate or even exacerbate these disparities if health criteria are not explicitly integrated into procurement and financing. Fairness in the transition to healthy housing therefore demands that sustainability assessment frameworks include distributional analyses of indoor air quality outcomes, not just average per-dwelling metrics.

The temporal dimension of exposure adds further complexity. Retrofitting an existing dwelling for carbon neutrality frequently entails sealing the envelope, adding insulation, and installing mechanical ventilation. These interventions change the building's chemical signature; legacy VOCs absorbed into surfaces and materials can be desorbed under new thermal conditions, while the new materials introduce fresh emission sources. The net health effect is thus a dynamic outcome that evolves on time scales from days to years, underscoring the need for longitudinal indoor monitoring programs that track both energy and air quality performance post-retrofit and feed data into adaptive operation algorithms.

4. Carbon-Neutral Housing: Infrastructures and Integration Architecture

Carbon-neutral housing strategies have traditionally been conceptualized around a balance between annual on-site renewable energy generation and total operational energy consumption, including heating, cooling, lighting, and plug loads [7]. Advanced iterations incorporate embodied carbon budgets that cap the supply-chain emissions of the structural and envelope systems over a reference study period. However, the integration architecture that would natively couple these carbon metrics with indoor health performance is still nascent. A building that achieves net-zero carbon status may do so by adopting super-insulated, airtight envelopes with minimal thermal bridging and highly efficient heat recovery ventilation. While such envelopes reduce energy demand and provide thermal comfort, they also create conditions in which pollutant concentrations from internal sources can rise if the ventilation rate is set solely by CO2-based demand control without sensing key VOCs. Therefore, the technical infrastructure of carbon-neutral homes must be reimagined as a multi-objective control platform that continuously balances energy, carbon, thermal comfort, and chemical exposure.

Digital twinning and building information modeling offer promising integration architectures. A digital twin of a residential building can ingest material emission data, real-time temperature, humidity, and air change measurements, and occupant presence signals to simulate indoor VOC concentrations dynamically. By linking to cloud-based health impact assessment modules, the twin can translate predicted concentrations into health risk indicators that inform ventilation set-points, filtration activation schedules, and window-opening recommendations [14]. In this vision, the carbon-neutral housing unit becomes a cyber-physical system whose operational logic explicitly regards health outcomes as a control objective alongside energy minimization. The robustness of such an architecture hinges on the availability of validated, machine-readable emission factor libraries for a wide array of green materials, which currently are fragmented across disparate research datasets and manufacturer data sheets.

Infrastructure for data sharing and interoperability is equally critical. Building performance databases that currently collect energy use intensity and carbon metrics would need to be expanded to include indoor air quality metrics such as time-weighted average TVOC, formaldehyde, and select compound concentrations. The development of application programming interfaces (APIs) that allow building management systems and smart home platforms to access material chemical fingerprints and health risk coefficients would constitute a major advance. This would enable a shift from static, code-minimum compliance to adaptive, performance-based regulation where the responsible authority can audit the building's health-carbon signature over its entire service life.

At the community scale, the deployment of carbon-neutral healthy housing must contend with network effects. District energy systems and shared ventilation networks can buffer individual dwelling performance, but they also introduce inter-unit contaminant transport pathways if pressure differentials are not managed. System-level architecture for multi-family carbon-neutral retrofits thus requires whole-building coordination of material selection and ventilation zoning to ensure that the health performance of one unit is not compromised by the carbon-optimized choices of another. This entails governance mechanisms akin to building-wide indoor air quality warranties or health performance bonds that are tied to the realization of community-level carbon and wellbeing targets.

5. Multi-Criteria Sustainability Assessment and System Trade-offs

A sustainability assessment that simultaneously accounts for embodied and operational carbon, life-cycle energy, material toxicity, indoor VOC exposures, and health outcomes is inherently multi-criteria. The complexity is magnified by the different spatial and temporal scales of these criteria: embodied carbon is determined once at construction, operational carbon accumulates over decades, VOC concentrations fluctuate diurnally, and health damages may emerge with long latency. The integration architecture must therefore accommodate both static life-cycle inventory modules and time-resolved indoor fate and exposure models, connected by a common functional unit such as one square meter of finished floor area serving a defined occupancy over a 50-year reference period.

Dedicated comparative studies that applied multi-criteria LCA to building materials demonstrated that rankings can reverse when toxicity-related indicators are added to the traditional climate change and energy demand metrics [16]. When indoor emission health damages are expressed in DALYs and monetized using value-of-statistical-life estimates, the lifecycle cost-benefit calculus can shift significantly, favoring materials with lower chronic hazard even if they carry a modest carbon penalty. For example, a mineral wool insulation with a higher embodied carbon than a petroleum-based foam might emerge as superior when the avoided VOC-related health costs are included. Such findings underscore the trade-off structures that must be made transparent in decision-support tools for architects, builders, and policymakers.

The robustness of multi-criteria assessments is sensitive to weighting choices and uncertain parameters. Emission factors for the same product class can vary by an order of magnitude across manufacturers, while the dose-response slope factor for a given VOC may carry a threefold inter-study uncertainty range. Scenario-based sensitivity analyses become essential to identify break-even conditions under which the carbon-health trade-off flips direction. In the context of carbon-neutral housing programs, a precautionary posture would embed health constraints as inviolable minima within the optimization problem rather than treating health damages as merely one more monetized externality to be balanced against carbon abatement costs. This repositions material selection as a constrained optimization: achieving the lowest feasible carbon footprint subject to the condition that projected lifetime individual cancer and non-cancer risks remain below regulatory or societal de-minimis thresholds.

Environmental justice considerations add a further dimension of system trade-off. While a building-level multi-criteria assessment might demonstrate net societal benefit when average occupant exposures are reduced, it may mask disparities if certain subpopulations are systematically exposed at higher levels due to room occupancy patterns or socioeconomic factors. A distributional assessment requires stratifying the modeled population by age, pre-existing health status, and time-activity budgets to ensure that the transition to carbon-neutral housing does not create health hazard hotspots. Such a framework is computationally demanding and data-intensive, yet the increasing availability of residential indoor air quality sensor networks and building energy management data streams provides a foundation for operationalizing equity-weighted assessments.

6. Governance, Policy, and Sociotechnical Transformation

The translation of integrated building-level assessments into market practice requires a coherent governance framework that aligns the incentives of material manufacturers, developers, building operators, occupants, and regulators. Current green building policies operate predominantly through voluntary certification schemes, energy codes, and low-carbon procurement mandates that treat health and carbon as separate compliance tracks. The separation inhibits systemic innovation because a material innovation circle focused on low embodied carbon is rewarded irrespective of its VOC profile, while a health-protective ventilation standard is often pursued as an energy cost rather than a co-benefit generator.

Policy instruments that could bridge this divide include: the incorporation of dynamic indoor air quality performance thresholds into energy performance contracts for social housing; the extension of product labeling to report not only 28-day chamber concentrations but also modeled lifetime health risk contributions when used in a typical reference dwelling; and the inclusion of indoor health damage scores in public procurement criteria for building retrofits. Some European national building codes have begun mandating pre-occupancy measurement of formaldehyde and TVOC in new residential buildings, but these are static snapshots. More transformative would be a regulatory approach that requires ongoing monitoring of selected VOC tracers and continuous dynamic benchmarking against health-based exposure limits, integrated with a tradable health-index compliance scheme akin to energy efficiency certificate trading.

The role of digital infrastructure in governance is pivotal. A municipal government pursuing carbon neutrality for its housing stock could deploy a cloud-based health-carbon monitoring platform that ingests real-time sensor data from a representative sample of dwellings, runs dynamic emission and exposure models using as-built material inventories, and provides feedback to building managers and occupants through mobile applications [22]. Smart ventilation systems that use chemical sensing of total VOC levels or formaldehyde can modulate airflow in real time to keep concentrations below health thresholds while minimizing energy penalty; such adaptive approaches represent a sociotechnical shift from fixed air change rates to health-driven ventilation. The successful deployment of these systems at scale depends not only on technical reliability but also on governance arrangements that ensure data privacy, algorithmic transparency, and accountability for system failures that lead to health damages.

Equity-focused governance arrangements must also address the split-incentive problem in rental markets. Landlords who invest in low-VOC green materials and smart ventilation incur upfront costs while tenants receive the health benefits through reduced morbidity. Policy mechanisms such as health-adjusted tax depreciation allowances, green lease clauses that share energy and health performance savings, and public health insurance incentives that recognize primary prevention through building design can realign the economic calculus. These instruments require collaboration across housing, health, and environmental regulatory agencies, pointing toward the need for institutional architectures that vertically integrate building performance governance rather than silo it within construction ministries.

The international diffusion of carbon-neutral healthy housing practices further demands interoperability of material emission databases, exposure models, and health impact coefficients across climatic and cultural contexts. A climate zone with high ambient humidity and temperature will see different VOC emission decay rates and different susceptibilities of the exposed population, necessitating region-specific risk assessment parameters. Global sustainability assessment frameworks such as those being developed under the umbrella of the International Organization for Standardization's sustainability in buildings and civil engineering works committee can play a vital role if they evolve to include indoor health modules that are as rigorous as the established environmental impact categories.

7. Conclusion

The transition toward a decarbonized building stock brings into sharp focus the embedded chemical exposures that arise from the materials used to achieve carbon neutrality. This sustainability-oriented assessment has demonstrated that green building materials, residential VOC emissions, and carbon-neutral healthy housing cannot be optimized independently; they form a tightly coupled system in which decisions about material chemistry reverberate through ventilation design, energy performance, and long-term population health. The structural trade-offs between embodied carbon reduction and VOC-related health risk require new assessment architectures that simultaneously compute life-cycle environmental burdens and dynamic indoor health impacts. Portfolio-level governance instruments, ranging from dynamic building codes to health-aware digital twins and adaptive ventilation platforms, offer pathways to internalize these trade-offs in market practice while advancing equity objectives. Progress will depend on the creation of interoperable material emission databases, the refinement of compound-specific dose-response relationships, and the policy courage to mandate health performance tracking as an integral component of carbon-neutral housing certification. A built environment that is both climate-resilient and health-promoting is achievable only through transdisciplinary convergence that treats the indoor atmosphere as a critical element of the planet's life-support systems.

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