

Review

Indoor Odor Pollution: An Interdisciplinary Review from Sources to Control and an Intelligent Building Environment Management Framework

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Abstract

Indoor environmental quality directly affects public health and quality of life, among which odor pollution is one of the primary drivers of indoor environmental complaints. Traditional research and management approaches, which rely predominantly on mass concentrations of individual chemical compounds, are fundamentally inadequate for addressing the inherent sensory complexity, dynamic evolution, and subjective perception of indoor odors. Through a systematic literature review, this paper for the first time establishes an integrated research framework for indoor odor pollution across the whole-life-cycle management of the built environment, structured around “source–evolution–evaluation–control”. This framework systematically analyzes emission characteristics of building-related pollution sources, revealing the profound impact of indoor dynamic chemical and biological transformation processes on odor properties. Sensory analysis, instrumental measurements, and intelligent sensing approaches are critically compared in terms of their underlying principles and application boundaries. From an engineering perspective, the effectiveness and limitations of source prevention, ventilation dilution, and terminal purification strategies are comprehensively evaluated. The analysis demonstrates that effective indoor odor management must transcend passive and fragmented mitigation practices, and that its future development depends on the deep integration of environmental chemistry, sensory science, materials science, and artificial intelligence. Finally, this review proposes that by constructing regulation systems based on real-time sensing, digital twins, and intelligent decision-making, indoor odor management can fundamentally shift from reactive complaint-driven responses to proactive health-oriented protection. This paradigm transformation provides a systematic theoretical foundation and a technological roadmap for achieving healthy, comfortable, and sustainable building environments.

Keywords: indoor air quality; odor pollution; sensory evaluation; electronic nose; intelligent control; building environment management



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1. Introduction

In modern society, individuals spend approximately 90% of their lifetime indoors [1], making Indoor Environmental Quality (IEQ) a critical determinant of public health, human well-being, and economic productivity [2,3]. Among the various components of IEQ,

indoor odor pollution, characterized by unpleasant smells, has emerged as a major cause of occupant complaints, reduced environmental satisfaction, and a series of associated health and socio-economic issues due to its prevalence, persistence, and significant sensory intrusion [4–8]. According to reports from the World Health Organization, nearly 90% of the global population is exposed to indoor air pollutants at levels exceeding recommended limits, with odor-related issues consistently reported as one of the leading drivers of indoor air quality complaints [9,10]. Exposure to indoor odor pollution may directly trigger acute health symptoms such as headaches, nausea, irritation of the eyes, nose, and throat, as well as stress-related responses. Long-term exposure has been closely associated with the development and progression of Sick Building Syndrome (SBS) and Building-Related Illnesses (BRI) [11–15]. Beyond the health implications, the economic ramifications are substantial, including property devaluation and reduced labor productivity [16,17].

The essence of indoor odor pollution lies in its pronounced complexity and dynamic nature. Odor sources are highly diverse, encompassing building and decoration materials, human daily activities, and microbial metabolism, collectively emitting hundreds of volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and inorganic substances [18–21]. Instead, they actively participate in heterogeneous chemical reactions with strong oxidants—such as ozone, hydroxyl radicals, and nitrate radicals—introduced via ventilation or generated indoors, producing secondary pollutants and secondary organic aerosols (SOA) with altered and often more unpleasant sensory characteristics [22,23]. Simultaneously, human olfactory perception is highly subjective, involving a complex psychophysiological process from peripheral receptor binding to higher-level cognitive interpretation [24]. Olfactory adaptation, inter-individual variability, and cultural context further modulate odor perception [25–27]. Consequently, the indoor odor environment constitutes a coupled system characterized by multi-source emissions, dynamic transformations, and complex perception.

For a long time, research on indoor odor pollution has been largely framed within the analytical framework focused on broad-spectrum volatile organic compounds. This traditional approach, centered on the mass concentration of individual substances, has fundamental limitations when addressing odor pollution characterized by “sensory attribute”. First, such approaches often neglect the critical role of odor activity value (OAV, the ratio of compound concentration to its odor threshold), thereby overemphasizing high-concentration compounds with high odor thresholds while overlooking trace-level compounds with extremely low odor thresholds that dominate perceived odor [28]. Second, the additive assumption based on individual substances struggles to explain the widespread synergistic (where the overall odor exceeds the sum of its parts) and antagonistic (masking or weakening) effects among mixed odorants [29]. Third, these approaches fail to reflect the nonlinear psychophysical relationship inherent to olfactory perception itself [30]. These theoretical shortcomings directly constrain its practical application in engineering, resulting in existing control strategies that predominantly rely on passive, isolated end-of-pipe treatments targeting individual pollutants. Consequently, there is a lack of comprehensive, end-to-end system solutions that integrate multiple technologies from source to terminal.

In recent years, several excellent studies have provided valuable summaries of evaluation methods and standard systems for indoor odor pollution, as well as control strategies that treat it as part of indoor pollution alongside volatile organic compounds [31–35]. However, most of these studies have not adequately addressed the specificity and systematic nature of indoor odor as an independent sensory pollution phenomenon. In particular, there remains a lack of a coherent framework that integrates source characterization, dynamic evolution mechanisms, multidimensional evaluation methods, and building-integrated control strategies within a unified “source–evolution–evaluation–control” perspective.

To address these gaps, this review aims to overcome the aforementioned limitations by constructing and elaborating, for the first time, an integrated “source–evolution–evaluation–control” research framework for indoor odor pollution within the context of whole-life-cycle building management (Figure 1). The core objectives of this paper are: (1) to systematically characterize building-related odor sources and their emission mechanisms; (2) to elucidate the physicochemical and biological transformation pathways of odorants in dynamic indoor environments; (3) to critically evaluate and compare sensory-based, instrument-based, and intelligent sensing approaches in terms of their principles and applicability; (4) to propose engineering-oriented solutions for intelligent odor management, comprehensively assessing the effectiveness, limitations, and synergistic potential of source prevention, ventilation dilution, terminal purification, and smart control strategies. By integrating Internet of Things technologies, artificial intelligence, and building system integration, this review further examines the feasibility and pathways for transitioning indoor odor management from reactive complaint response to proactive health protection. Through this framework, the present work seeks to provide a clear knowledge map and a forward-looking technical roadmap, thereby promoting the evolution of indoor odor pollution management from a passive, fragmented mitigation toward a proactive, systematic, and health-oriented paradigm of intelligent building environment assurance.

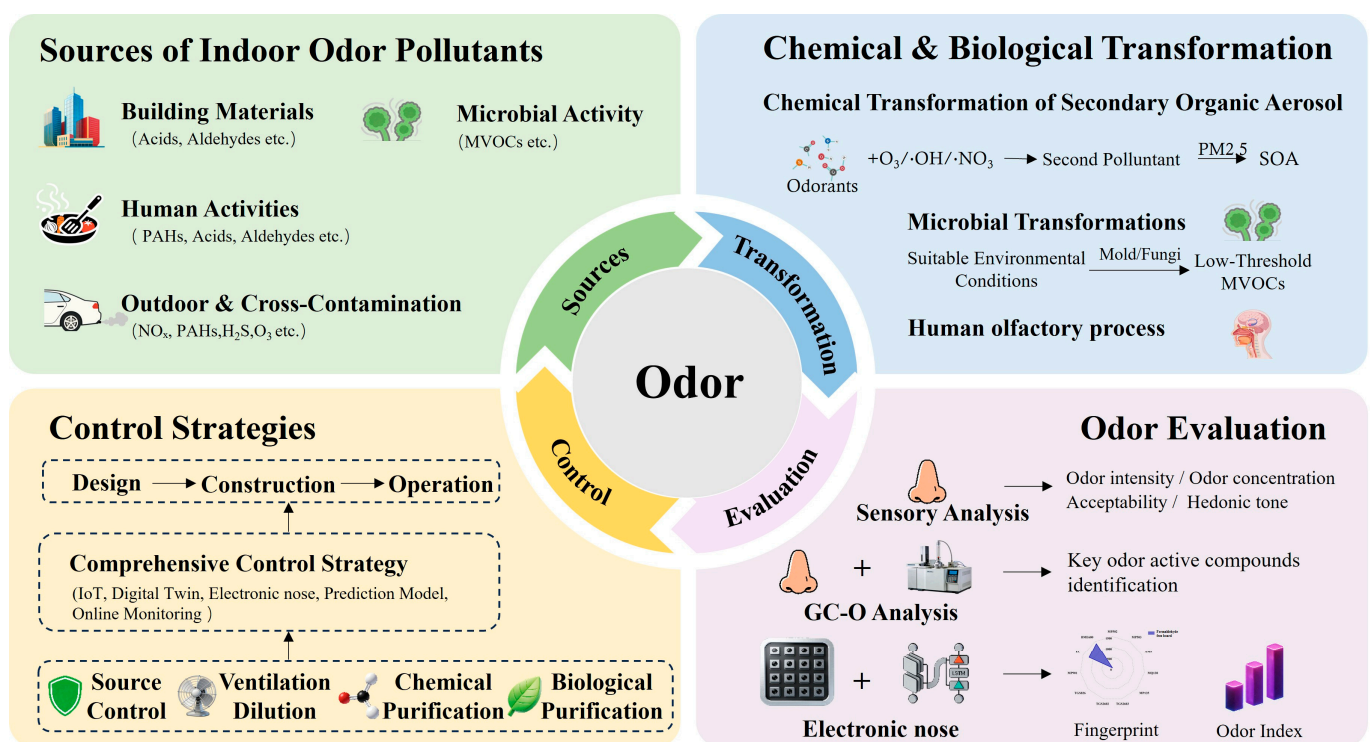


Figure 1. “Source–evolution–evaluation–control” research framework for indoor odor pollution.

2. Research Design and Methodology

To systematically construct a comprehensive knowledge framework for indoor odor pollution based on the “source–evolution–evaluation–control” paradigm, this review provides an integrative examination of indoor odor pollution in building environments as a highly interdisciplinary research field. The scope of the review encompasses odor source characterization, dynamic transformation processes, multidimensional evaluation approaches, and integrated control strategies, with particular emphasis on recent advances in intelligent sensing technologies and data-driven management paradigms (Figure 2).

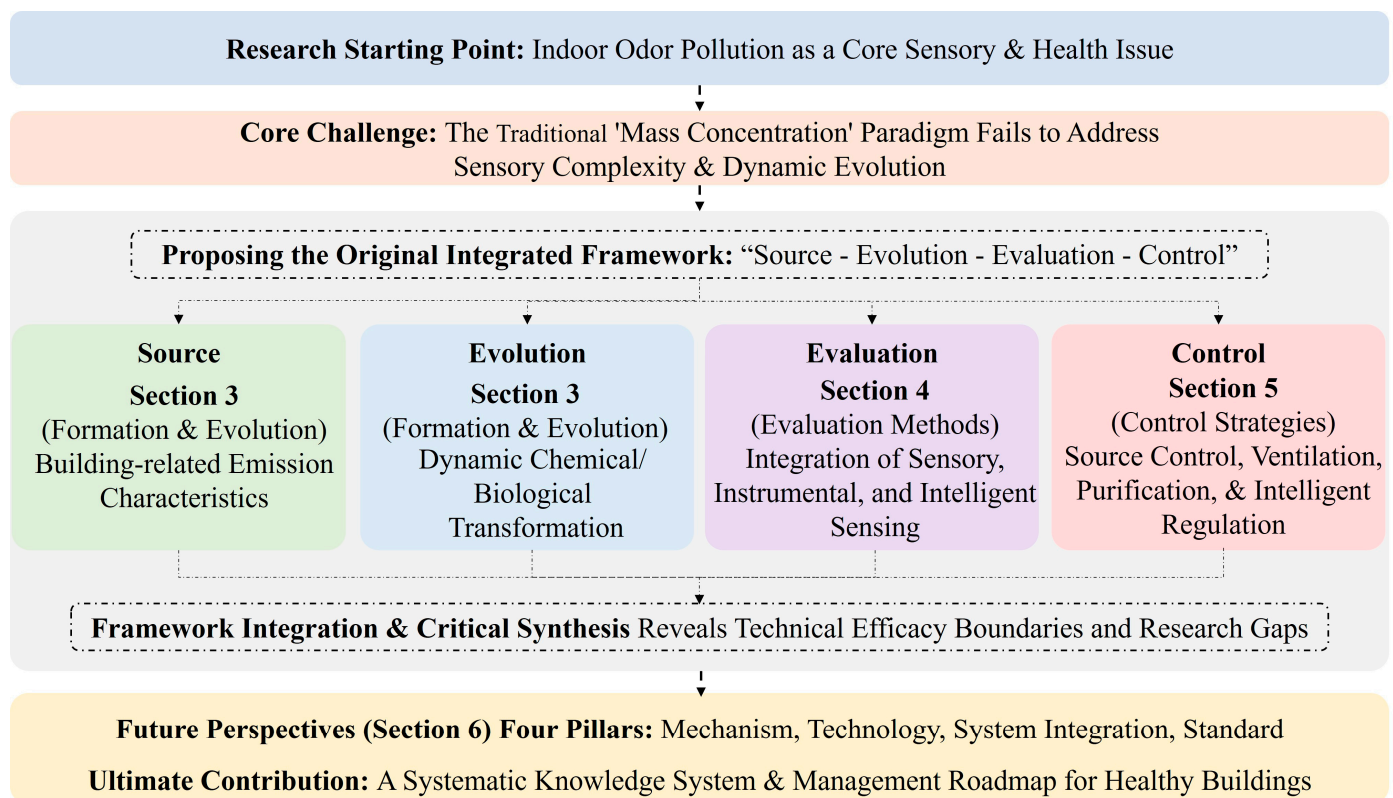


Figure 2. Overall Research Architecture and Conceptual Framework for Indoor Odor Pollution.

2.1. Literature Search Strategy

A systematic literature retrieval strategy was adopted to ensure comprehensive coverage in terms of breadth, depth, and temporal relevance. The primary literature sources included authoritative Chinese and international databases, namely Web of Science, Scopus, EI Compendex, PubMed, and China National Knowledge Infrastructure (CNKI).

The search was conducted using combinations of keywords such as "indoor odor", "building", "emissions from building materials", "sensory evaluation", "volatile organic compounds (VOCs)", "indoor air quality (IAQ)", "electronic nose", and "control technologies", in conjunction with Boolean operators and supplementary terms including "review", "assessment", "technology", and "system". This strategy was designed to capture both fundamental research and applied engineering studies relevant to indoor odor pollution.

2.2. Time Span and Focus Areas

The literature search covered publications from 1990 to 2025, reflecting the evolution of indoor odor research over the past three decades. Particular attention was devoted to studies published between 2020 and 2025, in order to capture the most recent developments in intelligent sensing technologies (e.g., electronic noses and artificial intelligence-based algorithms) and smart control strategies, which have experienced rapid advancement in recent years.

The selection and inclusion of literature followed predefined eligibility criteria to ensure relevance and scientific rigor.

The inclusion criteria were as follows:

- (i) Studies explicitly addressing odor pollution in building indoor environments, including residential buildings, offices, and educational facilities;
- (ii) Studies involving at least one core element of the indoor odor pollution chain, namely odor sources, dynamic transformation processes, evaluation methods, or control technologies;

(iii) Peer-reviewed original research articles, review papers, as well as influential international or national standards.

The exclusion criteria included:

(i) Studies primarily focused on industrial exhaust gases, outdoor atmospheric pollution, or non-building enclosed environments such as vehicle cabins;

(ii) Purely theoretical modeling studies lacking experimental validation or practical application relevance.

After preliminary screening, approximately 390 papers were shortlisted, and 159 studies that met all criteria were included in this review.

3. Formation Mechanisms and Dynamic Evolution of Indoor Odor Pollution

A thorough understanding of the formation and evolution of indoor odors is a prerequisite for their effective evaluation and control. This section examines indoor odor pollution from its multi-source origins to its ultimate human perception, with particular emphasis on the complex and dynamic processes governing odor transformation in building environments.

3.1. Diverse Sources and Emission Characteristics of Indoor Odors

Indoor odor pollution constitutes a complex system derived from multiple and diverse sources [7,36]. These sources can be primarily categorized into four major groups (Table 1), which differ substantially in emission intensity, duration, and chemical composition, collectively forming the source characteristics of the indoor odor environment [37–39].

The diversity of odor sources and their heterogeneous emission patterns result in extreme chemical complexity, typically involving hundreds of compounds with varying polarity, volatility, and reactivity [52,53]. This complexity not only complicates the accurate identification of key odorants but also provides a rich reactant pool for subsequent physicochemical transformations occurring in indoor environments [54].

Table 1. Primary sources, representative pollutants, and characteristics of indoor odors.

Primary Source Category	Specific Source Examples	Representative Odorants	Odor Character	Formation/Emission Conditions	Ref.
Building Materials	Plaster/Gypsum	Acetic acid, Pentanoic acid, Hexanoic acid	Sour, sweaty, musty	Material curing, hydrolysis of organic binders	[18]
		Dimethyl trisulfide, Propanethiol	Sulfurous, putrid	Sulfur impurities in raw materials, specific processing	[40]
	Wood & Wood-Based Panels	Formaldehyde, Pentanal, Hexanal	Pungent, grassy, fatty	Release from resin binders, emission from wood itself, oxidation	[18]
		1-Methylene-1H-indene, 2-Methylnaphthalene, α -Pinene, Δ^3 -Carene	Slightly bitter, wheat aroma, piney, resinous	Inherent release from wood	[18,41]
		Pentachlorophenol (PCP), Pentachloroanisole (PCA), Chlorophenol derivatives, PAHs	Pungent, earthy, musty, tarry	Microbial transformation of preservative-treated wood	[42]
		2-Nonenal, 1-Octen-3-one	Rancid, mushroomy, earthy	Oxidation of the polymer matrix during processing or use	[18]
	Polymer Materials (e.g., PP, PE, PVC)	Triethyl phosphate, Cyclohexanone, n-Butyl acetate, 4-Methyl-2-pentanone, 2-Ethyl-1-hexanol	Pungent, sweet, musty, plastic-like	Primary emissions from PVC flooring and wallcoverings	[43]
		Styrene	Plastic-like, solvent-like	Release from polystyrene-containing composites	[44]
	Rubber	Benzothiazole	Rubber-like, sulfurous	Release of accelerators used in vulcanization	[45]

Table 1. Cont.

Primary Source Category	Specific Source Examples	Representative Odorants	Odor Character	Formation/Emission Conditions	Ref.
Human Activities	Bioeffluents (Breath/Sweat)	Acetone, Isoprene, Methanol	Sweet, fruity	Basic metabolic products released via breath and skin	[46]
		6-Methyl-5-hepten-2-one (6-MHO), 4-Oxopentanal (4-OPA)	Sweaty, oily, sulfurous	Reaction of skin lipids (e.g., squalene) with ozone	[46]
	Cooking & Smoking	Aromatic Hydrocarbons (PAHs)	Oily, burnt	High-temperature cooking, incomplete tobacco combustion	[19]
		Fatty acids (e.g., Palmitic acid), Aldehydes (Formaldehyde, Acetaldehyde, Acrolein)	Cooking fume, rancid, pungent	High-temperature heating of cooking oil and food	[47]
	Cleaning & Air Freshening Agents	Limonene, α -Pinene, β -Pinene, Eucalyptol	Citrus, pine, fresh herbal	Volatilization of intentionally added fragrances	[20,48]
		Ethanol, Methanol	Alcoholic, sharp	Volatilization of solvents during use or at high temps	[48]
		Formaldehyde, Acetaldehyde, Nonanal, Decanal	Pungent, citrus peel, waxy	Direct emission or generated from terpene oxidation	[18,48]
	Microbial Activity	1-Octen-3-ol, 3-Methyl-1-butanol, 2-Ethyl-1-hexanol	Musty, earthy, alcoholic	Growth on damp, poorly ventilated building materials/furniture	[21]
		Geosmin	Strong earthy	Metabolites from microbes (e.g., actinobacteria); common in damp environments	[18]
Outdoor & Cross-Contamination	Vehicle Exhaust	Nitrogen Oxides (NO _x), PAHs, Ozone	Pungent, gasoline-like, metallic	Infiltration through windows, doors, building cracks	[49]
	Industrial Emissions	Hydrogen Sulfide, Ammonia	Rotten egg, pungent	Emissions from waste facilities, transported by wind	[50]
		Aldehydes, Acids, Aromatic hydrocarbons (e.g., BTEX)	Pungent, sour, aromatic	Industrial processes (chemical, plastic, pharma)	[51]

Ref. stands for References.

From the perspective of the built environment, odor sources exhibit distinct spatial attribution and material dependency. Building and finishing materials act as long-term, low-intensity background sources, with emission rates governed by material type, service age, and ambient temperature and humidity. Human activities like cooking and cleaning represent intermittent, high-intensity event-driven sources, closely linked to space function, such as kitchens and bathrooms. Microbial metabolic activity, which is typically associated with damp environments resulting from building defects such as leaks and condensation, is a source of persistent malodors. Outdoor infiltration and cross-contamination further highlight the importance of building envelope airtightness and ventilation strategies. Consequently, source control must be integrally considered alongside building design, material selection, and functional zoning.

3.2. Physiological and Psychological Basis of Odor Perception

The essence of odor pollution lies in the negative sensory perception it evokes. This perception is not a direct reflection of chemical concentration, but rather the outcome of a complex psychophysiological process that begins with molecular interactions and culminates in cognitive and emotional interpretation [55]. Understanding this process is essential for revealing the limitations of traditional chemical concentration-based management paradigms and for justifying the development of new evaluation and control frameworks.

Odor perception is initiated by the specific binding of odorant molecules to olfactory receptor proteins in the olfactory epithelium [56]. This binding is inherently competitive, as structurally similar molecules may compete for the same receptor sites, leading to suppression of perception, which is the molecular basis for odor masking effects [30]. Receptor activation triggers neural signals that are transmitted via the olfactory bulb to higher brain regions, including the cortex and limbic system [57]. At both the olfactory bulb and higher neural processing levels, nonlinear integration mechanisms play a critical role. Signal convergence

from multiple receptors can generate synergistic effects, whereby the perceived intensity of an odor mixture exceeds the sum of its individual components [58], while inhibitory neural circuits induce lateral inhibition, attenuating or filtering minor components within mixtures [59]. Ultimately, these signals are interpreted in brain regions associated with emotion and memory, yielding subjective experiences imbued with hedonic tone [60].

This complex perceptual pathway results in two fundamental characteristics with decisive implications for indoor odor management: high subjectivity and strong nonlinearity. Subjectivity arises from inter-individual variability in olfactory receptor genetics, cultural background, and personal experience, leading to markedly different evaluations of the same odor environment [25–27]. Nonlinearity implies that the overall intensity and quality of an odor mixture cannot be inferred through simple additive models, as synergistic and antagonistic interactions are pervasive.

As a result, a fundamental management dilemma emerges: even if the mass concentrations of all chemical constituents in indoor air could be precisely quantified, it remains nearly impossible to reliably predict the overall sensory impression, population acceptability, or complaint risk. Traditional indoor environmental standards that rely on individual compound limits or total volatile organic compound (TVOC) concentrations often fail to address actual odor complaints because they overlook the complexity and nonlinearity of odor perception. This contradiction underscores the urgent need for new evaluation paradigms capable of bridging chemical metrics and sensory responses.

3.3. *Dynamic Evolution Patterns of Indoor Odors*

The indoor odor environment is continuously evolving. Primary pollutants released into buildings undergo complex physical, chemical, and biological transformations that profoundly alter odor characteristics and intensity [61,62].

3.3.1. Chemical Transformation and Secondary Organic Aerosol Formation

Indoor atmospheric chemistry plays a pivotal role in odor evolution. Reactive odorants, such as terpenes emitted from cleaning products and unsaturated aldehydes generated during cooking, readily undergo heterogeneous reactions with strong oxidants introduced via ventilation or generated indoors, including ozone (O_3), hydroxyl radicals ($\cdot OH$), and nitrate radicals ($NO_3\cdot$). These reactions form secondary pollutants that often exhibit stronger sensory irritation [63]. Ozone–alkene reactions are particularly significant. For example, limonene, a citrus-scented compound commonly emitted from cleaning agents or wood products, reacts with O_3 to produce low-molecular-weight oxygenated volatile organic compounds (OVOCs) such as formaldehyde and acetic acid [64]. These secondary products typically possess much lower odor thresholds and are often described as “pungent”, “irritating”, or “oily”, leading to increased odor offensiveness. Hydroxyl radicals dominate daytime oxidation chemistry, reacting with a wide range of VOCs, while nitrate radicals contribute to nighttime nitration reactions, forming organic nitrates [65]. A further critical consequence of these oxidation processes is the formation and growth of secondary organic aerosols (SOA). Low-volatility products formed in the gas phase condense into the particle phase through gas–particle partitioning, generating SOA with large specific surface areas. These particles can strongly adsorb odorant molecules, acting as mobile reservoirs that delay odor removal via ventilation and potentially enhance sensory irritation and health risks through respiratory deposition [66,67].

3.3.2. Microbial Transformations

In damp and poorly ventilated building areas, microbial metabolism, particularly by molds and actinomycetes, represents a dominant biological pathway for the generation and persistence of characteristic musty and earthy odors [68,69]. Microorganisms metabolize

complex organic substrates, such as moisture-damaged gypsum board or cellulose fibers in carpets, into secondary metabolites with strong sensory signatures, including geosmin and a variety of microbial volatile organic compounds (MVOCs) such as alcohols and esters [70]. As long as favorable temperature, humidity, and nutrient conditions persist, microbial metabolic activity continues, rendering such odors resistant to removal by ventilation alone. Consequently, effective building management must prioritize moisture control and the complete removal of contaminated materials at the source.

3.3.3. Interactions Among Odorants

Dynamic changes in indoor odor environments are not solely driven by primary emissions and secondary transformations but also arise from direct interactions among existing odorants, which can instantaneously alter mixture composition and sensory properties.

Synergistic effects occur via two main pathways. First, new odor-active molecules may be formed, such as ethyl acetate with fruity notes produced through esterification between ethanol and acetic acid under suitable conditions. Second, physical encapsulation or complexation can modify volatility, as exemplified by cyclodextrin inclusion complexes that entrap hydrophobic odorants such as limonene and slow their release [71]. Antagonistic effects are manifested as reactions that directly eliminate odor molecules, such as the neutralization of ammonia and acetic acid to form odorless ammonium acetate. These rapid interactions occurring in the gas phase or at gas–liquid interfaces contribute to the transient and unpredictable nature of indoor odor characteristics, making them difficult to predict based solely on source strength and initial composition.

At present, quantitatively predicting synergistic and antagonistic effects in real, complex building environments remains a frontier challenge. Existing studies largely focus on qualitative observations or simplified binary and ternary mixtures [72,73], lacking mechanistic, quantitative models. Addressing this challenge requires integration across multiple knowledge domains: first, molecular-level binding affinities and kinetics between odorants and olfactory receptors, which remains largely unknown for most human receptors; second, detailed understanding of neural signal integration in the olfactory bulb and higher brain centers; and third, accurate descriptions of complex gas-phase and surface reaction kinetics. Therefore, future research urgently requires cross-disciplinary collaboration among chemistry, neuroscience, and computational modeling to establish a predictive framework capable of deducing overall sensory output from molecular properties.

3.3.4. Spatiotemporal Distribution and Long-Term Evolution of Indoor Odors

The spatiotemporal distribution of indoor odor pollutants exhibits high heterogeneity and complex dynamic fluctuations, primarily regulated by the combined effects of source characteristics, human activities, environmental parameters, and ventilation conditions.

Spatially, source location is the primary determinant of distribution patterns. Kitchens, for example, serve as high-intensity sources of aldehydes, such as hexanal and octanal, generated by lipid oxidation and amino acid degradation during cooking, with emissions often transported upward by thermal plumes to form vertical gradients [74,75]. Bathrooms primarily emit sulfur-containing compounds such as hydrogen sulfide and amines such as trimethylamine, both originating from microbial metabolism [34]. Driven by ventilation systems, buoyancy-induced convection, and occupant movement, airflow controls pollutant transport and mixing. The adsorption and subsequent re-emission of pollutants on material surfaces play dual roles as sinks and secondary sources. For instance, fabrics, carpets, and porous building materials can adsorb VOCs and later release them slowly when temperatures rise or ambient concentrations decrease, prolonging odor persistence and producing trailing effects [76].

Temporally, odor concentrations exhibit complex dynamic fluctuations. Transient peaks are typically synchronized with specific human activities, such as cooking or spraying. Intermittent fluctuations correlate with daily routines and the opening/closing of doors and windows [77,78]. On diurnal scales, aldehyde concentrations often peak in the afternoon due to temperature-driven emissions following Arrhenius behavior, and secondary reactions induced by outdoor ozone infiltration [78]. Seasonal variations are even more pronounced: high temperatures and humidity in summer generally enhance the release and impact of aldehydes. In regions with centralized heating, reduced ventilation combined with combustion activities in winter often leads to the accumulation of aromatic hydrocarbons and terpenes [79]. In contrast, emissions from materials and microbial metabolism constitute a long-term, slow-release pollution. Although their concentrations are low, their persistent nature forms the underlying “olfactory background” of indoor spaces and is the root cause of long-term exposure. This pronounced dynamism and heterogeneity imply that effective control strategies must be grounded in a deep understanding of space-specific usage patterns and environmental conditions, and must possess corresponding dynamic response capabilities.

Indoor odor pollution emerges from a multidimensional, dynamic process involving multi-source emissions, complex atmospheric chemistry and biological transformations, and physical transport and partitioning. Current research is limited by: (1) insufficient systematic comparisons of odor formation mechanisms and distribution characteristics across different building functions such as residential, office, and school environments; (2) limited quantitative predictive capability for synergistic and antagonistic effects in complex real-world mixtures, due to a lack of detailed chemometric and kinetic data; and (3) inadequate understanding of the combined health impacts of dynamic evolution processes such as SOA and MVOCs. Future research needs to develop more advanced online monitoring technologies and mechanism-based mathematical models to capture and predict the dynamic evolution of indoor odor environments in real time.

4. Evaluation of Indoor Odor Pollution

Accurate evaluation of indoor odor pollution constitutes the cornerstone of effective management and control. The essence of indoor odor pollution lies in the integrated physiological and psychological responses elicited by complex mixtures of volatile substances acting on the human olfactory system. These responses are jointly modulated by inter-individual variability, olfactory adaptation and fatigue, as well as synergistic and antagonistic interactions among odorants [80]. Consequently, even a complete chemical characterization of indoor air is insufficient to directly infer perceived odor quality, intensity, or the resulting comfort or annoyance. Therefore, effective evaluation methods must establish meaningful linkages between chemical metrics and sensory responses. This section systematically reviews three major categories of evaluation approaches: sensory analysis, instrumental analysis, and intelligent sensing. It critically examines their technical principles, applicability boundaries, as well as the challenges and prospects for their integrated application in real building environments.

4.1. Sensory Analysis

Sensory evaluation directly employs the human nose as the “detector”, capturing the actual perceptual outcomes elicited by odors. As such, it holds ultimate authority in defining odor acceptability. To scientifically quantify subjective perception, international standards have established core sensory indicators, including odor concentration, odor intensity, hedonic tone, and acceptability, along with standardized experimental procedures (Table 2).

Table 2. Comparison of Core Indicators and Experimental Methodologies in International Standards of Olfactory Analysis Methods.

Odor Indicator	Standard/Method	Panel Size	Key Assessment Method	Output/Scale	Ref.
Odor Concentration	EN 13725:2022	≥ 4	Dynamic dilution; Yes/No or forced-choice detection	European Odor Unit (ou_e/m^3)	[81]
	ASTM E679-19	No fixed minimum	Dynamic dilution; forced-choice (3-AFC)	Best-Estimate Threshold (BET)	[82]
	Japan Triangular Odor Bag Method	≥ 6	Static dilution; triangle odor bag	Odor Index = $10 \times \log$ (Odor Concentration)	[83]
	HJ 1262-2022 (China)	$\geq 4-6$	Pressure-assisted static dilution; triangle odor bag	Dimensionless dilution factor	[84]
Odor Intensity	ASTM E544-10	≥ 6	Matching to n-butanol reference series	Geometric progression (step factor 2)	[85]
	VDI 3882 Blatt 1 (2021)	≥ 8	7-point descriptive scale rating	0 (undetectable) to 6 (extremely strong)	[86]
	Japan Triangular Odor Bag Method	≥ 6	6-point descriptive scale rating	0 (no odor) to 5 (repulsive)	[87]
	GB/T 43353-2023 (China)	≥ 8	Matching to acetone scale + 7-point rating	Linear pi scale (0–20) and 7-point descriptive scale	[88]
Acceptability	GB/T 43353-2023 (China)	≥ 15	Direct sniffing and rating	−1 (completely unacceptable) to +1 (completely acceptable)	[88]
	ASTM E619-17	≥ 5	Indirect determination based on guidelines/experience	Qualitative decision (no direct scale)	[89]
Hedonic Tone	VDI 3882 Blatt 2	≥ 15	9-point scale rating	−4 (extremely unpleasant) to +4 (extremely pleasant)	[90]
	T/ACEF 155-2024 (China)	≥ 4	5-point scale rating	−3 (extremely unpleasant) to +1 (pleasant)	[91]

Ref. stands for References.

While standardization partially mitigates subjectivity, the true value of sensory analysis in building environmental management lies in its translation into engineering standards and design guidance. In recent years, this translation has followed three complementary pathways.

First, the derivation of chemical limits from sensory thresholds. A representative example is the “odor guide value” proposed by the German Committee on Indoor Air Guide Values (AIR). Based on the Weber–Fechner law, this approach uses odor thresholds and intensity coefficients of individual compounds to calculate concentrations corresponding to “clearly perceptible odor” (typically intensity level 3) [92]. This provides a rigorous pathway for directly embedding sensory impact into concentration-based regulatory limits, achieving explicit coupling between sensory science and chemical standards.

Second, standardized testing and grading of source emissions. Standards such as ISO 16000-28:2020 [93] and China’s GB/T 43353-2023 [88] adopt environmental chamber testing under simulated use conditions to evaluate gaseous emissions from building materials and products, followed by sensory assessment. The resulting outputs, such as odor concentration and intensity grades, can be directly used for product environmental labeling and market access control, enabling effective odor management at the material selection stage of building design. This represents a successful application of sensory evaluation within construction product supply-chain management.

Third, engineering control based on overall environmental performance. ASHRAE Standard 62.1-2022 [94] exemplifies this approach. Rather than prescribing odor limits for specific compounds, it ensures acceptable perceived air quality indirectly by specifying minimum ventilation rates to dilute the combined “sensory load” arising from human bioeffluents and material emissions. By employing perceived air quality models, complex

sensory issues are translated into designable and implementable ventilation parameters, representing an alternative engineering pathway from source limits to terminal dilution.

Together, these three pathways translate sensory science into practical engineering tools from the perspectives of substance regulation, product qualification, and environmental control. They demonstrate that sensory analysis has evolved beyond a purely laboratory-based technique and is now deeply integrated into building lifecycle environmental management. Nevertheless, these approaches largely rely on evaluations of individual compounds or idealized odor loads and remain limited in their ability to predict dynamic interactions within complex real-world odor mixtures, which constitutes a central bottleneck for current engineering applications.

4.2. Instrumental Analysis and Intelligent Sensing

To overcome the limited source-resolving capability of sensory analysis and to enable dynamic monitoring, instrumental analysis and intelligent sensing technologies seek to elucidate the chemical basis of odors and emulate human olfactory perception.

4.2.1. Gas Chromatography–Olfactometry (GC–O)

Gas chromatography–olfactometry (GC–O) is widely regarded as the “gold standard” for resolving complex odor mixtures. Its core principle lies in coupling the high separation capability of gas chromatography with the sensitivity of the human nose. Via a splitter device, the effluent from the chromatographic column is directed simultaneously to a physical detector for compound identification and quantification, such as mass spectrometry, and to a trained assessor’s nose for sensory description [95].

The primary strength of GC–O lies in its ability to establish direct causal relationships between chemical components and their sensory attributes, such as odor character and intensity. It enables both the identification of key odor active compounds within complex VOC mixtures and the assessment of each component’s relative odor contribution through intensity scaling methods, including Frequency Detection, Detection Frequency, and the OSME time intensity method [96]. Furthermore, GC–O serves as the foundation for constructing accurate odor activity value (OAV) models and predicting overall odor characteristics. The OAV is defined as the ratio of a compound’s concentration in a sample to its odor threshold, with higher OAVs indicating a greater contribution to the odor. By summing the OAVs of individual active compounds or employing more complex mathematical models, it is possible to predict, to some extent, the overall intensity and character of an odor mixture [97].

In indoor environmental research, GC–O is extensively used to deeply profile the characteristic odor signatures emitted by building materials, furniture, cleaning products, etc., identifying the “culprits” responsible for indoor malodors. When combined with advanced separation techniques like comprehensive two-dimensional gas chromatography ($GC \times GC$), GC–O significantly enhances the ability to separate and identify trace-level odorants and co-eluting compounds [98].

Despite its analytical power, GC–O has inherent limitations that restrict its applicability in real-time building operation. It is an offline technique incapable of continuous monitoring and requires costly instrumentation and highly trained panelists. Most critically, it evaluates individual compounds sequentially after chromatographic separation. This approach neglects pre-mixing effects and synergistic or antagonistic interactions occurring in the nasal cavity, thereby preventing faithful reproduction of actual human perception. These limitations highlight the insufficiency of relying solely on offline analytical techniques for building-scale odor management.

4.2.2. Electronic Nose

Electronic noses aim to emulate the holistic logic of biological olfaction by employing sensor arrays that generate broad-spectrum responses to complex gas mixtures, forming characteristic “odor fingerprints” subsequently analyzed using pattern recognition algorithms. This paradigm provides a theoretical foundation for real-time, online monitoring of indoor odors, with technological progress driven by advances in both sensor arrays and intelligent algorithms [99].

As the perceptual core of electronic nose systems, sensor arrays must be designed to combine the compositional characteristics of indoor odor pollutants with monitoring requirements, considering sensor type, quantity, and spatial layout. Given the span of indoor odor components from inorganic gases to diverse VOCs, practical arrays need to integrate units based on different sensing principles to achieve complementary coverage [100,101]. Metal oxide semiconductor (MOS) sensors are commonly used due to their high VOC sensitivity and mature fabrication processes; however, their high operating temperatures result in elevated power consumption and thermal disturbance, while humidity sensitivity and long-term drift constrain maintenance-free deployment in buildings. To address these limitations, materials research has focused on enhancing environmental adaptability. Strategies such as constructing p–n heterojunctions (e.g., NiO/ZnO) or incorporating noble metal dopants (e.g., Au) improve selectivity toward target compounds such as formaldehyde while optimizing response and recovery dynamics [102]. Resistive sensors based on carbon nanotubes, reduced graphene oxide, or MoS₂ have demonstrated ppb-level detection at room temperature with microwatt-level power consumption, providing a hardware foundation for distributed, embedded sensing nodes [103]. Electrochemical sensors offer high selectivity for key inorganic malodorants such as H₂S and NH₃, with electrode modifications such as PEDOT:PSS and nanocomposites, improving stability under complex background conditions [104]. Optical techniques such as surface-enhanced Raman scattering can provide molecular “fingerprints” but remain more suitable for targeted source identification than dense sensor networks due to cost and size constraints [105].

Once odor fingerprints are acquired, pattern recognition algorithms determine system accuracy and robustness. Electronic noses rely on machine learning techniques to extract representative features from sensor responses and construct predictive models (Table 3).

Table 3. Comparison of mainstream e-nose technology pathways.

Technology/Sensing Material	Key Advantages	Main Limitations	Typical Applications	Ref.
Metal Oxide Semiconductor (MOS/MOX)	High sensitivity, low cost, robust, MEMS-compatible	High power (high temp.), drift, humidity interference	Indoor/outdoor air quality, industrial odor monitoring, pollutant detection (paints, repellents)	[106–108]
Quantum Dots (PbS CQD, MCSQD)	ppb-level sensitivity, room-temp. operation, printable, tunable selectivity via ligand exchange	Ink stability issues, complex synthesis	Wearable e-nose, TVOC/NO ₂ /CO monitoring, breath analysis	[109]
2D Materials (Graphene, TMDs, MXene, BP)	Large surface area, room-temp. operation, fast response, FET-compatible	Humidity/oxygen sensitivity, fabrication scaling	VOC detection, healthcare diagnostics, food quality, robotics	[110]
Conductive Polymers	Flexible, low-cost, room-temp. operation	Poor long-term stability, slow response	Food freshness, medical diagnostics	[111,112]
MOS + Advanced ML (CNN, LSTM, Domain Adaptation)	Excellent classification (>97%), drift compensation, quantitative prediction	Needs large training data, computational load	Disease diagnosis, food authentication, odor intensity regression	[113–115]
IoT + Cloud-Enabled E-nose	Real-time remote monitoring, portable, scalable	Connectivity dependency, data privacy	Smart homes, mosquito-repellent pollutant tracking, indoor IAQ	[107,109]

Ref. stands for References.

Traditional machine learning methods, such as Support Vector Machines (SVMs), Random Forest (RF), Artificial Neural Networks (ANNs), and gradient-boosted decision trees

(XGBoost), can learn the distinctive response patterns of different pollution sources, musty odors, cooking fumes, and renovation volatiles included. This enables rapid source identification, with classification accuracy generally reaching 85–95% [107]. However, real-world building applications demand robustness under dynamic and uncertain conditions. Deep learning models such as convolutional neural networks (CNNs) and long short-term memory networks (LSTM) can automatically extract spatiotemporal features from sensor signals, improving concentration prediction accuracy and resistance to sensor drift—which is critical for long-term indoor monitoring [116,117]. Nevertheless, model transferability remains a major challenge. Models trained under controlled laboratory conditions often experience significant performance degradation when exposed to fluctuating temperature and humidity, complex background odors, and unknown interferents. Advanced domain adaptation and transfer learning approaches are being explored to mitigate this issue, but their effectiveness and computational cost in specific building scenarios remain to be validated [117].

Despite continued technological advances, the transition of electronic noses from controlled laboratories to real building environments faces substantial engineering challenges. Environmental adaptability is paramount, as fluctuating conditions and complex odor backgrounds undermine model generalization. Long-term stability and maintenance pose persistent obstacles due to sensor drift, aging, and contamination, compounded by the lack of convenient, low-cost calibration methods in operational settings. Finally, system integration and cost-effectiveness must be balanced. Achieving effective spatial coverage necessitates deploying numerous nodes, imposing stringent demands on cost, power consumption, and size. Moreover, integrating their data streams into existing Building Management Systems (BMS) involves complex protocol interfacing and custom development, and system costs still need optimization.

In summary, the fundamental value of electronic noses in building environmental management does not lie in replacing precision laboratory instruments, but in serving as distributed digital olfactory sensors that provide continuous, real-time perception. This role necessitates a shift away from laboratory-centric accuracy toward addressing core real-world challenges, namely environmental robustness, long-term stability, cost efficiency, and integration. Future research should focus on developing robust and maintainable sensor units, constructing heterogeneous sensor networks tailored to specific space functions, and standardizing odor fingerprint data streams that can be interpreted and utilized by building management systems. Only through deep integration with building information modeling (BIM), computational fluid dynamics (CFD), and intelligent ventilation and purification systems can electronic noses evolve from standalone detectors into indispensable components of intelligent building odor sensing and control systems, enabling a paradigm shift from reactive complaint response to proactive environmental protection.

4.3. Methodological Integration and Prospects for a Comprehensive Evaluation Framework

At present, no single evaluation method is capable of independently addressing the comprehensive assessment of indoor odor pollution. Future development will inevitably move toward the integration and convergence of multiple methods across multiple dimensions.

An ideal comprehensive evaluation framework should follow a logical sequence of “screening–identification–quantification–validation”. First, electronic noses or low-cost sensor networks deployed at key locations within buildings can be utilized for broad-spectrum, real-time monitoring, enabling early warning and trend tracking of odor events. Once anomalies or odor complaints are detected, portable or laboratory-based gas chromatography–mass spectrometry (GC–MS), in combination with gas chromatography–olfactometry (GC–O), can be applied to air samples collected on site for in-depth analysis, thereby accurately identifying key odor-active compounds and their sources through source

attribution and diagnostic analysis. Finally, for the identified key pollutants or odor events, standardized sensory evaluation panels can be organized to conduct on-site or sample-based assessments, quantifying actual sensory impacts such as odor intensity, hedonic tone, and acceptability, in order to validate the results of chemical analysis and establish priorities for control and mitigation.

The implementation of such a framework requires overcoming several challenges related to technological and managerial coordination. First, more stable and cost-effective intelligent sensing hardware must be developed to support large-scale deployment. Second, shared and high-quality databases linking “indoor odor fingerprints” with chemical composition are needed to provide a data foundation for algorithm training and model transferability. Third, standardized protocols for multi-source data fusion and interpretation must be established. By promoting deep integration among sensory analysis, instrumental analysis, and intelligent sensing, indoor odor pollution evaluation can evolve from fragmented and lagging diagnostics toward systematic and forward-looking intelligent monitoring and management, thereby providing robust technical support for healthy and comfortable building environments.

5. Control of Indoor Odor Pollution

Based on a deep understanding of odor sources, evolution, and evaluation, effective control strategies should go beyond isolated and passive end-of-pipe treatments to establish a holistic, multi-barrier integrated management system that covers the entire building life cycle. Consequently, effective odor mitigation relies on a multi-level strategy encompassing source control, ventilation-based dilution, terminal purification technologies, and intelligent management systems. This section synthesizes current research progress in indoor odor control and highlights emerging trends toward integrated and data-driven solutions.

5.1. Source Control

Source control is widely recognized as the most fundamental and cost-effective strategy for indoor odor management, with its effectiveness highly depending on proactive intervention during the stages of building design, material selection, and user behavior management.

Regarding material selection, prioritizing products certified by authoritative domestic and international green standards is essential. Key examples include China’s GB/T 43353-2023 standard which specifies odor intensity and concentration grading [88], the U.S. green building rating systems which strictly limits TVOC and specific harmful substances [118], and Germany’s Blue Angel label which sets limits for both VOCs and odor [119]. These standards effectively control odors by directly limiting odor emissions or restricting the release of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs). Specific measures include key practices such as using solid wood or formaldehyde-free engineered wood bonded with MDI adhesives to avoid continuous formaldehyde release; promoting water-based and plant-derived coatings to replace solvent-based products; selecting natural-fiber or low-VOC carpets installed via adhesive-free methods; and sealing exposed edges and cut surfaces of panels. These selections directly shape the building’s long-term odor baseline.

Design-phase architectural controls are equally critical. Humidity management serves as the key to preventing mold growth and the release of their microbial volatile organic compounds (MVOCs), necessitating the implementation of rational building envelope design and HVAC systems for effective moisture control. Humidity control is key to preventing mold growth and the release of microbial volatile organic compounds (MVOCs). It is recommended to maintain indoor relative humidity (RH) using air conditioning, dehumidifiers, or other appropriate means [120]. Regarding spatial layout and pressure management, measures

such as airlock doors or negative-pressure design can be implemented. These establish a stable pressure gradient between high-odor-intensity areas (e.g., garages, bathrooms, printing rooms) and clean living/working zones, effectively preventing pollutant dispersion. Furthermore, regular cleaning and maintenance of heating, ventilation, and air conditioning (HVAC) systems, especially for damp components such as condensate drain pans and cooling coils, can prevent these systems from becoming sources of secondary microbial contamination and pathways for odor diffusion. Furthermore, regular cleaning and maintenance of heating, ventilation, and air conditioning (HVAC) systems with special attention to damp components such as condensate drain pans and cooling coils can prevent them from becoming sources of secondary microbial contamination and pathways for odor diffusion [121].

Behavioral intervention and management constitute another critical component of source control. Comprehensive smoking bans are the most effective measure for controlling the thousands of odorants present in tobacco smoke, such as nicotine, acetaldehyde, and acrolein [122]. During cooking, high-efficiency range hoods should be activated concurrently and supplemented with general ventilation to achieve local capture of emissions at the source, including those from lipid pyrolysis and the volatilization of flavor compounds [19]. Promoting the use of clean energy sources, such as electricity, to replace solid fuels like coal and biomass can significantly reduce the generation of strongly odorous products from incomplete combustion, including PM_{2.5} and polycyclic aromatic hydrocarbons (PAHs), at the source [123]. Additionally, advocating for the use of fragrance-free or plant-based cleaning and personal care products helps avoid introducing new secondary pollutants, such as synthetic fragrances.

Overall, source control strategies are systematic, involving multiple disciplines such as materials science, architectural design, and behavioral science, and require multi-stakeholder collaboration. While they yield the greatest effectiveness, their success depends on a sound regulatory framework, transparent market information, and heightened environmental awareness among consumers. It should be noted that even when exclusively low-emitting materials are used in new construction or renovation, an airing-out period of several weeks to months should still be allocated to address the initial, often intense release of odorants, a phase commonly described as the “burst” emission period.

5.2. Ventilation Dilution

Ventilation dilution is a foundational measure for reducing indoor pollutant concentrations by introducing clean or relatively clean outdoor air, thereby mitigating sensory irritation. The primary technical approaches include natural ventilation and mechanical ventilation. Natural ventilation relies on wind-driven pressure and buoyancy-driven pressure, requiring no energy consumption. It offers a cost-effective solution in scenarios with favorable climates, clean outdoor air, and low occupant density, such as in residences and small venues. However, its performance is unstable, significantly influenced by weather and seasonal variations. Moreover, when outdoor air itself contains odorous compounds or precursors like O₃ and PM_{2.5}, it can become a new source of pollution. By comparison, mechanical ventilation employs fans to provide airflow, can be integrated with a building’s heating, ventilation, and air conditioning (HVAC) system, and enables precise control over airflow organization. It also actively ensures the cleanliness of supplied air through processes such as filtration and thermal/humidity treatment. Despite its higher energy consumption, mechanical ventilation provides reliable assurance for maintaining stable indoor odor levels in complex and variable indoor/outdoor environments [124].

The efficacy of ventilation hinges on the air exchange rate and its efficiency. Relevant standards, such as ASHRAE 62.1 and GB/T 18883-2022, provide recommended minimum ventilation rates or air change rates for different types of spaces. However, these standard

values are typically based on static assumptions and may not fully align with the dynamic nature of odor release. Computational Fluid Dynamics (CFD) simulation has emerged as a crucial tool for optimizing airflow organization and achieving precise, efficient odor removal. CFD models can visually reveal the propagation paths and stagnant zones of odorants indoors. For instance, by simulating and optimizing the layout of supply and exhaust openings, fresh air can be preferentially delivered to occupied zones, while odors near pollution sources like kitchens and bathrooms, can be rapidly captured and expelled. This approach enables superior sensory outcomes with lower energy consumption, representing the key shift in ventilation strategy from merely controlling “quantity” to actively optimizing “quality” [125].

It must be emphasized that the removal efficacy of ventilation technology for odor pollutants is inherently bounded by physicochemical constraints. Its effectiveness is highly dependent on outdoor air quality. More critically, ventilation frequently fails to adequately remove odorants possessing low volatility and strong adsorption tendencies, such as certain SVOCs that adsorb onto indoor materials and fabrics and re-emit gradually [126], or those with extremely low odor thresholds like ppb-level sulfur compounds or indoles. For the former, the limitation lies in the mass transfer rate from material surfaces to the air. For the latter, excessively high and costly dilution factors would be required to achieve a perceived “odor-free” state. Therefore, ventilation should be regarded as one component within an integrated indoor odor management system and must be applied in coordination with source control and terminal purification technologies.

5.3. Terminal Purification Technologies

When source control and ventilation are insufficient or impractical, terminal purification technologies provide an essential supplementary line of defense. These technologies aim to remove or transform odor-active compounds through physical adsorption, chemical reactions, or biological processes (Table 4).

While Table 4 elucidates the performance boundaries of individual purification technologies, translating these methods from laboratory settings or standalone devices into reliable and efficient components of building environments presents a series of more complex challenges. Future research should shift from pursuing the ultimate performance of individual technologies toward addressing their integration, adaptability, and sustainability in real building scenarios.

First, suitability matching is the primary engineering consideration in technology selection. For example, although non-thermal plasma technologies exhibit rapid reaction kinetics, their inevitable ozone by-product necessitates the integration of catalytic decomposition units and real-time monitoring systems, substantially increasing cost and control complexity. Similarly, biofiltration offers low energy consumption, but its long start-up and acclimation periods, as well as their sensitivity to environmental fluctuations require stable operating conditions and specialized expertise in building operation and maintenance. Therefore, there is no universally optimal technology; rather, appropriate technology combinations must be matched to specific building functions, pollution load characteristics, and operational capabilities. For instance, in densely occupied and continuously used office spaces, low-risk and low-noise adsorption or photocatalytic materials may be more appropriate, whereas in intermittently used areas with high pollution loads, such as waste rooms, powerful but isolated plasma-based units may be considered.

Second, technology integration poses both physical and control-related challenges. Constructing coupled processes such as “adsorption–catalysis” or “plasma–catalysis” involves more than simple equipment serial connection. Conflicts may arise between optimal airflow velocities, temperature, and humidity conditions required by different units, necessitating careful optimization of ductwork and reactor design to prevent performance inhibition. More

critically, the control logic of multi-technology systems is far more complex than that of single devices. An intelligent purification system must dynamically determine which purification stage to activate and at what operational intensity based on real-time sensor data—including pollutant species, concentrations, and environmental parameters. This requires the development of advanced multi-objective optimization algorithms and predictive control strategies to balance purification efficiency, energy consumption, and equipment lifespan.

Table 4. Comparison and Performance Boundary Analysis of Indoor Odor Terminal Purification Technologies.

Technology Category	Representative Technology	Core Principle	Advantages	Limitations	Application Scenarios & Building Integration Considerations	Ref.
Adsorption Technology	Activated Carbon/Modified Adsorbents	Physisorption/chemisorption on porous surfaces	- Broad efficacy vs. non-polar VOCs - Mature, low-cost - Simple, passive operation	- Limited capacity; requires regeneration - Low efficiency for polar molecules - Sensitive to humidity/temperature - Performance unpredictable in mixtures	- Emergency use for intermittent, medium–low events - Pre-treatment unit - Requires scheduled maintenance	[127,128]
	Metal/Covalent Organic Framework Materials (MOFs/COFs)	Selective adsorption via ultra-high surface area & tunable pores	- High theoretical capacity & selectivity - Pore size designability	- Very high cost - Limited long-term stability data (real air)	- Experimental; lab/high-value venues only - Future depends on stable, low-cost models	[129]
Chemical Catalysis & Oxidation	Photocatalytic Oxidation (PCO)	UV light generates reactive oxygen species (ROS) to degrade pollutants	- Broad-spectrum degradation - Stable catalysts (e.g., TiO₂) - Uses sunlight/low-power UV	- Low quantum efficiency; slow - May produce toxic intermediates - Catalyst deactivation by fouling	Integration into building materials (passive, large surface)	[130,131]
	Non-Thermal Plasma (NTP)	High-voltage discharge creates plasma, degrade odorants	- Very fast; handles peak concentrations - Effective for VOCs, odorous inorganics - Microbial disinfection	- Ozone (O₃) byproduct - High energy use	- High-pollutant-load, isolated, non-continuous spaces - Embeddable in building ventilation systems or internal interfaces - Must couple with O₃ destruction	[132,133]
Biological Purification	Microbial Filtration	Immobilized microbes metabolize pollutants	- Low energy; eco-friendly - Complete mineralization (to CO₂/H₂O)	- Long startup/acclimation - Slow kinetics; not for fluctuating loads - Sensitive to environment; high maintenance	- Stable pollutant composition environments - Requires pre-filter, humidification, & continuous operation	[134,135]
	Plant–Microbe Synergistic Systems	Plants & rhizosphere microbes degrade synergistically	- Ecological & aesthetic benefits - Removes some VOCs & particulates - Minimal energy use	- Low purification rate; large footprint - Specialized plant care needed - Slow response to spikes	Aesthetic auxiliary for low-pollutant-load spaces	[136,137]
	Enzyme-based catalytic purification	Immobilized enzymes catalyze specific reactions	- Highly specific & efficient - No living system; no bioaerosols - Theoretically no secondary pollution	- High cost; - Long-term stability challenges - Narrow substrate range - Immobilization affects activity/lifetime	- Targeted removal of specific dominant pollutants - Functional additive in filters	[138]

Ref. stands for References.

Finally, a paradigm shift from single devices to building systems is essential. Ideally, odor purification technologies should not be treated as standalone appliances retrofitted after construction but rather as integral components of building environmental control systems incorporated during the design stage. This entails investigating the long-term performance and durability of passive purification elements, such as photocatalytic coatings and adsorptive wall materials, at the material level; developing standardized and modular purification components that can be readily integrated into ceilings, ductwork, or fresh air units at the equipment level; and establishing IoT-based digital operation and maintenance platforms at the management level to enable filter life prediction, performance degradation warnings, and preventive maintenance. Only through holistic optimization across design, materials, equipment, and operation can purification technologies evolve from reactive end-of-pipe solutions into inherent performance attributes that safeguard indoor odor quality. This evolution is an essential step toward advancing healthy building development.

5.4. Integrated Management and Intelligent Regulation: A New Paradigm

The preceding analyses of source control, ventilation dilution, and terminal purification technologies demonstrate that each individual approach has inherent performance boundaries and applicable scenarios. The most effective strategy is to establish a multi-stage, collaborative control framework spanning the entire building life cycle of “design–construction–operation” (Figure 3). During the design phase, spatial layout and material selection should be systematically planned to minimize pollution release potential at the source; during construction, low-emission materials and processes must be rigorously implemented to ensure design intent is realized; and during operation, multi-barrier coordination of source control, ventilation dilution, and terminal purification should be supported by real-time monitoring to enable dynamic regulation. Together, these measures form an integrated pollution control chain that provides continuous temporal coverage and multi-layered spatial defense.

With advances in the Internet of Things, big data, and artificial intelligence, indoor odor management is evolving from traditional static approaches toward dynamic, intelligent, and precision regulation. The core of this transition lies in the construction of a closed-loop system: deploying low-cost, high-stability sensor networks (e.g., advanced electronic noses) to continuously perceive indoor odor fingerprints and key pollutant concentrations; utilizing cloud-based or edge computing platforms to operate AI- and CFD-based digital twin models that predict odor transport and evolution; and ultimately enabling intelligent decision-making systems to automatically adjust ventilation rates, activate or deactivate air purification devices, and even coordinate lighting control via curtain systems to modulate photocatalytic intensity. This enables integrated “monitoring–warning–control” and demand-responsive management of indoor odor environments, fundamentally shifting from passive response to proactive warning and precise regulation. Nevertheless, significant barriers remain in advancing toward this intelligent paradigm. From a technical perspective, long-term sensor stability and the generalization capability of algorithms in complex real-world environments remain key bottlenecks. From an economic perspective, initial investment and life-cycle costs must be further optimized to enhance market attractiveness. From a regulatory and standardization perspective, there is a lack of design, commissioning, and evaluation standards tailored to dynamic intelligent control systems. From a cross-disciplinary collaboration perspective, deep cooperation among experts in architecture, environmental science, information technology, chemistry, and materials science is required. Future research and practice should address these challenges to promote the transition of indoor odor management from passive complaint-driven responses to proactive systems that safeguard health and comfort, thereby providing critical technical support for the realization of healthy buildings and sustainable cities.

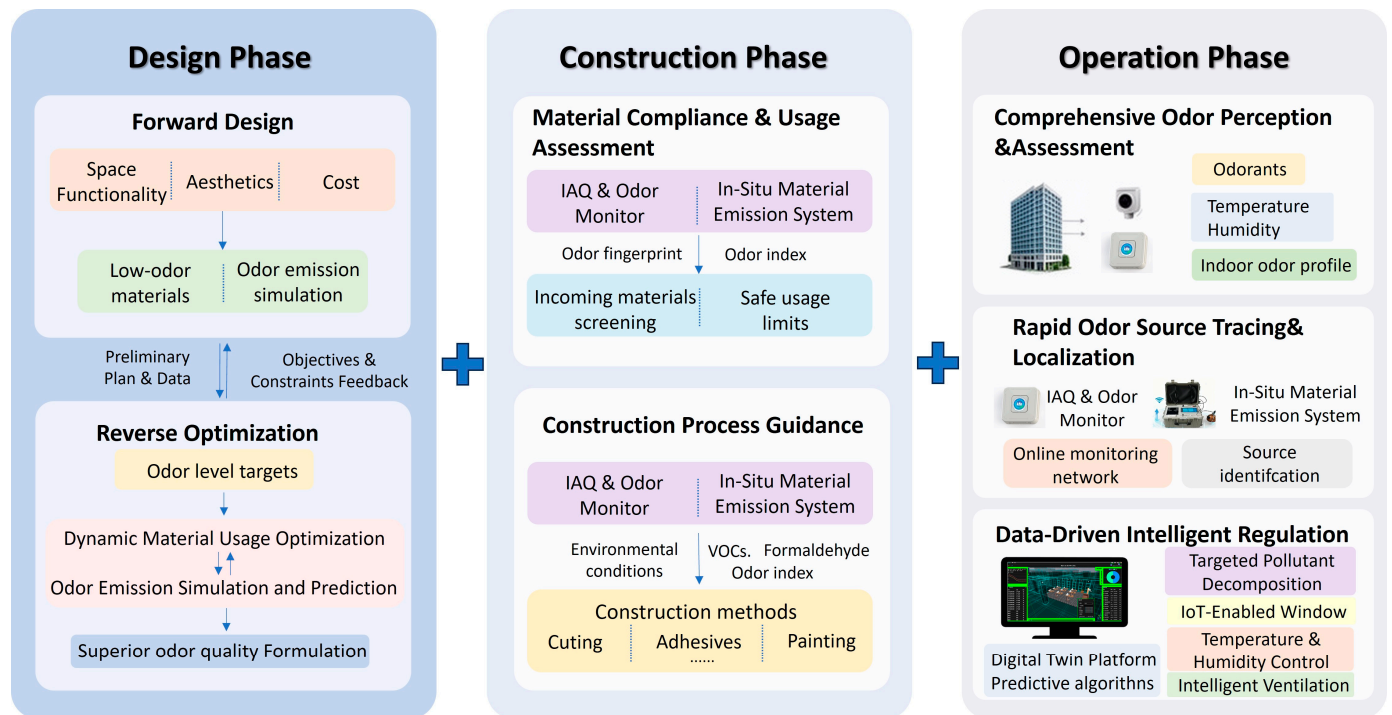


Figure 3. Building Life-Cycle Multi-Phase Collaborative Management and Control System.

6. Conclusions and Perspectives

Through a systematic review, this study constructs and elucidates an integrated “source–evolution–evaluation–control” framework for indoor odor pollution, oriented toward full life-cycle management of building environments. The analysis indicates that indoor odor pollution is inherently a complex, interdisciplinary system problem involving multi-source dynamic emissions, intricate physicochemical and biological transformations, and nonlinear human perceptual responses. Traditional management approaches based solely on the “mass concentration” of individual substances exhibit fundamental limitations in addressing real-world odor complaints, as they fail to characterize the odor activity values of key odorants, inadequately quantify synergistic or antagonistic interactions among mixed odors, and neglect the profound reshaping of sensory characteristics induced by secondary transformations. Consequently, future research and practice must adopt sensory impact and health risk as core guiding principles, promoting deep integration across environmental science, building engineering, sensory neuroscience, and data intelligence.

Within this framework, the present review provides a critical synthesis of multidimensional evaluation methods and integrated control strategies. First, it proposes a process-oriented analytical framework that spans the entire pollution pathway, for the first time placing building-related emission source characteristics, indoor dynamic chemical and biological transformation mechanisms, multidimensional evaluation approaches, and hierarchical control strategies within a unified logical chain. This framework reveals the interactions and constraints among different stages of odor generation, perception, and mitigation. Second, an in-depth technical critique and integrative analysis is conducted, not only clarifying the principles and effectiveness of various evaluation and control technologies but also emphasizing their performance boundaries, engineering challenges, and synergistic potential in real building environments. In particular, the review delineates distinct pathways for translating sensory evaluation into engineering standards and explicitly identifies the gaps that electronic noses and advanced purification technologies must bridge when transitioning from laboratory settings to real-world applications. Third, the necessity and feasibility of an intelligent management paradigm are substantiated. By constructing closed-loop control systems based on

real-time sensing networks, digital twin models, and intelligent decision-making algorithms, indoor odor management can shift from a “passive complaint-driven response” to a “proactive safeguard for health and comfort”, and a conceptual vision for technology integration and system architecture is outlined accordingly.

It should be acknowledged that the framework developed in this review is primarily derived from literature synthesis and logical inference. Its effectiveness in practical applications—particularly regarding implementation strategies and cost–benefit performance across different climate zones and building types such as hospitals, schools, and residential buildings, requires extensive empirical validation and further refinement.

Looking ahead, to realize the proposed intelligent management paradigm and fundamentally improve indoor odor environmental quality, future research and practice should focus on the following key directions:

1. **Mechanistic elucidation and data-driven modeling:** Advanced techniques such as exposomics and single-cell sequencing should be leveraged to elucidate microbial metabolic pathways and olfactory receptor response mechanisms under complex exposure scenarios. Concurrently, multi-source monitoring data should be integrated with building information modeling to develop digital twin systems capable of high-fidelity simulation of odor dispersion, transformation, and sensory impacts, providing essential tools for prediction and scenario analysis.
2. **Technological Innovation and Material Development:** Priority should be given to the development of next-generation adsorptive materials, such as functionalized MOFs and COFs, with high selectivity, large capacity, and low flow resistance, as well as stable catalysts exhibiting high quantum efficiency, broadband light responsiveness, and product pathways favoring complete mineralization. In parallel, synthetic biology approaches should be employed to select and engineer high-performance functional microbial strains and enzymes, alongside optimized bioreactor designs, to enhance the robustness of biological purification technologies.
3. **Intelligent system integration and engineering implementation:** A central challenge lies in overcoming the engineering bottlenecks associated with low-cost, long-lifespan, and highly reliable intelligent sensor networks, as well as in developing robust algorithms capable of adapting to variability in real-world environments. Furthermore, open interface standards should be established to enable seamless interoperability and intelligent coordination among sensing networks, building automation systems, and purification actuators, thereby reducing technical and economic barriers to large-scale deployment.
4. **Health-oriented reconstruction of standard systems:** Management paradigms should evolve from focus on sensory comfort and chemical concentration limit toward comprehensive standard systems integrating health risk assessment. This requires the establishment of health risk databases for odorants based on exposure–dose–response relationships and the exploration of incorporating dynamic sensory evaluation indicators into green building certification and post-occupancy evaluation frameworks, thereby providing a more scientific basis for healthy building governance.

Through sustained exploration and breakthroughs in these areas, indoor odor pollution management can transition from its current passive and lagging control paradigm toward a forward-looking, preventive, and health-centered intelligent environmental assurance paradigm. This transformation is not only essential for improving indoor environmental quality at the individual building level but will also lay a solid scientific and technological foundation for achieving broader goals related to sustainable cities and public health.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
ANN	Artificial Neural Networks
BRI	Building-Related Illness
cAMP	Cyclic adenosine monophosphate
CFD	Computational Fluid Dynamics
CNG	Cyclic nucleotide-gated
COFs	Covalent organic frameworks
DBD	Dielectric barrier discharge
GC-O	Gas chromatography olfactometry
HVAC	Heating ventilation and air conditioning
IAQ	Indoor air quality
IEQ	Indoor Environmental Quality
IoT	Internet of Things
IVOCs	Intermediate-volatility organic compounds
MDI	Methylene Diphenyl Diisocyanate
MEMS	Micro Electro Mechanical System
MOFs	Metal–organic frameworks
MOS	Metal oxide semiconductor
MVOCs	Microbial volatile organic compounds
NTP	Non thermal plasma
OAV	Odor activity value
ORs	Olfactory receptors
OSNs	Olfactory sensory neurons
OVOCs	Oxygenated volatile organic compounds
PAHs	Polycyclic aromatic hydrocarbons
PCO	Photocatalytic oxidation
PIDs	Photoionization detectors
RF	Random Forest
SBS	Sick Building Syndrome
SOA	Secondary organic aerosols
SVM	Support Vector Machines
SVOCs	Semi-volatile organic compounds
VOCs	Volatile organic compounds

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