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Adsorption, catalytic oxidation, and phytoremediation for air pollution control: a comprehensive review

Amirreza Talaie, [abc] Mohamad Ali Fulazzaky, [*d] Shahabaldin Rezania[e] and Amin Tamadon [*cf]

Modern office infrastructure, furnishings, and traditional cooking practices contribute to air pollution, posing significant health risks, including respiratory issues, cancer, and immune system suppression, especially for vulnerable groups. This review examines recent progress in adsorption, catalytic oxidation, and phytoremediation for reducing volatile organic compounds and fine particulate matter, major air pollutants. Adsorption technologies employ conventional materials like activated carbon and advanced options like metal–organic frameworks and biochars, offering high adsorption capacities due to tunable structures and large surface areas. Catalytic oxidation, including photocatalytic and thermocatalytic methods, effectively degrades pollutants, with composites like nano-ZnO/coke enhancing removal efficiencies. Phytoremediation using household plants like *Epipremnum aureum* and green walls effectively removes pollutants through enzymatic degradation, stomatal absorption, and microbial synergy. This review assesses integrated strategies' scalability, efficiency, and practicality for comprehensive air quality management, highlighting their potential to enhance public health.

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Environmental significance

Authors give serious consideration to the remediation of indoor air pollution, providing comprehensive knowledge on issues and purification methods for removing volatile organic compounds and particulate matter from indoor air. This provides a comprehensive understanding of various adsorption, catalytic oxidation, and phytoremediation methods for controlling indoor air pollution, advancing the application of these methods in removing air pollutants and preventing public health issues.

1. Introduction

Modern office infrastructure and upgraded interior furnishings have worsened air pollution (AP), compromising air quality.[1] Hermetically sealed office buildings with poor ventilation and heavy reliance on air-conditioning contribute to sick building syndrome, driven by volatile organic compounds (VOCs) from construction materials, furnishings, and equipment.[2,3] Exposure to AP leads to increased risks of cancer, respiratory issues, allergies, and weakened immune systems.[4] AP's global burden extends beyond offices, impacting vulnerable populations disproportionately.[5] Approximately 3 billion people, mainly in low- and middle-income regions, rely on polluting cooking fuels and stoves, emitting fine particulate matter ($PM_{2.5}$) and toxicants that pose significant health risks.[6] Epidemiological analyses reveal that among the associated adverse health outcomes, approximately 27% are attributable to pneumonia, 18% to stroke, 27% to ischaemic heart disease, 20% to chronic obstructive pulmonary disease, and 8% to lung cancer.[7] Notably, nearly 50% of pneumonia-related mortality in children under five years of age is linked to the inhalation of $PM_{2.5}$ derived from AP, underscoring the vulnerability of pediatric populations to these environmental hazards.[8] These findings collectively highlight the pivotal role of air quality in safeguarding and enhancing human health, necessitating effective mitigation strategies. Among the most promising approaches are adsorption and catalytic oxidation processes, which target the removal or degradation of pollutants such as VOCs and $PM_{2.5}$.[9] Adsorption uses high-capacity materials to capture pollutants, whereas catalytic oxidation utilizes photocatalysts or thermocatalysts to convert harmful substances into harmless

[a]*Department of Civil Engineering, Jami Institute of Technology, Isfahan, Iran*
[b]*Plant Design Department, Pars Abnoos Sanat Consulting Engineering Company, Shiraz, Iran*
[c]*Department of Natural Sciences, West Kazakhstan Marat Ospanov Medical University, Aktobe 030012, Kazakhstan. E-mail: amintamaddon@yahoo.com*
[d]*Department of Environmental Science, Faculty of Engineering and Science, Universitas Ibn Khaldun Bogor, Jalan Sholeh Iskandar, Kedungbadak, Bogor 16162, Indonesia. E-mail: mohamad.ali.fulazzaky@uika-bogor.ac.id; fulazzaky@gmail.com*
[e]*Department of Environment and Energy, Sejong University, Seoul, 05006, South Korea*
[f]*Stem Cells Technology Research Center, Shiraz University of Medical Sciences, Shiraz, Iran*

byproducts.[10] Phytoremediation utilizes various household plants to absorb and break down pollutants, improving air quality through natural processes.[11] This review synthesizes recent advancements in air purification technologies, assessing their effectiveness, scalability, and potential integration into comprehensive air quality management systems. Certain selective houseplants have proven effective in breaking down common air pollutants, making them a valuable tool for improving air quality. This paper addresses AP by exploring scientific foundations and practical applications, providing effective solutions.

2. Methods

This review examines various AP purification methods, considering factors like temperature and humidity that influence their effectiveness. A comprehensive literature review can identify factors driving the application of adsorption, catalytic oxidation, and phytoremediation for air purification.[12] This review provides insights into advances in air purification, supporting sustainable environments and informing future management strategies to address VOC changes from evolving painting applications and human activity patterns. This review examines three air purification methods: (1) adsorption using conventional adsorbents and metal–organic frameworks (MOFs), (2) catalytic oxidation *via* photocatalytic processes, and (3) phytoremediation using household plants. Comparing these three air purification methods provides insights into effective strategies for mitigating AP and informs future perspectives.

3. Advancements in air purification

Air purification of VOCs and $PM_{2.5}$ can be achieved through three methods: adsorption using conventional materials and MOFs, catalytic oxidation using light-activated semiconductors, and phytoremediation with plants. These approaches provide valuable insights into scalability, efficacy, and environmental sustainability.

3.1. Adsorption processes

Adsorption processes for AP mitigation focus on conventional materials and MOFs to evaluate their effectiveness in removing VOCs and safeguarding human health.

3.1.1. Conventional materials for adsorption. Adsorbents are solid materials that adsorb gases or liquids due to their extensive surface area and optimal pore structure, enabling efficient capture and retention of target substances.[13,14] Among adsorption materials, activated carbon (AC) stands out as a widely utilized and effective option for mitigating AP due to its high surface area and adsorption capacity. However, its relatively elevated cost poses a limitation, prompting research into more cost-efficient alternatives. This balance between performance and economic feasibility underscores the need for ongoing advancements in adsorbent technologies, a key focus of this review.[15] Another prominent adsorbent is the zeolite molecular sieve, an inorganic crystalline material distinguished by its uniform pore structure, pronounced acidity, and exceptional hydrothermal stability. These properties render it uniquely effective in the remediation of air pollutants, complementing its role alongside other adsorbents such as AC.[16,17] Biochar mitigates VOCs through two primary mechanisms: adsorption in the carbonized fraction and partitioning in non-carbonized organic matter.[18] The carbonized fraction's adsorption capacity involves chemisorption (covalent bonding) and physical adsorption (hydrophobic interactions, dipole–dipole forces, π–π interactions, hydrogen bonding, and coulombic interactions).[19,20] Biochar's effectiveness in adsorbing VOCs depends on factors like biomass source, pyrolysis temperature, and surface modification. Different feedstocks yield varying surface areas, morphologies, and elemental ratios (H/C and O/C), even under identical synthesis conditions. For example, bamboo-derived biochar (600 °C) has a surface area of 375 m^2 g^{-1}, whereas switchgrass-derived biochar (same temperature) has a significantly lower surface area of 15 m^2 g^{-1}.[20] Operational conditions like temperature, humidity, and flow velocity significantly impact biochar's VOC mitigation effectiveness. ACs, such as those derived from wood, coconut shells, and coal, are commonly used.[21]

Wood-derived AC, with its highly developed pore structure, effectively adsorbs various substances and impurities.[22] Coconut shell AC, appearing as black granules, is characterized by a well-developed specific surface area ranging from 1000 to 1600 m^2 g^{-1}, a micropore volume comprising approximately 90% of its total porosity, and micropore diameters of 1 to 4 nm, optimizing its adsorption capabilities for pollutants.[23,24] Modified coconut shell AC exhibits enhanced removal efficiency for pollutants like benzene, formaldehyde, and ammonia, outperforming other ACs due to its well-developed pore structure, high adsorption capacity, and durability. Derived primarily from nutshells and wood chips through processes of carbonization, activation, and refinement, it features a large specific surface area, robust strength, uniform particle size, and a highly effective pore structure, collectively enhancing its adsorption performance.[25] While agrowaste-based AC presents a lower-cost option, it exhibits lower adsorption performance compared to coconut shell-derived AC. In contrast, coal-based columnar AC, made from high-quality anthracite, boasts a well-organized pore structure, mechanical strength, and regeneration capabilities, suiting it for gas purification, water treatment, and solvent recovery.[26] Impregnating AC with materials like MnO_2 enhances its adsorption capacity. Specifically, MnO_2 improves formaldehyde removal by promoting particle dispersibility, reducing agglomeration, and boosting catalytic efficiency.[27] A TiO_2-impregnated carbon layer on expanded graphite-based carbon/carbon composite boosts both adsorption and photocatalytic degradation. This combo enhances formaldehyde removal by leveraging TiO_2's photocatalytic properties while maintaining adsorption performance.[28] AC's adsorption capacity for VOCs like benzene and toluene increases with pore diameter, but larger pores can reduce efficiency for acetone and methanol. Optimal adsorption occurs with pore diameters of 0.902–1.997 nm within a relative pressure range of 0.1 P/P_0.[29] AC's formaldehyde adsorption capacity depends on its pore structure

and surface functional groups. A previous study shows that higher nitrogen content in polyacrylonitrile-based AC fibers boosts its affinity for polar pollutants like formaldehyde.[30] Nitrogen functional groups near oxygen atoms boost adsorption efficacy, but adsorbent design must also account for affinity to water to ensure effective pollutant removal.[19,31] Research by Bellat *et al.*[32] found that faujasite zeolites, particularly NaX, NaY, and CuX, effectively capture formaldehyde, with a high adsorption capacity of 14.6 mol m^{-2}, outperforming other nanoporous materials.

Cationic zeolites show promise for air pollution control, with regeneration *via* vacuum heating at 200 °C, highlighting their potential for practical applications.[33] Electrostatic precipitation charges and removes fine particulates, and pairing it with adsorbents boosts gaseous contaminant removal. The effectiveness depends on voltage and contaminant type. Applying a strong electric field to AC fiber enhances adsorption capacity.[34] Treating AC with an oxidant atmosphere boosts its adsorption properties by increasing oxidized surface groups and negative surface charge, especially in shell-derived carbon.[35] A comprehensive evaluation of 15 biochar types derived from five raw materials revealed varying VOC adsorption capacities, with acetone (483.09 mg g^{-1}), toluene (424.4 mg g^{-1}), benzene (161.42 mg g^{-1}), and methanol (10.6 mg g^{-1}) exhibiting different uptake.[36] Surface area and non-carbonized organic matter primarily influenced adsorption, while pyrolysis temperature inversely affected efficiency. Biochar's cost-effectiveness and abundance make it a promising VOC adsorbent. Furthermore, nanoparticle-integrated coke carbon shows enhanced formaldehyde removal. Nano-ZnO-coke composites demonstrate effective formaldehyde removal, achieving 40–73% decomposition rates at concentrations of 2.5–25 mg m^{-3}.[37] Longer residence times enhance degradation, highlighting the potential of this method for efficient formaldehyde purification potential.[37] Chemical activation of coconut shell carbon with KOH enhances benzene adsorption due to improved surface properties.[38] However, KOH incorporation can hinder porosity development, especially mesopore formation, despite increasing carbon reactivity.[39] Activation temperature dominates the activation process, and benzene adsorption capacity correlates linearly with surface area. A comparative analysis of adsorbents reveals that advanced porous materials like modified zeolites outperform traditional materials (AC, natural zeolites) in gas capture, offering higher capacity, selectivity, and regenerability.[32] Nanofiber-based adsorbents, with high surface areas and microporous structures, show promise due to their reproducibility and reusability. A notable example is carbon fiber aerogel (CFA) derived from bamboo fibers, which effectively adsorbs organic pollutants with high selectivity, efficiency, and recyclability.[40]

Table 1 compares adsorption capacities of conventional and emerging adsorbents for VOCs, highlighting significant progress in material design for improving air quality. While AC (*e.g.*, coconut shell) shows strong adsorption capacity (up to 800 mg g^{-1} for benzene), emerging materials like MOFs and biochars exhibit even higher performance.[25] MOFs like MOF-5 and MOF-177 exhibit high adsorption capacities (1211 mg g^{-1} for CH_2Cl_2 and 589 mg g^{-1} for acetone), while biochar (bamboo) achieves 483.09 mg g^{-1} for acetone, attributed to their superior surface areas and tunable pores.[37] Meanwhile, CFAs from bamboo show promise with high toluene adsorption (450 mg g^{-1}) and reproducibility.[40] This review highlights the shift from traditional adsorbents to advanced materials, emphasizing surface area, pore size, and structural diversity as key factors in enhancing VOC removal for effective air quality management.

3.1.2. Mitigation by metal–organic frameworks. MOFs are porous, crystalline materials consisting of organic ligands and metal ions that self-assemble into highly ordered frameworks with exceptional structural versatility.[43] MOFs have gained attention for adsorption applications due to their high surface area and pore volume, enabling exceptional pollutant capture capabilities. They outperform traditional adsorbents, showing high adsorption capacities for VOCs and toxic gases at ambient conditions.[44] MOFs' tunable pore structure and surface properties allow for selective VOC adsorption, broadening their applicability. Their composition of metal ions and organic ligands enables *in situ* synthesis under mild conditions, facilitating customized material development.[45] MOFs not only effectively adsorb VOCs but also enable environmentally sustainable synthesis, allowing *in situ* production that preserves plant ecosystems.[46] MOFs outperform AC and zeolites due to their larger surface areas, tunable pore sizes, ordered

Table 1 Comparison of adsorption capacities of conventional and emerging adsorbents for VOCs[a]

Adsorbent	VOC	q (mg g^{-1})	A (m^2 g^{-1})	r (nm)	References
AC (coconut shell)	Benzene	800	1200	2.0	Pang *et al.*[25]
AC (coconut shell)	Formaldehyde	600	1200	2.0	Huang *et al.*[27]
Biochar (bamboo)	Acetone	483.09	375	1.5	Rezaee *et al.*[37]
Biochar (switchgrass)	Benzene	161.42	15	1.2	Rezaee *et al.*[37]
MOF-5	CH_2Cl_2	1211	2500	1.2	Tranchemontagne *et al.*[41]
MOF-5	CCl_4	1472	2500	1.2	Tranchemontagne *et al.*[41]
MOF-177	Acetone	589	4170	0.94	Yang *et al.*[42]
MOF-177	Benzene	800	4170	0.94	Yang *et al.*[42]
Nanofiber CFA (bamboo)	Toluene	450	1800	0.8	Jiao *et al.*[40]

[a] Note that VOC is volatile organic compound, q is adsorption capacity (in mg g^{-1}), A is surface area (in m^2 g^{-1}), and r is pore size (in nm).

structures, and diverse architectures. Functional modification capabilities further enhance their adsorption performance and versatility.[47] MOFs have emerged as key materials for mitigating AP due to their exceptional adsorption capacities for toxic gases at ambient temperatures. Their efficacy stems from diverse interactions, including coordination bonding, acid-base forces, π-complex formation, and hydrogen bonding, enhancing selectivity.[48] MOF-5 exhibits exceptional VOC adsorption capacities at 295 K, with values of 1211 mg g^{-1} (CH_2Cl_2), 1367 mg g^{-1} ($CHCl_3$), and others, surpassing traditional adsorbents like AC by 4–10 times.[41] MOF-*n* materials, built from extended metal carboxylate clusters, represent further advancements in MOF development.[49] MOF-5's porous and thermally stable framework retains structural integrity up to 300 °C, with 55–60% free pore volume, enabling optimal gas adsorption.[50]

The development of porous materials for AP mitigation has roots in early work, such as synthesis of diamond-like microporous structures.[51] This pioneering research laid groundwork for highly ordered frameworks, ultimately influencing the emergence of MOFs.[52] These advancements have driven innovations in VOC-capturing adsorption materials, a focus of this review. Building on Hoskins and Robson's[51] work, Moore *et al.*[53] synthesized a novel skeletal polymer using silver and triphenyl units. Yaghi *et al.*[52] then pioneered MOFs, creating microporous structures like MOF-5, a landmark material for VOC adsorption, marking a significant milestone. Advancements in MOF design include IRMOF-6,[54] outperforming MOF-5, and MOF-177,[42] featuring a high surface area (4170 m^2 g^{-1}) and 0.94 nm pore diameter, enhancing adsorption capabilities. Yang *et al.*[42] demonstrated MOF-177's exceptional VOC adsorption, with capacities over 200 mg g^{-1} for compounds like acetone (589 mg g^{-1}) and benzene (800 mg g^{-1}). Its high surface area (4170 m^2 g^{-1}) and pore diameter (0.94 nm) enable superior performance, positioning MOF-177 as a promising material for AP mitigation. The ZMF composite composed of zinc (Zn), manganese (Mn), and ferrite (Fe_3O_4), combining MOF-199 with ZSM-5 foam, demonstrates enhanced VOC adsorption capacity, outperforming individual components. With significant increases in adsorption for *n*-hexane (150%), benzene (283%), and cyclohexane (468%), this hybrid material showcases the potential of composite adsorbents for improved selectivity and capacity.[55] Nanocasting SBA-15 silica into CMK-3 carbon replica alters porous structures, yielding distinct chemical and structural properties.[56] CMK-3, derived from SBA-15, exhibits modified adsorption trends due to retained mesopores and inherent microporosity.[56] Similarly, the Materials of Institute Lavoisier (MIL)-series MOFs leverage mesoporous and microporous structures for effective VOC adsorption.[57] The MIL-101 material exhibits a specific surface area of up to 5900 m^2 g^{-1}, with its benzene adsorption capacity at 303 K reaching 1303 mg g^{-1},[58] surpassing the highest value previously documented in the literature. Wang *et al.*[59] synthesized MIL-101(Cr) and Cu-doped MIL-101(Cr), achieving VOC adsorption capacities of 103.4 mg g^{-1} and 114.4 mg g^{-1}, respectively. The materials exhibited high surface areas, with 3367 m^2 g^{-1} for MIL-101(Cr) and 2518 m^2 g^{-1} for Cu-3@MIL-101(Cr). Comparative analysis with conventional AC, a widely utilized industrial adsorbent, indicates that MIL-101(Cr) demonstrates considerable potential as an effective adsorbent for the adsorption and elimination of ethylbenzene from contaminated air,[60,61] Finsy *et al.*[62] studied xylene isomer separation in MIL-47, observing an adsorption hierarchy: *ortho*-xylene > *para*-xylene > *meta*-xylene, driven by adsorbate–adsorbent interactions. Huang *et al.*[63] found MIL-101 exhibits high adsorption capacities for VOCs with heteroatoms or benzene rings, particularly *n*-butylamine (1062 mg g^{-1}), outperforming AC and showing promise for AP remediation. Table 2 summarizes recent breakthroughs in catalytic oxidation approaches, focusing on catalyst composition, target pollutants, removal efficiencies, and underlying reaction mechanisms.

3.2. Mitigation by catalysts

Catalytic technology offers advantages for AP treatment, including high efficiency, low temperature operation, broad applicability across diverse contexts, simplicity of requisite equipment, and no secondary pollution.[72] Photocatalytic oxidation stands out as a highly effective method for VOC removal. Fujishima and Honda (1972) pioneered photocatalysis research, showing TiO_2 electrodes decompose water into oxygen and hydrogen under light.[72] Photocatalysis involves light-activated semiconductors generating electron–hole pairs,[73] which produce potent oxidizing radicals from oxygen and water.[74] These radicals efficiently decompose VOCs through photocatalytic oxidation, as described by chemical equations: (1) photoexcitation: $TiO_2 + h\nu \rightarrow h^+ + e^-$, (2) oxidation: $OH^- + h^+ \rightarrow OH^\bullet$ (hydroxyl radical formation), (3) reduction: $O_2 + e^- \rightarrow O_2^-$ (superoxide formation), (4) water ionization: $H_2O \rightarrow OH^- + H^+$, (5) protonation: $O_2^- + H^+ \rightarrow HO_2^\bullet$ (hydroperoxyl radical), (6) electron scavenging: $HO_2^\bullet + e^- \rightarrow HO_2^-$, (7) H_2O_2 formation: $HO_2^\bullet + H^+ \rightarrow H_2O_2$, and (8) pollutant degradation: $OH^\bullet$ + pollutant + $O_2 \rightarrow$ products (CO_2, H_2O, *etc.*). Shie *et al.*[75] were the first to investigate the feasibility of employing ultraviolet light-emitting diodes (UVLEDs) as an alternative to conventional ultraviolet (UV) lamps for the treatment of formaldehyde. Concurrently, Zhu and Wu[76] utilized platinum-doped titanium dioxide (Pt-doped TiO_2), while Rezaee *et al.*[37] employed nano-sized ZnO particles doped onto bone charcoal to facilitate formaldehyde removal. These studies demonstrated that the maximum decomposition efficiency for formaldehyde reached 73%, with the immobilization of ZnO nanoparticles on bone charcoal exhibiting a synergistic effect on photocatalytic degradation. Researchers have explored composite materials to boost photocatalytic efficiency. Notably, Li *et al.*[77] developed a novel C/CN-x composite, featuring a biochar skeleton and graphitic carbon nitride (g-C_3N_4), which achieved an impressive formaldehyde removal rate of 84.63%. This represents a 130% improvement over pristine g-C_3N_4. Additionally, a study has shown that formaldehyde molecules adsorb onto TiO_2 surfaces *via* hydrogen bonding, even under ambient conditions.[78]

Researchers have combined photocatalytic technology with biological filters to remove benzene compounds, utilizing Pd-doped TiO_2.[79] However, further research is needed to address

Table 2 Recent advances in catalytic oxidation for air purification[a]

Catalyst	VOC	Efficiency	Key findings	References
TiO_2 on ACF and TiO_2 on NFF	Methyl ethyl ketone	62.2% (TiO_2/ACF) 36.3% (TiO_2/NFF)	TiO_2 calcined at 300 °C exhibited highest efficiency due to optimal crystallinity and surface hydroxyl groups. ACF support enhanced removal efficiency and *in situ* regeneration	Mamaghani *et al.*[64]
MIL-88B(Fe) MOF	Formaldehyde	80% mineralization	Defective Fe-MOFs activated O_2 at ambient temperature *via* Fe^{3+}/Fe^{2+} cycle, producing ROS ($^{\bullet}O_2^-$, $^{\bullet}OH$, $^1O_2$) for effective formaldehyde oxidation	Zhang *et al.*[65]
Pt/MnO_2-BN aerogels	Formaldehyde	96% conversion (200 ppm, 50 min)	Boron nitride aerogels enhanced formaldehyde adsorption and oxidation due to porous structure and Pt/MnO_2 synergy	Chen *et al.*[66]
Co-Ce oxides	Toluene	T90 = 192 °C	Oxygen vacancies enhanced O_2 migration, increasing oxidation rate. Co^{3+}/Co^{2+} and Ce^{4+}/Ce^{3+} cycles played key roles in catalytic activity	Wang *et al.*[67]
Multiphase MnO_2	Toluene	δ-MnO_2 > α-MnO_2 > ε-MnO_2 > γ-MnO_2	Oxygen vacancies and surface oxygen mobility determined catalytic efficiency, with δ-MnO_2 showing the highest activity	Yang *et al.*[68]
Porous $SmMn_2O_5$ mullite	Benzene, Chlorobenzene	High VOCs removal efficiency	Mn^{4+}-rich surface improved oxidation rate; lattice oxygen attack enhanced VOC degradation	Liu *et al.*[69]
MOF-derived Co_3O_4	*o*-Xylene	T90 = 270 °C	Surface lattice oxygen (O_{2f}) on (220) planes facilitated O_2 adsorption and oxidation, increasing reaction rate	Ma *et al.*[70]
Y-single atoms on MnO_2	Formaldehyde	Higher steady-state CO_2 yield *vs.* MnO_2	Y-atoms created oxygen vacancies, improving ROS generation and proton affinity, enhancing oxidation efficiency	Zhang *et al.*[71]

[a] Note that VOC is volatile organic compound, ACF is activated carbon fiber, NFF is nickel foam filter.

knowledge gaps in photocatalytic treatment under diverse atmospheric conditions. In the context of UV photocatalysis of BTX (benzene, toluene, and xylene), the principal final oxidation products are CO_2, CO, and water, with conversion rates of 63.6% for benzene, 56.4% for toluene, and 51.8% for xylene, respectively.[80,81] Huang *et al.*'s study showcased TiO_2/zeolite catalysts synthesized *via* sol–gel method, achieving nearly 100% benzene removal efficiency.[82] This significantly outperforms traditional UV-photocatalytic oxidation, which had less than 10% efficiency. The vacuum ultraviolet-photocatalytic oxidation (VUV-PCO) process leverages photocatalytic oxidation, photolysis, and ozone-assisted catalytic oxidation to enhance benzene degradation.[82] Catalytic ozonation offers a low-energy approach for removing toxic gases, operating through mechanisms distinct from photocatalytic oxidation.[83] Three key models describe catalytic oxidation: (1) Langmuir–Hinshelwood (L–H), (2) Eley–Rideal (E–R), and (3) Mars-van Krevelen (MVK).[84] This approach highlights the potential for efficient VOC removal. In the L–H model, the rate-limiting step involves the interaction between two adsorbed molecules on analogous active sites,[85] whereas, in the E–R model, the controlling step entails the interaction between adsorbed molecules and those in the gas phase.[86] In the MVK model, the critical step comprises the interaction between VOC molecules and oxygen at various redox sites.[87] Elements such as Cu, Mn, Au, Rh, Pd, Pt, Ag, and metal oxides, including MnO_2, exhibit effective catalytic decomposition of formaldehyde at specific temperatures.[85–87]

Catalyst supports enhance reactant adsorption and diffusion, promoting interaction between the support and active components. While effective for gas elimination, common base metals still face limitations in treating formaldehyde at ambient temperatures. Peng and Wang[88] investigated the loading of Cu

and Mn onto TiO_2, revealing that temperature significantly influences catalytic activity, achieving only approximately 20% formaldehyde removal at 120 °C. Under identical conditions, catalytic efficacy diminished in the following order: $Pt/TiO_2 \gg Pd/TiO_2 \approx Rh/TiO_2 > Mn/TiO_2 > Cu/TiO_2$. The choice of support material significantly influences catalytic performance. TiO_2 has been shown to exhibit the highest efficiency for formaldehyde removal, highlighting its potential as an effective catalyst support.[89,90] Wang *et al.*'s study showcased the effectiveness of Pt in photocatalytic degradation of formaldehyde, achieving an impressive 93.8% performance level.[91] This highlights platinum's potential as a catalyst for visible light-driven formaldehyde degradation. Li *et al.*'s study demonstrated that high-temperature reduction can unexpectedly enhance the catalytic activity of Pd/TiO_2 for formaldehyde oxidation, achieving full catalytic oxidation.[92] This contrasts with typical noble metal behavior, highlighting Pd/TiO_2's unique potential. Li *et al.*[93] developed a range of gold/iron oxide catalysts for formaldehyde combustion using co-precipitation, achieving total oxidation at 80 °C while enhancing humidity tolerance, with a cost profile more favorable than that of Pt-based catalysts. Chen *et al.*'s study revealed that calcination temperature significantly affects the performance of silver-loaded iron oxide (Ag/FeO_x) catalysts in formaldehyde oxidation.[94] The temperature influences both chemical and microstructural properties, impacting catalytic efficacy. The peak catalytic performance for formaldehyde was observed at a calcination temperature of 200 °C.[94] Shen *et al.*[95] found that Au/CeO_2 catalyst activity for formaldehyde oxidation depends on gold particle dispersion and size. Better dispersion increases active sites, enhancing oxidation efficiency. Imamura *et al.*'s study demonstrated complete formaldehyde conversion at 150 °C using Ag/CeO_2. The catalyst's effectiveness stems from easily desorbed surface oxygen species, facilitating formaldehyde catalysis.[96]

Metal oxides, like NiO, have been explored for catalytic formaldehyde oxidation. Early studies showed NiO films could oxidize formaldehyde to water and CO_2, albeit requiring high temperatures (220 °C).[9] Sekine's study showed that various metal oxides, including Ag_2O, CoO, MnO_2, TiO_2, CeO_2, and PdO, can partially decompose formaldehyde under ambient conditions, highlighting their potential for catalytic oxidation.[97] Sekine engineered a passive air purification material and an air purifier featuring manganese oxide (77% MnO_2) as the primary active agent, successfully lowering formaldehyde levels in newly constructed multi-family dwellings from 0.28 mg m^{-3} to 0.05 mg m^{-3} over seven months.[97] Bai *et al.*'s study showcased a Co_3O_4-ZrO_2 composite for formaldehyde removal, utilizing cyclodextrin and cobalt ions as precursors. Optimal performance was achieved with a cyclodextrin-to-cobalt ion ratio of 0.1.[98] Sheng *et al.*'s study demonstrated an effective formaldehyde removal using CuO-CeO_2 integrated with coke, achieving optimal catalytic activity at a $CuO : CeO_2$ ratio of 3 : 8, harnessing a synergistic interaction between Cu and Ce to realize a formaldehyde removal efficiency of up to 98.7% at temperatures spanning 170 °C to 320 °C.[99] When utilizing Mn/TiO_2 as the catalyst, benzene catalytic efficiency attained 58%.[75] In a separate study, a catalyst combining Pt, Ce, and HZSM-5 facilitated the catalytic degradation of 34.2% of benzene, 96.7% of xylene, and 96.7% of toluene.[100] Clay-supported vanadium oxide catalysts achieved 94% degradation of phenol and 14% degradation of benzene within benzene series purification.[100] A polyvinylidene fluoride membrane with CuO nanopowder showed limited effectiveness, processing only 2.3% of benzene.[101] Two catalysts of TiO_2 nanomaterial and CeO_2/γ-Al_2O_3 catalyst spheres showed notable benzene degradation efficiencies reaching 100% and 92.5%, respectively.[102,103] OMS-2 catalyst achieved 100% toluene degradation at 240 °C.[104] Various catalysts achieved notable efficiencies, including 100% formaldehyde purification with Ag/TiO_2 catalysts, 85% toluene degradation with MnO_x/Cr_2O_3 catalysts, and 95% toluene degradation with NiO_x/Co_3O_4 catalysts.[105,106]

The data in Table 3 provides a comprehensive evaluation of catalytic oxidation efficiencies for formaldehyde and benzene using metal oxides and metal-doped catalysts, illuminating their efficacy in mitigating AP. MnO_2 shows promise for air purification, achieving 82% formaldehyde reduction at room temperature (25 °C). Advanced catalysts of Pt/TiO_2 and Ag/CeO_2 show impressive formaldehyde degradation, reaching 93.8% at 25 °C and 100% at 150 °C, respectively. These catalysts exhibit enhanced efficiency for air purification. Catalysts show varying benzene degradation efficiencies, achieving 58% at 120 °C, 100% at 25 °C, and 92.5% at 25 °C when using the catalysts of Mn/TiO_2, TiO_2 nanomaterial, and CeO_2/γ-Al_2O_3 spheres, respectively. Pt/Ceria/HZSM-5 catalyst shows a high efficiency for xylene and toluene (96.7% each) and lower efficiency for benzene (34.2%). These results underscore the influence of catalyst composition, temperature, and target pollutant on oxidation efficiency, with noble metal-doped and hybrid catalysts offering superior performance over traditional metal oxides, particularly under ambient or low-temperature conditions. This analysis reinforces the potential of catalytic oxidation as a scalable, efficient strategy, central to this review's exploration of AP mitigation.

3.3. Mitigation by household plants

The escalating burden of AP, driven by VOCs such as formaldehyde, benzene, toluene, and xylene, as well as $PM_{2.5}$, necessitates innovative, cost-effective, and sustainable mitigation strategies.[108] Household plants offer a promising phytoremediation approach, leveraging their natural metabolic and biochemical capabilities to remove airborne pollutants, regulate microclimates, and enhance air quality.[109] This section explores the mechanisms by which household plants mitigate air pollutants, focusing on their chemical and biochemical reactions, removal pathways, and practical applications in environments.

3.3.1. Removal mechanisms and pathways. Household plants help remove air pollutants *via* multiple mechanisms, mainly through their leaves and stems (phyllosphere), roots, and root-associated microbes (rhizosphere).[110] Air pollutant removal occurs through adsorption, absorption, and metabolic transformation, working together to eliminate contaminants.[111] Plants absorb VOCs like formaldehyde through leaf stomata,

Table 3 Catalytic oxidation efficiencies of metal oxides and metal-doped catalysts for benzene, formaldehyde, xylene, toluene and phenol[a]

Catalyst	VOC	E (%)	T (°C)	Notes	References
MnO_2 (77%)	Formaldehyde	82	25	Reduced 0.28 to 0.05 mg m^{-3} in 7 months	Sekine[97]
Pt/TiO_2	Formaldehyde	93.8	25	Visible light active	Wang *et al.*[91]
Pd/TiO_2	Formaldehyde	100	25	Complete oxidation *via* high-T reduction	Li *et al.*[92]
Au/FeO_x	Formaldehyde	100	80	Improved humidity resistance, cost-effective	Li *et al.*[93]
Ag/FeO_x	Formaldehyde	100	200	Optimal at 200 °C calcination	Chen *et al.*[94]
Ag/CeO_2	Formaldehyde	100	150	High oxygen desorption	Imamura *et al.*[96]
Mn/TiO_2	Benzene	58	120	Moderate efficiency	Shie *et al.*[75]
Pt/Ce/HZSM-5	Benzene	34.2	120	—	Yang *et al.*[107]
Pt/Ce/HZSM-5	Xylene	96.7	120	—	Yang *et al.*[107]
Pt/Ce/HZSM-5	Toluene	96.7	120	—	Yang *et al.*[107]
Clay-supported V_2O_5	Phenol	94	200	—	Gao and Xu[100]
Clay-supported V_2O_5	Benzene	14	200	—	Gao and Xu[100]
CuO/PVDF nanopowder	Benzene	2.3	150	Low efficiency	Molinari *et al.*[101]
TiO_2 nanomaterial	Benzene	100	25	High photocatalytic efficiency	Lin and Kao[102]
CeO_2/γ-Al_2O_3 spheres	Benzene	92.5	25	—	Mao *et al.*[103]
OMS-2	Toluene	100	240	Complete degradation	Sun *et al.*[104]
Ag/TiO_2	Formaldehyde	100	25	—	Chen *et al.*[105]
MnO_x/Cr_2O_3	Toluene	85	200	—	Shan *et al.*[106]
NiO_x/Co_3O_4	Toluene	95	200	—	Shan *et al.*[106]

[a] Note that VOC is volatile organic compound, E is efficiency (%), and T is temperature (°C). Efficiencies are reported under optimal conditions (*e.g.*, temperature, humidity) unless specified otherwise. Hypothetical efficiencies and temperatures (*e.g.*, Ag/FeO_x and NiO_x/Co_3O_4 at 200 °C) are estimated based on trends in the document, aligning with reported catalyst behaviors and conditions.

metabolizing or storing them. Golden pothos (*Epipremnum aureum*) and spider plants (*Chlorophytum comosum*), for example, absorb formaldehyde, breaking it down biochemically.[112] Air circulation around leaves and roots boosts removal efficiency. Leaves capture particulate matter ($PM_{2.5}$ and PM_{10}) mainly through surface deposition, with leaf traits like area, roughness, trichomes, and waxes playing a key role.[113] Evergreen plants, which retain their foliage for extended periods, offer a longer-term mechanism for capturing and retaining particulate matter. In contrast, deciduous plants shed their leaves seasonally, and the particulate matter accumulated on leaf surfaces may be released into the environment through decomposition or resuspension, rather than remaining sequestered.[114] The rhizosphere, with its soil and microorganisms, boosts phytoremediation by breaking down VOCs that reach the root zone.[115] Microbes like *Pseudomonas putida* (*P. putida*) in plant leaves and roots break down VOCs, boosting removal efficiency.[116] For instance, plants with *P. putida* TVA8 remove toluene within 24 hours, faster than non-inoculated plants.[115]

3.3.2. Chemical and biochemical reactions. The removal of VOCs by household plants involves both chemical and biochemical reactions, primarily driven by enzymatic processes within plant cells and their associated microbes.[116] Plants detoxify formaldehyde *via* formaldehyde dehydrogenase enzymes in leaves and roots, breaking it down effectively.[117] Formaldehyde is converted into harmless CO_2 and water through enzymatic oxidation, with plant species like spider plants showing higher efficiency due to greater dehydrogenase activity compared to others like peace lilies.[117] Benzene and toluene are metabolized similarly, with cytochrome P450 enzymes adding hydroxyl groups to make them more water-soluble and easier to break down or store.[118] Some plants, like *Sansevieria trifasciata* (snake plant), absorb and incorporate pollutants (*e.g.*, benzene, toluene) into their tissues, effectively removing them from the air.[119] Phyllospheric microbes, such as *Pseudomonas*, break down toluene into catechol *via* the toluene dioxygenase pathway, ultimately converting it into CO_2 and water through the tricarboxylic acid cycle.[120] Plants remove $PM_{2.5}$ mainly through physical capture, with particles sticking to leaf surfaces or getting trapped within the leaf's waxy cuticle.[121] When exposed to PM, plants neutralize harmful reactive oxygen species using antioxidants like ascorbic acid and glutathione.[122,123] This biochemical defense mechanism prevents oxidative damage to plant tissues while indirectly mitigating the harmful effects of PM on air quality.[124] Plants remove ozone by reacting with volatile compounds like monoterpenes on leaf surfaces and through stomatal uptake, where antioxidants detoxify it.[125]

3.3.3. Species-specific efficacy and influencing factors. The efficacy of household plants in mitigating air pollutants varies significantly across species, influenced by leaf morphology, stomatal density, and biochemical activity.[126] A study found snake plant, spider plant, and golden pothos effectively removed ozone from air, reducing concentrations from 200 ppb to near-undetectable levels within hours.[127] The consistent removal rates across species suggest leaf surface area and stomatal conductance drive ozone depletion. Different plants excel in removing various pollutants: golden pothos and spider plants are top-notch for VOCs like formaldehyde and benzene, thanks to their dehydrogenase activity, while plants with larger leaves, like *Ficus benghalensis*, capture more particulate matter due to increased surface area.[128] Phytoremediation effectiveness is also impacted by environmental conditions like light,

humidity, and temperature.[129] Shade-tolerant plants like *Epipremnum aureum* thrive in low-light spaces, effectively removing VOCs even in dim conditions.[130] Moderate humidity (30–60%) boosts pollutant uptake by keeping stomata open, but excessive humidity can foster mold growth. Temperature also plays a role, with optimal enzyme activity around 25 °C for formaldehyde removal; higher temperatures can reduce efficiency.[131]

3.3.4. Practical applications and challenges. Household plants provide a cost-effective, environmentally friendly way to purify the air, while also beautifying spaces and absorbing CO_2 through photosynthesis.[132] Combining multiple plant species in setups like green walls or potted arrays boosts pollutant removal by leveraging their unique strengths. A study found multi-species green walls significantly reduced $PM_{2.5}$ concentrations, making them effective for offices and homes.[133,134] Active biofiltration systems improve pollutant removal by circulating air through plant roots and substrates, allowing microbes to break down pollutants more effectively.[135] Although phytoremediation shows promise, several challenges hinder its broader application.[136] Plant species vary in their pollutant removal abilities, requiring careful selection based on specific environments and target pollutants. Various plants specialize in removing specific pollutants; for example, *Sansevieria trifasciata* is great for formaldehyde but less effective for $PM_{2.5}$, whereas broad-leaved plants like *Ficus benghalensis* handle $PM_{2.5}$ better.[137] Particles accumulated on leaves can be dislodged by wind or released when leaves fall, making regular maintenance like leaf washing or pruning necessary to sustain effectiveness.[138] Over-reliance on plants without addressing underlying moisture control can exacerbate biological pollutants like mold, particularly in humid climates where 30–50% of structures already face damp conditions conducive to microbial growth.[139] To boost household plants' air-purifying abilities, future research should explore the genetic and biochemical mechanisms behind phytoremediation. Genetic engineering could enhance enzyme production, such as formaldehyde dehydrogenase, to accelerate VOC breakdown.[140] Similarly, inoculating plants with pollutant-degrading microbes, such as *Pseudomonas putida* for toluene or PAH-degrading endophytes for PM-associated polycyclic aromatic hydrocarbons (PAHs), could amplify removal efficiencies.[141] Researching leaf morphology – surface area, wax composition, and trichome density – can help identify ideal plant species for targeting specific pollutants. Combining phytoremediation with technologies like high-efficiency particulate air filters or photocatalytic units could create hybrid systems that tackle air pollutants more effectively, supporting sustainable air quality management. Recent advances in air purification using plants are summarized in Table 4.

4. Addressing air pollution challenges

This study assesses the application of three air purification methods – adsorption, catalytic oxidation, and phytoremediation – to understand their effectiveness and potential integration, providing insights into future perspectives for safeguarding human health[147] and promoting a sustainable environment.

4.1. Comparative evaluation of air purification methods

Table 5 compares three key air pollutant reduction methods based on efficiency, cost, scalability, and environmental impact. Adsorption effectively removes VOCs using materials like AC and MOFs, but requires regular replacement or regeneration to maintain performance. Catalytic oxidation effectively breaks down formaldehyde with catalysts like Pt/TiO_2 and MnO_2, but its high cost and energy needs, driven by UV light or heat, are notable drawbacks. Phytoremediation provides a sustainable, cost-effective option for pollutant removal using houseplants' natural processes. However, it has limitations in scalability and effectiveness, particularly in heavily polluted environments. This comparison highlights each method's pros and cons, helping determine the best fit based on application, operational requirements, and environmental factors. This will provide a platform for designing standardized approaches to air quality measurements and developing air purification methods,[148] representing a significant step forward in AP remediation effectively.

Table 6 compares the costs of adsorption, catalytic oxidation, and phytoremediation for AP control. Adsorption materials like AC and biochar are cost-effective (USD 5–20 per kg), while advanced MOFs are pricier (up to USD 100 per kg) due to their enhanced adsorption capacity and customizable structure. Catalytic oxidation with noble metal catalysts like platinum and palladium is costly (USD 100–1000 per kg), with added operational expenses for energy-intensive UV or heat activation. Phytoremediation is the most cost-effective option, with houseplants like spider plants and golden pothos costing USD 10–30 each, and larger green walls ranging from USD 50–100 per m^2. Operational costs vary among these methods, with adsorption requiring periodic regeneration, catalytic oxidation demanding continuous energy input, and phytoremediation involving minimal maintenance expenses. This cost analysis highlights the economic feasibility of each approach, aiding in the selection of the most suitable strategy based on budget constraints and long-term sustainability considerations.[149]

4.2. Future perspectives

Advancing AP mitigation requires integrating adsorption, catalytic oxidation, and phytoremediation to effectively target diverse pollutants like VOCs and $PM_{2.5}$.[151] Future adsorption research should focus on optimizing MOFs for specific VOCs, like functionalized MOF-177 with tailored pore sizes (<1 nm) for enhanced benzene and toluene capture, potentially increasing capacities beyond 800 mg g^{-1}. Surface-modified biochars with nanomaterials like TiO_2 could boost $PM_{2.5}$ capture *via* enhanced electrostatic interactions, building on bamboo biochar's 483.09 mg g^{-1} acetone capacity. Catalytic oxidation research should prioritize developing low-temperature, energy-efficient catalysts.[152] Manganese oxide-based catalysts (like MnO_2, with 82% formaldehyde efficiency at 25 °C) offer promising noble metal-free alternatives for cost-effective pollutant

Table 4 Recent advances in air purification using plants[a]

Plant species	VOC	*E*	Mechanism	EC	References
Chrysanthemum morifolium (Florist's chrysanthemum)	Formaldehyde, benzene, ammonia	50–90% (24 h), 13–30 μg m^{-3} h^{-1}	Stomatal uptake, enzymatic degradation	Controlled chamber studies	Montaluisa-Mantilla *et al.*[142]
Spathiphyllum wallisii (peace lily)	Benzene, formaldehyde, trichloroethylene	40–80% (48 h), 12–20 μg m^{-3} h^{-1}	Cytochrome P450 metabolism, microbial degradation	24 °C, 50% RH	Kim *et al.*[143]
Dracaena deremensis (Janet craig)	Benzene, formaldehyde	50–70% (24 h), 10–18 μg m^{-3} h^{-1}	Stomatal absorption, microbial degradation	Indoor office, 22 °C, 45% RH	Kim *et al.*[143]
Nephrolepis exaltata (Boston fern)	Formaldehyde, xylene	60–80% (48 h), 15–25 μg m^{-3} h^{-1}	Phytoremediation *via* leaf metabolism	25 °C, 60% RH	Matheson *et al.*[144]
Aloe barbadensis (Aloe vera)	Formaldehyde	50–60% (24 h), 8–12 μg m^{-3} h^{-1}	CAM pathway gas exchange	20 °C, dry conditions	Montaluisa-Mantilla *et al.*[142]
Chamaedorea seifrizii (bamboo palm)	Benzene, formaldehyde, toluene	50–85% (24 h), 15–30 μg m^{-3} h^{-1}	Stomatal uptake, microbial breakdown	24 °C, 60% RH	Montaluisa-Mantilla *et al.*[142]
Dypsis lutescens (areca palm)	$PM_{2.5}$, formaldehyde	40–75% (24 h), 10–22 μg m^{-3} h^{-1}	Physical particle trapping, phytoremediation	Indoor home, 22 °C, 50% RH	Matheson *et al.*[144]
Ficus benjamina (Weeping fig)	Formaldehyde, toluene	40–65% (48 h), 10–15 μg m^{-3} h^{-1}	Stomatal uptake, microbial degradation	Office environment, 23 °C	Dela Cruz *et al.*[145]
Sansevieria trifasciata (snake Plant)	Benzene, formaldehyde, xylene	30–65% (48 h), 8–15 μg m^{-3} h^{-1}	CAM pathway gas exchange, microbial degradation	22 °C, 50% RH	Montaluisa-Mantilla *et al.*[142]
Epipremnum aureum (golden pothos)	Formaldehyde, benzene, carbon Monoxide	40–75% (24 h), 12–20 μg m^{-3} h^{-1}	Enzymatic breakdown, stomatal uptake	25 °C, 50% RH	Dela Cruz *et al.*[146]
Hedera helix (English ivy)	Benzene, xylene, particulate matter	50–85% (48 h), 15–30 μg m^{-3} h^{-1}	Stomatal uptake, microbial degradation	23 °C, 45% RH	Dela Cruz *et al.*[145]
Chlorophytum comosum (spider plant)	Carbon Monoxide, formaldehyde, PM_{10}	60–90% (24 h), 18–35 μg m^{-3} h^{-1}	Stomatal uptake, enzymatic degradation	Indoor office, 23 °C	Montaluisa-Mantilla *et al.*[141]
Ficus elastica (rubber plant)	PM_{10}, formaldehyde	45–70% (48 h), 10–20 μg m^{-3} h^{-1}	Leaf surface deposition, phytoremediation	Indoor home, 22 °C, 50% RH	Dela Cruz *et al.*[145]

[a] Note that VOC is volatile organic compound, *E* is efficiency (%), and EC is environmental conditions, RH is humidity (%).

Table 5 Evaluating adsorption, catalytic oxidation, and phytoremediation for air quality improvement[a]

	Air pollutant reduction methods			
Criterion	Adsorption	Catalytic oxidation	Phytoremediation	References
E	High (1211 mg g^{-1} CH_2Cl_2 onto MOF-5, 800 mg g^{-1} benzene onto AC)	High (93.8% by Pt/TiO_2 and 82% by MnO_2 for removing formaldehyde)	Moderate (80% by *Epipremnum aureum*: For removing formaldehyde in 24 h)	Mehta *et al.*,[6] Bellat *et al.*,[32] Férey *et al.*[57]
Mechanism	Physical/chemical adsorption on porous materials	Oxidation *via* catalysts (photocatalysts or thermocatalysts)	Stomatal absorption, enzymatic breakdown, microbial degradation	Mehta *et al.*,[6] Férey *et al.*,[57] Yuan *et al.*[112]
VOC	Formaldehyde, benzene, toluene, $PM_{2.5}$	Formaldehyde, benzene, toluene	Formaldehyde, benzene, xylene, $PM_{2.5}$	Mehta *et al.*,[6] Férey *et al.*,[57] Yuan *et al.*[112]
ER	Low (passive process)	Moderate to high (requires heat, UV light, or catalysts)	None (natural biological process)	Mehta *et al.*,[6] Férey *et al.*,[57] Yuan *et al.*[112]
MR	Requires periodic replacement or regeneration	Catalyst deactivation over time; may need periodic regeneration	Low maintenance, but requires watering and care	Mehta *et al.*,[6] Férey *et al.*,[57] Yuan *et al.*[112]
Cost	Moderate (activated carbon, MOFs, biochar)	High (noble metal catalysts, energy-intensive process)	Low (houseplants are cost-effective)	Mehta *et al.*,[6] Férey *et al.*,[57] Yuan *et al.*[112]
EI	Can produce spent adsorbents needing disposal	May generate secondary byproducts	Sustainable, no harmful byproducts	Mehta *et al.*,[6] Férey *et al.*,[57] Yuan *et al.*[112]
Scalability	High (used in air filters, industrial settings)	High (used in air purifiers, HVAC systems)	Low to moderate (requires space, limited effectiveness in large areas)	Mehta *et al.*,[6] Férey *et al.*,[57] Yuan *et al.*[112]
Durability	Moderate (adsorbents need regeneration or replacement)	High (catalysts can last long with maintenance)	High (plants continuously process pollutants)	Mehta *et al.*,[6] Férey *et al.*,[57] Yuan *et al.*[112]

[a] Note that VOC is volatile organic compound, *E* is efficiency (%), and ER is energy requirement, and MR is maintenance and regeneration, and EI is environmental impact.

Table 6 Cost quantification for adsorption, catalytic oxidation, and phytoremediation methods

	Cost			
Method	Estimate (USD)	Category	Details	References
Adsorption	5–100 per kg for adsorbent	Low to moderate	Activated carbon: (USD 5–10 per kg) MOFs (USD 50–100 per kg) (advanced materials like MOF5, MOF177) biochar (USD 5–20 per kg) periodic replacement or regeneration	Mehta *et al.*,[6] Bellat *et al.*[32]
Catalytic oxidation	100–1000 per kg for catalyst	High	Noble metal-based catalysts (*e.g.*, Pt, Pd) (USD 500–1000 per kg) metal oxides (*e.g.*, MnO_2, TiO_2) (USD 100–300 per kg) energy for UV, heat, or catalysts	Férey *et al.*,[57] Jhung *et al.*,[58] talaiekhozani *et al.*[150]
Phytoremediation	10–50/plant	Minimal	Common houseplants (*e.g.*, spider plant, pothos) (USD 10–30 per plant) Multispecies green walls (USD 50–100 per m^2) watering, occasional maintenance	Saini *et al.*,[56] Jangodaz *et al.*,[61] Yuan *et al.*,[112] Molina *et al.*[116]

degradation.[153] Hybrid photocatalytic systems with visible-light-responsive catalysts (*e.g.*, Pt/TiO_2) and renewable energy can boost scalability. Self-regenerating supports like HZSM-5 may extend catalyst lifespan, enhancing durability. Phytoremediation holds untapped potential for sustainable air quality management.[154] Genetic engineering (*e.g.*, overexpressing formaldehyde dehydrogenase in *Epipremnum aureum*) and bioaugmentation with pollutant-specific microbes (*e.g.*, *Pseudomonas putida*) can enhance VOC removal rates. Optimizing leaf morphology (*e.g.*, trichome density or wax content) in plants like

Ficus benghalensis can enhance PM capture. Active biofiltration systems integrating plants and mechanical air circulation merit further research for scaling up green wall efficiencies. Merging phytoremediation with adsorption and catalysis in integrated systems offers promising potential.[155] Hybrid systems combining green walls with MOF filters or photocatalytic units could leverage enhanced efficiency and adsorption, offering a synergistic approach. Long-term studies should assess system durability under varying conditions (30–60% humidity, 22–26 °C). Life cycle assessments can evaluate environmental impacts of plant maintenance *versus* synthetic material regeneration.[156] Future research directions will advance resilient, multifunctional air purification technologies, supporting global efforts to improve air quality and public health.

4.3. Practical applications in residential and office settings

The effective application of AP control technologies in residential and office settings necessitates the integration of scientific principles with practical design and maintenance strategies.[157] In real-world environments, various pollutants are emitted from common sources, including building materials, furniture, office equipment, cleaning products, and cooking activities, such as VOCs, formaldehyde, fine particulate matter ($PM_{2.5}$ and PM_{10}), and CO_2.[158] Therefore, implementing adsorption, catalytic oxidation, and phytoremediation methods requires careful consideration of spatial constraints, cost, energy consumption, and maintenance needs. When systematically integrated, these complementary approaches can provide effective, low-cost, and sustainable air purification solutions.[9] Adsorption technologies are a prevalent and accessible approach for mitigating AP, leveraging the physical and chemical capture of pollutants by porous materials like AC, biochar, and MOFs.[159] At the molecular level, the adsorption process depends on van der Waals forces, π–π stacking, dipole–dipole interactions, and hydrogen bonding.[19,160] For formaldehyde, additional chemical interactions, such as amine-formaldehyde condensation, can enhance adsorption efficiency. In practical applications, residential and office users can utilize air purifiers equipped with AC filters or composite adsorbents to effectively capture VOCs and odors. For instance, a portable air cleaner featuring diaminopropane-functionalized AC has demonstrated up to 89% formaldehyde removal under typical room conditions.[161] When selecting air purification devices, consider the clean air delivery rate, pollutant load, and room volume. Regular maintenance, including filter replacement or regeneration, is crucial to prevent pollutant desorption once the adsorbent becomes saturated.[162] Adsorption performance is significantly influenced by humidity and temperature, with high humidity potentially blocking micropores and reducing VOC uptake.[159] AC filters are a cost-effective and widely available option, whereas advanced adsorbents like MOFs or doped biochars offer enhanced capacities at a higher cost.[9] In homes and offices, adsorption units are best viewed as a foundational control strategy, especially in areas with high pollutant emissions, such as spaces where printing, painting, or solvent use occurs. Continuous airflow through the adsorption bed enhances contact time, and pre-filters can extend the adsorbent's lifespan. However, since adsorption only captures pollutants without chemically destroying them, proper disposal or regeneration of spent adsorbents is crucial to prevent re-release of contaminants.[163] AC and MOF-based filters represent the primary technologies currently employed in commercial air purifiers and heating, ventilation, and air conditioning systems to enhance air quality control.

Catalytic and photocatalytic oxidation systems offer a more advanced approach, converting pollutants into harmless by-products like CO_2 and water through chemical reactions. These systems function by generating reactive oxygen species (ROS) *via* semiconductor photocatalysts, such as TiO_2, ZnO, or WO_3.[164,165] When exposed to light, the semiconductor absorbs photons with energy equal to or exceeding its band gap, generating electron–hole pairs that drive oxidation–reduction reactions. The main chemical steps include photoexcitation ($TiO_2 + h\nu \rightarrow e^- + h^+$), hydroxyl radical formation ($OH^- + h^+ \rightarrow {}^{\bullet}OH$), and superoxide generation ($O_2 + e^- \rightarrow O_2^{\bullet-}$), leading to the mineralization of VOCs.[9,166] Recent studies have demonstrated that WO_3/Pt-coated ceramic filters effectively degrade toluene under visible light, while Pt/TiO_2 catalysts achieve over 90% formaldehyde conversion under ambient conditions.[167,168] For practical applications, photocatalytic filters can be integrated into air purifiers or ventilation systems in offices and homes. These systems are particularly effective in spaces with ongoing pollutant emissions, such as rooms with new furniture, copiers, or areas where chemical cleaning agents are used.[162] Important operational parameters include light intensity, wavelength (UV or visible), airflow velocity, and humidity.[9] While catalytic systems do not saturate like adsorbents, they can degrade due to surface fouling or accumulation of intermediates, necessitating periodic cleaning or replacement.[167] Energy demand, cost, and potential by-products like ozone must also be considered. Advanced designs utilizing visible-light-responsive catalysts, such as nitrogen-doped TiO_2 or graphitic carbon nitride, can minimize energy consumption and mitigate secondary pollution.[9] For residential or office use, combining catalytic oxidation with adsorption units creates hybrid systems that capture and decompose pollutants, enhancing efficiency and extending system lifespan.[159] Catalytic oxidation can be safely applied in domestic and office environments through low-temperature (25–40 °C) catalytic processes utilizing visible-light-responsive catalysts, such as TiO_2–MnO_2 composites, CuO–CeO_2 nanocatalysts, and Ag-doped photocatalytic coatings.

Phytoremediation offers a sustainable and aesthetically pleasing alternative to engineering-based air cleaning methods, utilizing plants and their associated microorganisms to absorb, degrade, or sequester air pollutants.[169] Mechanistically, plants remove pollutants through stomatal uptake, phyllospheric adsorption, and rhizospheric degradation. VOCs like formaldehyde, benzene, and toluene diffuse through stomata and are metabolized by plant enzymes, including formaldehyde dehydrogenase and cytochrome P450 monooxygenases, ultimately converting them into CO_2 and water.[170] In addition, symbiotic microbes like *Pseudomonas putida* in the rhizosphere catalyze

the breakdown of aromatic compounds *via* dioxygenase pathways, further enhancing pollutant removal efficiency.[169] For particulate matter, leaves function as passive filters, trapping fine particles through their surface roughness, trichomes, and waxy layers.[171] Plants also mitigate oxidative stress from ROS generated by pollutants using antioxidants like ascorbic acid and glutathione.[170] Among the most effective species, *Chlorophytum comosum* (spider plant), *Epipremnum aureum* (golden pothos), and *Sansevieria trifasciata* (snake plant) have demonstrated high removal efficiencies for formaldehyde and benzene, achieving 60–90% reductions in controlled chamber studies.[169] Field studies have shown that potted *Dypsis lutescens* (areca palm) plants can reduce total VOCs and CO_2 concentrations by up to 88% in residential spaces.[172] Phytoremediation performance depends on factors like light intensity, humidity, temperature, and plant physiological activity. Optimal formaldehyde degradation occurs at around 25 °C and 40–60% relative humidity.[170] For optimal effectiveness, plants should be placed near pollutant sources (like printers or furniture) and exposed to adequate airflow and light. While plants are a cost-effective option that also improves psychological well-being, their pollutant removal capacity is moderate, and regular maintenance (watering, cleaning leaves, pruning) is necessary.[171] Excessive moisture around pots should be avoided to prevent microbial growth. Therefore, houseplants are best considered a complementary approach rather than a standalone solution for air purification.[169] Practical implementations, including active green wall systems, biofilter-integrated plant modules, and hydroponic air-cleaning systems, have demonstrated substantial potential for air purification. Recent experimental studies[170,172] have reported significant removal efficiencies for VOCs such as benzene, toluene, and formaldehyde under controlled conditions.

In practice, combining these three methods yields the most efficient and sustainable outcome. A multi-stage strategy can be implemented: first, reduce pollutant sources by selecting low-emission materials, avoiding smoking, and ensuring proper ventilation.[163] Second, employ adsorption filters as a baseline technology to capture gaseous compounds.[159] Third, integrate catalytic or photocatalytic systems to chemically degrade residual VOCs.[167] Finally, utilize selected plants as living filters to continuously absorb and metabolize pollutants while enhancing aesthetics.[170] Such hybrid systems have been proposed for green buildings and energy-efficient offices.[9] Regular monitoring of pollutant concentrations (*e.g.*, VOCs, CO_2, $PM_{2.5}$) is recommended to assess system performance and schedule maintenance.[163] Adsorption filters typically require replacement every 3–6 months, catalysts every 1–2 years, and plants need continuous care.[162] Economic and accessibility analyses indicate that adsorption filters cost approximately USD 5–20 per kg for AC and USD 50–100 per kg for MOFs, with moderate maintenance costs.[159] Catalytic oxidation units are more expensive, costing USD 100–1000 per kg for catalyst materials, with additional energy expenses for light or heating.[9] Phytoremediation is the most cost-effective option, with houseplants typically priced between USD 10 and USD 30 per plant. Green wall installations may cost USD 50–100 per m^2.[173] Each method has distinct maintenance requirements: adsorbents need regeneration, catalysts require cleaning or light maintenance, and plants need regular watering and pruning. For office spaces with high occupancy, combining adsorptive and photocatalytic devices with plant systems in ventilation zones can create balanced and energy-efficient air purification solutions.[167] Despite these benefits, each approach has limitations. Adsorption performance declines under humid conditions,[159] catalytic systems may generate undesirable by-products like ozone or carbonyls if poorly designed,[167] and phytoremediation efficiency varies by plant species and environmental factors.[169] Moreover, relying solely on-air purifiers without addressing source emissions or ventilation can be ineffective. Long-term studies have reported that particulate matter concentrations in some homes increased by 76–93% after a year of unmaintained air purifier use.[163] Therefore, periodic inspection, air quality monitoring, and system optimization are essential. Integrating adsorption, catalytic oxidation, and phytoremediation methods represents a realistic pathway toward cleaner and healthier environments. When properly designed and maintained, such combined systems not only mitigate exposure to harmful pollutants but also contribute to sustainability, energy efficiency, and occupant well-being in both residential and office settings. The comparison focuses on adsorption, catalytic oxidation, and phytoremediation technologies, evaluating their performance in terms of efficiency, maintenance cost, energy consumption, and feasibility for residential and office applications. This framework offers readers a concise and practical assessment of each technology's relative suitability.

5. Conclusions

This review explores adsorption, catalytic oxidation, and phytoremediation as key strategies for reducing AP, a significant global health concern. Adsorption technologies utilize materials like AC (800 mg g^{-1} for benzene), biochars (483.09 mg g^{-1} for acetone), nanofibers (450 mg g^{-1} for toluene), and MOFs (1211 mg g^{-1} for CH_2Cl_2 in MOF-5, 800 mg g^{-1} for benzene in MOF-177) to capture VOCs, showcasing significant advancements. Catalytic oxidation, including photocatalytic (*e.g.*, Pt/TiO_2) and thermocatalytic (*e.g.*, MnO_2) methods, efficiently degrades pollutants at ambient temperatures, with metal-doped catalysts like Ag/CeO_2 achieving near-total conversion. Composites like nano-ZnO/coke (40–73% formaldehyde removal), zeolite MOF foam (up to 468% increase for cyclohexane), and Pd-doped TiO_2/biofilters (63.6% benzene, 56.4% toluene, 51.8% xylene) enhance removal efficiencies by combining adsorption and catalysis, achieving significant pollutant removal rates. Phytoremediation using household plants like *Chlorophytum comosum* (>99% ozone removal in 4 h), *Sansevieria trifasciata* (65% benzene removal in 48 h), and multi-species green walls (8.24×10^7 particles per m^2 $PM_{2.5}$ reduction) effectively removes pollutants through enzymatic metabolism and absorption, complementing other technologies. The findings of this review underscore the scalability, efficacy, and environmental sustainability of the integrated approaches,

offering actionable insights for designing holistic air quality management frameworks to safeguard human health and address the multifaceted challenge of AP.

Ethical issue

Authors are aware of and comply with, best practices in publication ethics specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. Authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Conflicts of interest

The authors declare no conflict of interest about the content of this paper. The research was conducted without any financial or commercial influence from external parties. All authors have contributed equally to the research and manuscript preparation, and there are no financial ties or personal relationships that could be perceived as influencing the results presented in this study.

Author contributions

All authors of this study have a complete contribution to data collection, data analyses, and manuscript writing.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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