



Cite this: *Environ. Sci.: Atmos.*, 2026, **6**, 27

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

Amirreza Talaie, <sup>abc</sup> Mohamad Ali Fulazzaky, <sup>\*d</sup> Shahabaldin Rezania<sup>e</sup> and Amin Tamadon <sup>\*cf</sup>

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.

Received 10th July 2025  
 Accepted 13th November 2025  
 DOI: 10.1039/d5ea00079c  
 rsc.li/esatmospheres

### 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.<sup>1</sup> 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.<sup>2,3</sup> Exposure to AP leads to increased risks of cancer, respiratory issues, allergies, and weakened immune systems.<sup>4</sup> AP's global burden

extends beyond offices, impacting vulnerable populations disproportionately.<sup>5</sup> Approximately 3 billion people, mainly in low- and middle-income regions, rely on polluting cooking fuels and stoves, emitting fine particulate matter (PM<sub>2.5</sub>) and toxicants that pose significant health risks.<sup>6</sup> 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.<sup>7</sup> Notably, nearly 50% of pneumonia-related mortality in children under five years of age is linked to the inhalation of PM<sub>2.5</sub> derived from AP, underscoring the vulnerability of pediatric populations to these environmental hazards.<sup>8</sup> 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<sub>2.5</sub>.<sup>9</sup> Adsorption uses high-capacity materials to capture pollutants, whereas catalytic oxidation utilizes photocatalysts or thermocatalysts to convert harmful substances into harmless

<sup>a</sup>Department of Civil Engineering, Jami Institute of Technology, Isfahan, Iran

<sup>b</sup>Plant Design Department, Pars Abnoos Sanat Consulting Engineering Company, Shiraz, Iran

<sup>c</sup>Department of Natural Sciences, West Kazakhstan Marat Ospanov Medical University, Aktobe 030012, Kazakhstan. E-mail: amintamaddon@yahoo.com

<sup>d</sup>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

<sup>e</sup>Department of Environment and Energy, Sejong University, Seoul, 05006, South Korea

<sup>f</sup>Stem Cells Technology Research Center, Shiraz University of Medical Sciences, Shiraz, Iran



byproducts.<sup>10</sup> Phytoremediation utilizes various household plants to absorb and break down pollutants, improving air quality through natural processes.<sup>11</sup> 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.<sup>12</sup> 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<sub>2.5</sub> 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.<sup>13,14</sup> 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.<sup>15</sup> 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.<sup>16,17</sup> Biochar mitigates VOCs through two primary mechanisms: adsorption in the carbonized fraction and partitioning in non-carbonized organic matter.<sup>18</sup> The carbonized fraction's adsorption capacity involves chemisorption (covalent bonding) and physical adsorption (hydrophobic interactions, dipole-dipole forces,  $\pi$ - $\pi$  interactions, hydrogen bonding, and coulombic interactions).<sup>19,20</sup> 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<sup>2</sup> g<sup>-1</sup>, whereas switchgrass-derived biochar (same temperature) has a significantly lower surface area of 15 m<sup>2</sup> g<sup>-1</sup>.<sup>20</sup> 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.<sup>21</sup>

Wood-derived AC, with its highly developed pore structure, effectively adsorbs various substances and impurities.<sup>22</sup> Coconut shell AC, appearing as black granules, is characterized by a well-developed specific surface area ranging from 1000 to 1600 m<sup>2</sup> g<sup>-1</sup>, a micropore volume comprising approximately 90% of its total porosity, and micropore diameters of 1 to 4 nm, optimizing its adsorption capabilities for pollutants.<sup>23,24</sup> 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.<sup>25</sup> 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.<sup>26</sup> Impregnating AC with materials like MnO<sub>2</sub> enhances its adsorption capacity. Specifically, MnO<sub>2</sub> improves formaldehyde removal by promoting particle dispersibility, reducing agglomeration, and boosting catalytic efficiency.<sup>27</sup> A TiO<sub>2</sub>-impregnated carbon layer on expanded graphite-based carbon/carbon composite boosts both adsorption and photocatalytic degradation. This combo enhances formaldehyde removal by leveraging TiO<sub>2</sub>'s photocatalytic properties while maintaining adsorption performance.<sup>28</sup> 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<sub>0</sub>.<sup>29</sup> 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.<sup>30</sup> Nitrogen functional groups near oxygen atoms boost adsorption efficacy, but adsorbent design must also account for affinity to water to ensure effective pollutant removal.<sup>19,31</sup> Research by Bellat *et al.*<sup>32</sup> found that faujasite zeolites, particularly NaX, NaY, and CuX, effectively capture formaldehyde, with a high adsorption capacity of 14.6 mol m<sup>-2</sup>, 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.<sup>33</sup> 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.<sup>34</sup> Treating AC with an oxidant atmosphere boosts its adsorption properties by increasing oxidized surface groups and negative surface charge, especially in shell-derived carbon.<sup>35</sup> A comprehensive evaluation of 15 biochar types derived from five raw materials revealed varying VOC adsorption capacities, with acetone (483.09 mg g<sup>-1</sup>), toluene (424.4 mg g<sup>-1</sup>), benzene (161.42 mg g<sup>-1</sup>), and methanol (10.6 mg g<sup>-1</sup>) exhibiting different uptake.<sup>36</sup> 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<sup>-3</sup>.<sup>37</sup> Longer residence times enhance degradation, highlighting the potential of this method for efficient formaldehyde purification potential.<sup>37</sup> Chemical activation of coconut shell carbon with KOH enhances benzene adsorption due to improved surface properties.<sup>38</sup> However, KOH incorporation can hinder porosity development, especially mesopore formation, despite increasing carbon reactivity.<sup>39</sup> 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.<sup>32</sup> 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.<sup>40</sup>

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<sup>-1</sup> for benzene), emerging materials like MOFs and biochars exhibit even higher performance.<sup>25</sup> MOFs like MOF-5 and MOF-177 exhibit high adsorption capacities (1211 mg g<sup>-1</sup> for CH<sub>2</sub>Cl<sub>2</sub> and 589 mg g<sup>-1</sup> for acetone), while biochar (bamboo) achieves 483.09 mg g<sup>-1</sup> for acetone, attributed to their superior surface areas and tunable pores.<sup>37</sup> Meanwhile, CFAs from bamboo show promise with high toluene adsorption (450 mg g<sup>-1</sup>) and reproducibility.<sup>40</sup> 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.<sup>43</sup> 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.<sup>44</sup> 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.<sup>45</sup> MOFs not only effectively adsorb VOCs but also enable environmentally sustainable synthesis, allowing *in situ* production that preserves plant ecosystems.<sup>46</sup> 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<sup>a</sup>

Adsorbent	VOC	<i>q</i> (mg g <sup>-1</sup> )	<i>A</i> (m <sup>2</sup> g <sup>-1</sup> )	<i>r</i> (nm)	References
AC (coconut shell)	Benzene	800	1200	2.0	Pang <i>et al.</i> <sup>25</sup>
AC (coconut shell)	Formaldehyde	600	1200	2.0	Huang <i>et al.</i> <sup>27</sup>
Biochar (bamboo)	Acetone	483.09	375	1.5	Rezaee <i>et al.</i> <sup>37</sup>
Biochar (switchgrass)	Benzene	161.42	15	1.2	Rezaee <i>et al.</i> <sup>37</sup>
MOF-5	CH <sub>2</sub> Cl <sub>2</sub>	1211	2500	1.2	Tranchemontagne <i>et al.</i> <sup>41</sup>
MOF-5	CCl <sub>4</sub>	1472	2500	1.2	Tranchemontagne <i>et al.</i> <sup>41</sup>
MOF-177	Acetone	589	4170	0.94	Yang <i>et al.</i> <sup>42</sup>
MOF-177	Benzene	800	4170	0.94	Yang <i>et al.</i> <sup>42</sup>
Nanofiber CFA (bamboo)	Toluene	450	1800	0.8	Jiao <i>et al.</i> <sup>40</sup>

<sup>a</sup> Note that VOC is volatile organic compound, *q* is adsorption capacity (in mg g<sup>-1</sup>), *A* is surface area (in m<sup>2</sup> g<sup>-1</sup>), and *r* is pore size (in nm).



structures, and diverse architectures. Functional modification capabilities further enhance their adsorption performance and versatility.<sup>47</sup> 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,  $\pi$ -complex formation, and hydrogen bonding, enhancing selectivity.<sup>48</sup> MOF-5 exhibits exceptional VOC adsorption capacities at 295 K, with values of  $1211 \text{ mg g}^{-1}$  ( $\text{CH}_2\text{Cl}_2$ ),  $1367 \text{ mg g}^{-1}$  ( $\text{CHCl}_3$ ), and others, surpassing traditional adsorbents like AC by 4–10 times.<sup>41</sup> MOF-*n* materials, built from extended metal carboxylate clusters, represent further advancements in MOF development.<sup>49</sup> 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.<sup>50</sup>

The development of porous materials for AP mitigation has roots in early work, such as synthesis of diamond-like micro-porous structures.<sup>51</sup> This pioneering research laid groundwork for highly ordered frameworks, ultimately influencing the emergence of MOFs.<sup>52</sup> These advancements have driven innovations in VOC-capturing adsorption materials, a focus of this review. Building on Hoskins and Robson's<sup>51</sup> work, Moore *et al.*<sup>53</sup> synthesized a novel skeletal polymer using silver and triphenyl units. Yaghi *et al.*<sup>52</sup> 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,<sup>54</sup> outperforming MOF-5, and MOF-177,<sup>42</sup> featuring a high surface area ( $4170 \text{ m}^2 \text{ g}^{-1}$ ) and 0.94 nm pore diameter, enhancing adsorption capabilities. Yang *et al.*<sup>42</sup> demonstrated MOF-177's exceptional VOC adsorption, with capacities over  $200 \text{ mg g}^{-1}$  for compounds like acetone ( $589 \text{ mg g}^{-1}$ ) and benzene ( $800 \text{ mg g}^{-1}$ ). Its high surface area ( $4170 \text{ m}^2 \text{ g}^{-1}$ ) 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 ( $\text{Fe}_3\text{O}_4$ ), 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.<sup>55</sup> Nanocasting SBA-15 silica into CMK-3 carbon replica alters porous structures, yielding distinct chemical and structural properties.<sup>56</sup> CMK-3, derived from SBA-15, exhibits modified adsorption trends due to retained mesopores and inherent microporosity.<sup>56</sup> Similarly, the Materials of Institute Lavoisier (MIL)-series MOFs leverage mesoporous and microporous structures for effective VOC adsorption.<sup>57</sup> The MIL-101 material exhibits a specific surface area of up to  $5900 \text{ m}^2 \text{ g}^{-1}$ , with its benzene adsorption capacity at 303 K reaching  $1303 \text{ mg g}^{-1}$ ,<sup>58</sup> surpassing the highest value previously documented in the literature. Wang *et al.*<sup>59</sup> synthesized MIL-101(Cr) and Cu-doped MIL-101(Cr), achieving VOC adsorption capacities of  $103.4 \text{ mg g}^{-1}$  and  $114.4 \text{ mg g}^{-1}$ , respectively. The materials exhibited high surface areas, with  $3367 \text{ m}^2 \text{ g}^{-1}$  for MIL-101(Cr) and  $2518 \text{ m}^2 \text{ g}^{-1}$  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.<sup>60,61</sup> Finsy *et al.*<sup>62</sup> 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.*<sup>63</sup> found MIL-101 exhibits high adsorption capacities for VOCs with heteroatoms or benzene rings, particularly *n*-butylamine ( $1062 \text{ mg g}^{-1}$ ), 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.<sup>72</sup> Photocatalytic oxidation stands out as a highly effective method for VOC removal. Fujishima and Honda (1972) pioneered photocatalysis research, showing  $\text{TiO}_2$  electrodes decompose water into oxygen and hydrogen under light.<sup>72</sup> Photocatalysis involves light-activated semiconductors generating electron–hole pairs,<sup>73</sup> which produce potent oxidizing radicals from oxygen and water.<sup>74</sup> These radicals efficiently decompose VOCs through photocatalytic oxidation, as described by chemical equations: (1) photoexcitation:  $\text{TiO}_2 + h\nu \rightarrow \text{h}^+ + \text{e}^-$ , (2) oxidation:  $\text{OH}^- + \text{h}^+ \rightarrow \text{OH}^\cdot$  (hydroxyl radical formation), (3) reduction:  $\text{O}_2 + \text{e}^- \rightarrow \text{O}_2^\cdot$  (superoxide formation), (4) water ionization:  $\text{H}_2\text{O} \rightarrow \text{OH}^- + \text{H}^+$ , (5) protonation:  $\text{O}_2^\cdot + \text{H}^+ \rightarrow \text{HO}_2^\cdot$  (hydroperoxy radical), (6) electron scavenging:  $\text{HO}_2^\cdot + \text{e}^- \rightarrow \text{HO}_2^-$ , (7)  $\text{H}_2\text{O}_2$  formation:  $\text{HO}_2^\cdot + \text{H}^+ \rightarrow \text{H}_2\text{O}_2$ , and (8) pollutant degradation:  $\text{OH}^\cdot + \text{pollutant} + \text{O}_2 \rightarrow \text{products} (\text{CO}_2, \text{H}_2\text{O}, \text{etc.})$ . Shie *et al.*<sup>75</sup> 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<sup>76</sup> utilized platinum-doped titanium dioxide (Pt-doped  $\text{TiO}_2$ ), while Rezaee *et al.*<sup>37</sup> 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.*<sup>77</sup> developed a novel C/CN-x composite, featuring a biochar skeleton and graphitic carbon nitride ( $\text{g-C}_3\text{N}_4$ ), which achieved an impressive formaldehyde removal rate of 84.63%. This represents a 130% improvement over pristine  $\text{g-C}_3\text{N}_4$ . Additionally, a study has shown that formaldehyde molecules adsorb onto  $\text{TiO}_2$  surfaces *via* hydrogen bonding, even under ambient conditions.<sup>78</sup>

Researchers have combined photocatalytic technology with biological filters to remove benzene compounds, utilizing Pd-doped  $\text{TiO}_2$ .<sup>79</sup> However, further research is needed to address



Table 2 Recent advances in catalytic oxidation for air purification<sup>a</sup>

Catalyst	VOC	Efficiency	Key findings	References
TiO <sub>2</sub> on ACF and TiO <sub>2</sub> on NFF	Methyl ethyl ketone	62.2% (TiO <sub>2</sub> /ACF) 36.3% (TiO <sub>2</sub> /NFF)	TiO <sub>2</sub> calcined at 300 °C exhibited highest efficiency due to optimal crystallinity and surface hydroxyl groups. ACF support enhanced removal efficiency and <i>in situ</i> regeneration	Mamaghani <i>et al.</i> <sup>64</sup>
MIL-88B(Fe) MOF	Formaldehyde	80% mineralization	Defective Fe-MOFs activated O <sub>2</sub> at ambient temperature <i>via</i> Fe <sup>3+</sup> /Fe <sup>2+</sup> cycle, producing ROS (·O <sub>2</sub> <sup>-</sup> , ·OH, <sup>1</sup> O <sub>2</sub> ) for effective formaldehyde oxidation	Zhang <i>et al.</i> <sup>65</sup>
Pt/MnO <sub>2</sub> -BN aerogels	Formaldehyde	96% conversion (200 ppm, 50 min)	Boron nitride aerogels enhanced formaldehyde adsorption and oxidation due to porous structure and Pt/MnO <sub>2</sub> synergy	Chen <i>et al.</i> <sup>66</sup>
Co-Ce oxides	Toluene	T <sub>90</sub> = 192 °C	Oxygen vacancies enhanced O <sub>2</sub> migration, increasing oxidation rate. Co <sup>3+</sup> /Co <sup>2+</sup> and Ce <sup>4+</sup> /Ce <sup>3+</sup> cycles played key roles in catalytic activity	Wang <i>et al.</i> <sup>67</sup>
Multiphase MnO <sub>2</sub>	Toluene	δ-MnO <sub>2</sub> > α-MnO <sub>2</sub> > ε-MnO <sub>2</sub> > γ-MnO <sub>2</sub>	Oxygen vacancies and surface oxygen mobility determined catalytic efficiency, with δ-MnO <sub>2</sub> showing the highest activity	Yang <i>et al.</i> <sup>68</sup>
Porous SmMn <sub>2</sub> O <sub>5</sub> mullite	Benzene, Chlorobenzene	High VOCs removal efficiency	Mn <sup>4+</sup> -rich surface improved oxidation rate; lattice oxygen attack enhanced VOC degradation	Liu <i>et al.</i> <sup>69</sup>
MOF-derived Co <sub>3</sub> O <sub>4</sub>	o-Xylene	T <sub>90</sub> = 270 °C	Surface lattice oxygen (O <sub>2t</sub> ) on (220) planes facilitated O <sub>2</sub> adsorption and oxidation, increasing reaction rate	Ma <i>et al.</i> <sup>70</sup>
Y-single atoms on MnO <sub>2</sub>	Formaldehyde	Higher steady-state CO <sub>2</sub> yield <i>vs.</i> MnO <sub>2</sub>	Y-atoms created oxygen vacancies, improving ROS generation and proton affinity, enhancing oxidation efficiency	Zhang <i>et al.</i> <sup>71</sup>

<sup>a</sup> 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<sub>2</sub>, CO, and water, with conversion rates of 63.6% for benzene, 56.4% for toluene, and 51.8% for xylene, respectively.<sup>80,81</sup> Huang *et al.*'s study showcased TiO<sub>2</sub>/zeolite catalysts synthesized *via* sol-gel method, achieving nearly 100% benzene removal efficiency.<sup>82</sup> 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.<sup>82</sup> Catalytic ozonation offers a low-energy approach for removing toxic gases, operating through mechanisms distinct from photocatalytic oxidation.<sup>83</sup> Three key models describe catalytic oxidation: (1) Langmuir–Hinshelwood (L–H),

(2) Eley–Rideal (E–R), and (3) Mars–van Krevelen (MVK).<sup>84</sup> 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,<sup>85</sup> whereas, in the E–R model, the controlling step entails the interaction between adsorbed molecules and those in the gas phase.<sup>86</sup> In the MVK model, the critical step comprises the interaction between VOC molecules and oxygen at various redox sites.<sup>87</sup> Elements such as Cu, Mn, Au, Rh, Pd, Pt, Ag, and metal oxides, including MnO<sub>2</sub>, exhibit effective catalytic decomposition of formaldehyde at specific temperatures.<sup>85–87</sup>

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<sup>88</sup> investigated the loading of Cu



and Mn onto  $\text{TiO}_2$ , 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:  $\text{Pt}/\text{TiO}_2 \gg \text{Pd}/\text{TiO}_2 \approx \text{Rh}/\text{TiO}_2 > \text{Mn}/\text{TiO}_2 > \text{Cu}/\text{TiO}_2$ . The choice of support material significantly influences catalytic performance.  $\text{TiO}_2$  has been shown to exhibit the highest efficiency for formaldehyde removal, highlighting its potential as an effective catalyst support.<sup>89,90</sup> Wang *et al.*'s study showcased the effectiveness of Pt in photocatalytic degradation of formaldehyde, achieving an impressive 93.8% performance level.<sup>91</sup> 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<sub>2</sub> for formaldehyde oxidation, achieving full catalytic oxidation.<sup>92</sup> This contrasts with typical noble metal behavior, highlighting Pd/TiO<sub>2</sub>'s unique potential. Li *et al.*<sup>93</sup> 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 ( $\text{Ag}/\text{FeO}_x$ ) catalysts in formaldehyde oxidation.<sup>94</sup> 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.<sup>94</sup> Shen *et al.*<sup>95</sup> found that Au/CeO<sub>2</sub> 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<sub>2</sub>. The catalyst's effectiveness stems from easily desorbed surface oxygen species, facilitating formaldehyde catalysis.<sup>96</sup>

Metal oxides, like NiO, have been explored for catalytic formaldehyde oxidation. Early studies showed NiO films could oxidize formaldehyde to water and CO<sub>2</sub>, albeit requiring high temperatures (220 °C).<sup>9</sup> Sekine's study showed that various metal oxides, including Ag<sub>2</sub>O, CoO, MnO<sub>2</sub>, TiO<sub>2</sub>, CeO<sub>2</sub>, and PdO, can partially decompose formaldehyde under ambient conditions, highlighting their potential for catalytic oxidation.<sup>97</sup> Sekine engineered a passive air purification material and an air purifier featuring manganese oxide (77% MnO<sub>2</sub>) as the primary active agent, successfully lowering formaldehyde levels in newly constructed multi-family dwellings from 0.28 mg m<sup>-3</sup> to 0.05 mg m<sup>-3</sup> over seven months.<sup>97</sup> Bai *et al.*'s study showcased a  $\text{Co}_3\text{O}_4\text{-ZrO}_2$  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.<sup>98</sup> Sheng *et al.*'s study demonstrated an effective formaldehyde removal using CuO-CeO<sub>2</sub> integrated with coke, achieving optimal catalytic activity at a CuO:CeO<sub>2</sub> 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.<sup>99</sup> When utilizing Mn/TiO<sub>2</sub> as the catalyst, benzene catalytic efficiency attained 58%.<sup>75</sup> 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.<sup>100</sup> Clay-supported vanadium oxide catalysts achieved 94% degradation of phenol and 14% degradation of benzene within benzene series purification.<sup>100</sup> A polyvinylidene fluoride membrane with CuO nanopowder showed limited effectiveness, processing only 2.3% of benzene.<sup>101</sup> Two catalysts of TiO<sub>2</sub> nanomaterial and CeO<sub>2</sub>/γ-Al<sub>2</sub>O<sub>3</sub> catalyst spheres showed notable benzene degradation efficiencies reaching 100% and 92.5%, respectively.<sup>102,103</sup> OMS-2 catalyst achieved 100% toluene degradation at 240 °C.<sup>104</sup> Various catalysts achieved notable efficiencies, including 100% formaldehyde purification with Ag/TiO<sub>2</sub> catalysts, 85% toluene degradation with MnO<sub>x</sub>/Cr<sub>2</sub>O<sub>3</sub> catalysts, and 95% toluene degradation with NiO<sub>x</sub>/Co<sub>3</sub>O<sub>4</sub> catalysts.<sup>105,106</sup>

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<sub>2</sub> shows promise for air purification, achieving 82% formaldehyde reduction at room temperature (25 °C). Advanced catalysts of Pt/TiO<sub>2</sub> and Ag/CeO<sub>2</sub> 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<sub>2</sub>, TiO<sub>2</sub> nanomaterial, and CeO<sub>2</sub>/γ-Al<sub>2</sub>O<sub>3</sub> 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<sub>2.5</sub>, necessitates innovative, cost-effective, and sustainable mitigation strategies.<sup>108</sup> Household plants offer a promising phytoremediation approach, leveraging their natural metabolic and biochemical capabilities to remove airborne pollutants, regulate microclimates, and enhance air quality.<sup>109</sup> 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).<sup>110</sup> Air pollutant removal occurs through adsorption, absorption, and metabolic transformation, working together to eliminate contaminants.<sup>111</sup> 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<sup>a</sup>

Catalyst	VOC	E (%)	T (°C)	Notes	References
MnO <sub>2</sub> (77%)	Formaldehyde	82	25	Reduced 0.28 to 0.05 mg m <sup>-3</sup> in 7 months	Sekine <sup>97</sup>
Pt/TiO <sub>2</sub>	Formaldehyde	93.8	25	Visible light active	Wang <i>et al.</i> <sup>91</sup>
Pd/TiO <sub>2</sub>	Formaldehyde	100	25	Complete oxidation <i>via</i> high-T reduction	Li <i>et al.</i> <sup>92</sup>
Au/FeO <sub>x</sub>	Formaldehyde	100	80	Improved humidity resistance, cost-effective	Li <i>et al.</i> <sup>93</sup>
Ag/FeO <sub>x</sub>	Formaldehyde	100	200	Optimal at 200 °C calcination	Chen <i>et al.</i> <sup>94</sup>
Ag/CeO <sub>2</sub>	Formaldehyde	100	150	High oxygen desorption	Imamura <i>et al.</i> <sup>96</sup>
Mn/TiO <sub>2</sub>	Benzene	58	120	Moderate efficiency	Shie <i>et al.</i> <sup>75</sup>
Pt/Ce/HZSM-5	Benzene	34.2	120	—	Yang <i>et al.</i> <sup>107</sup>
Pt/Ce/HZSM-5	Xylene	96.7	120	—	Yang <i>et al.</i> <sup>107</sup>
Pt/Ce/HZSM-5	Toluene	96.7	120	—	Yang <i>et al.</i> <sup>107</sup>
Clay-supported V <sub>2</sub> O <sub>5</sub>	Phenol	94	200	—	Gao and Xu <sup>100</sup>
Clay-supported V <sub>2</sub> O <sub>5</sub>	Benzene	14	200	—	Gao and Xu <sup>100</sup>
CuO/PVDF nanopowder	Benzene	2.3	150	Low efficiency	Molinari <i>et al.</i> <sup>101</sup>
TiO <sub>2</sub> nanomaterial	Benzene	100	25	High photocatalytic efficiency	Lin and Kao <sup>102</sup>
CeO <sub>2</sub> /γ-Al <sub>2</sub> O <sub>3</sub> spheres	Benzene	92.5	25	—	Mao <i>et al.</i> <sup>103</sup>
OMS-2	Toluene	100	240	Complete degradation	Sun <i>et al.</i> <sup>104</sup>
Ag/TiO <sub>2</sub>	Formaldehyde	100	25	—	Chen <i>et al.</i> <sup>105</sup>
MnO <sub>x</sub> /Cr <sub>2</sub> O <sub>3</sub>	Toluene	85	200	—	Shan <i>et al.</i> <sup>106</sup>
NiO <sub>x</sub> /Co <sub>3</sub> O <sub>4</sub>	Toluene	95	200	—	Shan <i>et al.</i> <sup>106</sup>

<sup>a</sup> 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<sub>x</sub> and NiO<sub>x</sub>/Co<sub>3</sub>O<sub>4</sub> 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 biologically.<sup>112</sup> Air circulation around leaves and roots boosts removal efficiency. Leaves capture particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>) mainly through surface deposition, with leaf traits like area, roughness, trichomes, and waxes playing a key role.<sup>113</sup> 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.<sup>114</sup> The rhizosphere, with its soil and microorganisms, boosts phytoremediation by breaking down VOCs that reach the root zone.<sup>115</sup> Microbes like *Pseudomonas putida* (*P. putida*) in plant leaves and roots break down VOCs, boosting removal efficiency.<sup>116</sup> For instance, plants with *P. putida* TVA8 remove toluene within 24 hours, faster than non-inoculated plants.<sup>115</sup>

**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.<sup>116</sup> Plants detoxify formaldehyde *via* formaldehyde dehydrogenase enzymes in leaves and roots, breaking it down effectively.<sup>117</sup> Formaldehyde is converted into harmless CO<sub>2</sub> 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.<sup>117</sup> 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.<sup>118</sup> Some plants, like *Sansevieria trifasciata* (snake plant), absorb and incorporate pollutants (e.g., benzene, toluene) into their tissues, effectively removing them from the air.<sup>119</sup> Phyllospheric microbes, such as *Pseudomonas*, break down toluene into catechol *via* the toluene dioxygenase pathway, ultimately converting it into CO<sub>2</sub> and water through the tricarboxylic acid cycle.<sup>120</sup> Plants remove PM<sub>2.5</sub> mainly through physical capture, with particles sticking to leaf surfaces or getting trapped within the leaf's waxy cuticle.<sup>121</sup> When exposed to PM, plants neutralize harmful reactive oxygen species using antioxidants like ascorbic acid and glutathione.<sup>122,123</sup> This biochemical defense mechanism prevents oxidative damage to plant tissues while indirectly mitigating the harmful effects of PM on air quality.<sup>124</sup> Plants remove ozone by reacting with volatile compounds like monoterpenes on leaf surfaces and through stomatal uptake, where antioxidants detoxify it.<sup>125</sup>

**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.<sup>126</sup> 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.<sup>127</sup> 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.<sup>128</sup> Phytoremediation effectiveness is also impacted by environmental conditions like light,



humidity, and temperature.<sup>129</sup> Shade-tolerant plants like *Epi-prenum aureum* thrive in low-light spaces, effectively removing VOCs even in dim conditions.<sup>130</sup> 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.<sup>131</sup>

**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<sub>2</sub> through photosynthesis.<sup>132</sup> 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<sub>2.5</sub> concentrations, making them effective for offices and homes.<sup>133,134</sup> Active biofiltration systems improve pollutant removal by circulating air through plant roots and substrates, allowing microbes to break down pollutants more effectively.<sup>135</sup> Although phytoremediation shows promise, several challenges hinder its broader application.<sup>136</sup> 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<sub>2.5</sub>, whereas broad-leaved plants like *Ficus benghalensis* handle PM<sub>2.5</sub> better.<sup>137</sup> 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.<sup>138</sup> 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.<sup>139</sup> 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.<sup>140</sup> 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.<sup>141</sup> 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<sup>147</sup> 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<sub>2</sub> and MnO<sub>2</sub>, 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,<sup>148</sup> 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<sup>2</sup>. 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.<sup>149</sup>

### 4.2. Future perspectives

Advancing AP mitigation requires integrating adsorption, catalytic oxidation, and phytoremediation to effectively target diverse pollutants like VOCs and PM<sub>2.5</sub>.<sup>151</sup> 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<sup>-1</sup>. Surface-modified biochars with nanomaterials like TiO<sub>2</sub> could boost PM<sub>2.5</sub> capture via enhanced electrostatic interactions, building on bamboo biochar's 483.09 mg g<sup>-1</sup> acetone capacity. Catalytic oxidation research should prioritize developing low-temperature, energy-efficient catalysts.<sup>152</sup> Manganese oxide-based catalysts (like MnO<sub>2</sub>, 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<sup>a</sup>

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

<sup>a</sup> 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<sup>a</sup>

Air pollutant reduction methods				
Criterion	Adsorption	Catalytic oxidation	Phytoremediation	References
E	High (1211 mg g <sup>-1</sup> CH <sub>2</sub> Cl <sub>2</sub> onto MOF-5, 800 mg g <sup>-1</sup> benzene onto AC)	High (93.8% by Pt/TiO <sub>2</sub> and 82% by MnO <sub>2</sub> for removing formaldehyde)	Moderate (80% by <i>Epipremnum aureum</i> : For removing formaldehyde in 24 h)	Mehta <i>et al.</i> , <sup>6</sup> Bellat <i>et al.</i> , <sup>32</sup> Férey <i>et al.</i> , <sup>57</sup>
Mechanism	Physical/chemical adsorption on porous materials	Oxidation <i>via</i> catalysts (photocatalysts or thermocatalysts)	Stomatal absorption, enzymatic breakdown, microbial degradation	Mehta <i>et al.</i> , <sup>6</sup> Férey <i>et al.</i> , <sup>57</sup> Yuan <i>et al.</i> <sup>112</sup>
VOC	Formaldehyde, benzene, toluene, PM <sub>2.5</sub>	Formaldehyde, benzene, toluene	Formaldehyde, benzene, xylene, PM <sub>2.5</sub>	Mehta <i>et al.</i> , <sup>6</sup> Férey <i>et al.</i> , <sup>57</sup> Yuan <i>et al.</i> <sup>112</sup>
ER	Low (passive process)	Moderate to high (requires heat, UV light, or catalysts)	None (natural biological process)	Mehta <i>et al.</i> , <sup>6</sup> Férey <i>et al.</i> , <sup>57</sup> Yuan <i>et al.</i> <sup>112</sup>
MR	Requires periodic replacement or regeneration	Catalyst deactivation over time; may need periodic regeneration	Low maintenance, but requires watering and care	Mehta <i>et al.</i> , <sup>6</sup> Férey <i>et al.</i> , <sup>57</sup> Yuan <i>et al.</i> <sup>112</sup>
Cost	Moderate (activated carbon, MOFs, biochar)	High (noble metal catalysts, energy-intensive process)	Low (houseplants are cost-effective)	Mehta <i>et al.</i> , <sup>6</sup> Férey <i>et al.</i> , <sup>57</sup> Yuan <i>et al.</i> <sup>112</sup>
EI	Can produce spent adsorbents needing disposal	May generate secondary byproducts	Sustainable, no harmful byproducts	Mehta <i>et al.</i> , <sup>6</sup> Férey <i>et al.</i> , <sup>57</sup> Yuan <i>et al.</i> <sup>112</sup>
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 <i>et al.</i> , <sup>6</sup> Férey <i>et al.</i> , <sup>57</sup> Yuan <i>et al.</i> <sup>112</sup>
Durability	Moderate (adsorbents need regeneration or replacement)	High (catalysts can last long with maintenance)	High (plants continuously process pollutants)	Mehta <i>et al.</i> , <sup>6</sup> Férey <i>et al.</i> , <sup>57</sup> Yuan <i>et al.</i> <sup>112</sup>

<sup>a</sup> 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

Method	Cost			References
	Estimate (USD)	Category	Details	
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 <i>et al.</i> , <sup>6</sup> Bellat <i>et al.</i> , <sup>32</sup>
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 <sub>2</sub> , TiO <sub>2</sub> ) (USD 100–300 per kg) energy for UV, heat, or catalysts	Férey <i>et al.</i> , <sup>57</sup> Jhung <i>et al.</i> , <sup>58</sup> talaiakhzani <i>et al.</i> <sup>150</sup>
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 <sup>2</sup> ) watering, occasional maintenance	Saini <i>et al.</i> , <sup>56</sup> Jangodaz <i>et al.</i> , <sup>61</sup> Yuan <i>et al.</i> , <sup>112</sup> Molina <i>et al.</i> <sup>116</sup>

degradation.<sup>153</sup> Hybrid photocatalytic systems with visible-light-responsive catalysts (e.g., Pt/TiO<sub>2</sub>) 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.<sup>154</sup> 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.<sup>155</sup> 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.<sup>156</sup> 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.<sup>157</sup> 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<sub>2.5</sub> and PM<sub>10</sub>), and CO<sub>2</sub>.<sup>158</sup> 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.<sup>9</sup> 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.<sup>159</sup> At the molecular level, the adsorption process depends on van der Waals forces, π–π stacking, dipole–dipole interactions, and hydrogen bonding.<sup>19,160</sup> 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.<sup>161</sup> 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.<sup>162</sup> Adsorption performance is significantly influenced by humidity and temperature, with high humidity potentially blocking micropores and reducing VOC uptake.<sup>159</sup> 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.<sup>9</sup> 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.<sup>163</sup> 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<sub>2</sub> and water through chemical reactions. These systems function by generating reactive oxygen species (ROS) *via* semiconductor photocatalysts, such as TiO<sub>2</sub>, ZnO, or WO<sub>3</sub>.<sup>164,165</sup> 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<sub>2</sub> + hν → e<sup>−</sup> + h<sup>+</sup>), hydroxyl radical formation (OH<sup>−</sup> + h<sup>+</sup> → ·OH), and superoxide generation (O<sub>2</sub> + e<sup>−</sup> → O<sub>2</sub><sup>·−</sup>), leading to the mineralization of VOCs.<sup>9,166</sup> Recent studies have demonstrated that WO<sub>3</sub>/Pt-coated ceramic filters effectively degrade toluene under visible light, while Pt/TiO<sub>2</sub> catalysts achieve over 90% formaldehyde conversion under ambient conditions.<sup>167,168</sup> 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.<sup>162</sup> Important operational parameters include light intensity, wavelength (UV or visible), airflow velocity, and humidity.<sup>9</sup> While catalytic systems do not saturate like adsorbents, they can degrade due to surface fouling or accumulation of intermediates, necessitating periodic cleaning or replacement.<sup>167</sup> 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<sub>2</sub> or graphitic carbon nitride, can minimize energy consumption and mitigate secondary pollution.<sup>9</sup> 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.<sup>159</sup> 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<sub>2</sub>–MnO<sub>2</sub> composites, CuO–CeO<sub>2</sub> 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.<sup>169</sup> 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<sub>2</sub> and water.<sup>170</sup> In addition, symbiotic microbes like *Pseudomonas putida* in the rhizosphere catalyze



the breakdown of aromatic compounds *via* dioxygenase pathways, further enhancing pollutant removal efficiency.<sup>169</sup> For particulate matter, leaves function as passive filters, trapping fine particles through their surface roughness, trichomes, and waxy layers.<sup>171</sup> Plants also mitigate oxidative stress from ROS generated by pollutants using antioxidants like ascorbic acid and glutathione.<sup>170</sup> 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.<sup>169</sup> Field studies have shown that potted *Dypsis lutescens* (areca palm) plants can reduce total VOCs and CO<sub>2</sub> concentrations by up to 88% in residential spaces.<sup>172</sup> 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.<sup>170</sup> 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.<sup>171</sup> 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.<sup>169</sup> 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<sup>170,172</sup> 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.<sup>163</sup> Second, employ adsorption filters as a baseline technology to capture gaseous compounds.<sup>159</sup> Third, integrate catalytic or photocatalytic systems to chemically degrade residual VOCs.<sup>167</sup> Finally, utilize selected plants as living filters to continuously absorb and metabolize pollutants while enhancing aesthetics.<sup>170</sup> Such hybrid systems have been proposed for green buildings and energy-efficient offices.<sup>9</sup> Regular monitoring of pollutant concentrations (*e.g.*, VOCs, CO<sub>2</sub>, PM<sub>2.5</sub>) is recommended to assess system performance and schedule maintenance.<sup>163</sup> Adsorption filters typically require replacement every 3–6 months, catalysts every 1–2 years, and plants need continuous care.<sup>162</sup> 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.<sup>159</sup> Catalytic oxidation units are more expensive, costing USD 100–1000 per kg for catalyst materials, with additional energy expenses for light or heating.<sup>9</sup> 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<sup>2</sup>.<sup>173</sup>

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.<sup>167</sup> Despite these benefits, each approach has limitations. Adsorption performance declines under humid conditions,<sup>159</sup> catalytic systems may generate undesirable by-products like ozone or carbonyls if poorly designed,<sup>167</sup> and phytoremediation efficiency varies by plant species and environmental factors.<sup>169</sup> 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.<sup>163</sup> 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<sup>-1</sup> for benzene), biochars (483.09 mg g<sup>-1</sup> for acetone), nanofibers (450 mg g<sup>-1</sup> for toluene), and MOFs (1211 mg g<sup>-1</sup> for CH<sub>2</sub>Cl<sub>2</sub> in MOF-5, 800 mg g<sup>-1</sup> for benzene in MOF-177) to capture VOCs, showcasing significant advancements. Catalytic oxidation, including photocatalytic (*e.g.*, Pt/TiO<sub>2</sub>) and thermocatalytic (*e.g.*, MnO<sub>2</sub>) methods, efficiently degrades pollutants at ambient temperatures, with metal-doped catalysts like Ag/CeO<sub>2</sub> 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<sub>2</sub>/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<sup>7</sup> particles per m<sup>2</sup> PM<sub>2.5</sub> 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.

## Acknowledgements

We would like to express our sincere gratitude to the Department of Natural Sciences at West Kazakhstan Marat Ospanov Medical University for their invaluable support in the development of this paper. Special thanks to the faculty and staff for their continued guidance, encouragement, and assistance throughout this research. Their dedication to fostering academic growth and advancing scientific understanding has played a crucial role in the successful completion of this study. During the preparation of this work the authors used ChatGPT and then Meta AI in order to enhance the manuscript writing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

## References

- 1 R. Perez-Padilla, Household air pollution: Consider lifelong exposure, *Am. J. Respir. Crit. Care Med.*, 2019, **199**, 553–555, DOI: [10.1164/rccm.201809-1656ED](https://doi.org/10.1164/rccm.201809-1656ED).
- 2 L. Li, A. Yang, X. He, J. Liu, Y. Ma, J. Niu and B. Luo, Indoor air pollution from solid fuels and hypertension: A

systematic review and meta-analysis, *Environ. Pollut.*, 2020, **259**, 113914, DOI: [10.1016/j.envpol.2020.113914](https://doi.org/10.1016/j.envpol.2020.113914).

- 3 Y. Sun, J. Hou, R. Cheng, Y. Sheng, X. Zhang and J. Sundell, Indoor air quality, ventilation and their associations with sick building syndrome in chinese homes, *Energy Build.*, 2019, **197**, 112–119, DOI: [10.1016/j.enbuild.2019.05.046](https://doi.org/10.1016/j.enbuild.2019.05.046).
- 4 Y. Lv, J. Liu, S. Wei and H. Wang, Experimental and simulation study on bake-out with dilution ventilation technology for building materials, *J. Air Waste Manage. Assoc.*, 2016, **66**, 1098–1108, DOI: [10.1080/10962247.2016.1200503](https://doi.org/10.1080/10962247.2016.1200503).
- 5 F. Wang, D. Chen, P. Wu, C. Klein and C. Jin, Formaldehyde, epigenetics, and alzheimer's disease, *Chem. Res. Toxicol.*, 2019, **32**, 820–830, DOI: [10.1021/acs.chemrestox.9b00090](https://doi.org/10.1021/acs.chemrestox.9b00090).
- 6 K. Mehta, N. Thrikutam, P. E. Hoyte-Williams, H. Falk, K. Nakarmi and B. Stewart, Epidemiology and outcomes of cooking- and cookstove-related burn injuries: A World Health Organization Global Burn Registry Report, *J. Burn. Care Res.*, 2023, **44**, 508–516, DOI: [10.1093/jbcr/irab166](https://doi.org/10.1093/jbcr/irab166).
- 7 H. Grigoryan, W. M. B. Edmonds, Q. Lan, H. Carlsson, R. Vermeulen, L. Zhang, S. N. Yin, G. L. Li, M. T. Smith, N. Rothman and S. M. Rappaport, Adductomic signatures of benzene exposure provide insights into cancer induction, *Carcinogenesis*, 2018, **39**, 661–668, DOI: [10.1093/carcin/bgy042](https://doi.org/10.1093/carcin/bgy042).
- 8 P. Sitthikarnkha, R. Uppala, L. Techasatian, S. Saengnipanthkul, S. Niamsanit, U. Peansukwech, S. Sutra, N. Anantasisit, J. Teeratakulpisarn, K. Jenwitheesuk and P. Kosararaksa, Air pollutants associated hospitalization in pediatric pneumonia: A national database analysis, *Pediatr. Pulmonol.*, 2025, **60**, e71009, DOI: [10.1002/ppul.71009](https://doi.org/10.1002/ppul.71009).
- 9 X. Yue, N. L. Ma, C. Sonne, R. Guan, S. S. Lam, Q. V. Le, X. Chen, Y. Yang, H. Gu, J. Rinklebe and W. Peng, Mitigation of indoor air pollution: A review of recent advances in adsorption materials and catalytic oxidation, *J. Hazard. Mater.*, 2021, **405**, 124138, DOI: [10.1016/j.jhazmat.2020.124138](https://doi.org/10.1016/j.jhazmat.2020.124138).
- 10 K. Vikrant, C. M. Park, K.-H. Kim, S. Kumar and E.-C. Jeon, Recent advancements in photocatalyst-based platforms for the destruction of gaseous benzene: Performance evaluation of different modes of photocatalytic operations and against adsorption techniques, *J. Photochem. Photobiol. C: Photochem. Rev.*, 2019, **41**, 100316, DOI: [10.1016/j.jphotochemrev.2019.08.003](https://doi.org/10.1016/j.jphotochemrev.2019.08.003).
- 11 L. Zhang, R. Routsong and S. E. Strand, Greatly enhanced removal of volatile organic carcinogens by a genetically modified houseplant, pothos ivy (*Epipremnum aureum*) expressing the *Mammalian Cytochrome P450 2e1 Gene*, *Environ. Sci. Technol.*, 2019, **53**, 325–331, DOI: [10.1021/acs.est.8b04811](https://doi.org/10.1021/acs.est.8b04811).
- 12 S. S. Patra, J. Liu, J. Jiang, X. Ding, C. Huang, C. Keech, G. Steiner, P. S. Stevens, N. Jung and B. E. Boor, Rapid nucleation and growth of indoor atmospheric nanocluster aerosol during the use of scented volatile chemical



products in residential buildings, *ACS ES&T Air*, 2024, **1**, 1276–1293, DOI: [10.1021/acs.estair.4c00118](https://doi.org/10.1021/acs.estair.4c00118).

13 O. O. Ayeleru, H. U. Modekwe, O. R. Onisuru, C. R. Ohoro, C. A. Akinnawo and P. A. Olubambi, Adsorbent technologies and applications for carbon capture, and direct air capture in environmental perspective and sustainable climate action, *Sustain. Chem. Climate Act.*, 2023, **3**, 100029, DOI: [10.1016/j.scca.2023.100029](https://doi.org/10.1016/j.scca.2023.100029).

14 M. M. Sabzehmeidani, S. Mahnaee, M. Ghaedi, H. Heidari and V. A. L. Roy, Carbon based materials: a review of adsorbents for inorganic and organic compounds, *Mater. Adv.*, 2021, **2**, 598–627, DOI: [10.1039/D0MA00087F](https://doi.org/10.1039/D0MA00087F).

15 Y. Li, Y. Dai, Z. Gao, Z. Li, F. He, L. Xu and Q. Tao, Adsorption of uranium onto amidoxime-group mesoporous biomass carbon: kinetics, isotherm and thermodynamics, *J. Radioanal. Nucl. Chem.*, 2022, **331**, 353–364, DOI: [10.1007/s10967-021-08115-x](https://doi.org/10.1007/s10967-021-08115-x).

16 M. E. Davis, New vistas in zeolite and molecular sieve catalysis, *Acc. Chem. Res.*, 1993, **26**, 111–115, DOI: [10.1021/ar00027a006](https://doi.org/10.1021/ar00027a006).

17 M. R. Silva, A. Lecus, M. Gajdardziska-Josifovska, M. Schofield, M. Virnoche, J. Chang, J. Chen and D. Garman, Graphene-oxide loading on natural zeolite particles for enhancement of adsorption properties, *RSC Adv.*, 2020, **10**, 4589–4597, DOI: [10.1039/C9RA00572B](https://doi.org/10.1039/C9RA00572B).

18 X. Zhang, B. Gao, A. E. Creamer, C. Cao and Y. Li, Adsorption of VOCs onto engineered carbon materials: A review, *J. Hazard. Mater.*, 2017, **338**, 102–123, DOI: [10.1016/j.jhazmat.2017.05.013](https://doi.org/10.1016/j.jhazmat.2017.05.013).

19 M. A. Fulazzaky, Study of the dispersion and specific interactions affected by chemical functions of the granular activated carbons, *Environ. Nanotechnol. Monit. Manage.*, 2019, **12**, 100230, DOI: [10.1016/j.enmm.2019.100230](https://doi.org/10.1016/j.enmm.2019.100230).

20 Y. Tong, P. J. McNamara and B. K. Mayer, Adsorption of organic micropollutants onto biochar: a review of relevant kinetics, mechanisms and equilibrium, *Environ. Sci.: Water Res. Technol.*, 2019, **5**, 821–838, DOI: [10.1039/C8EW00938D](https://doi.org/10.1039/C8EW00938D).

21 M. A. Fulazzaky, Determining the resistance of mass transfer for adsorption of the surfactants onto granular activated carbons from hydrodynamic column, *Chem. Eng. J.*, 2011, **166**, 832–840, DOI: [10.1016/j.cej.2010.11.052](https://doi.org/10.1016/j.cej.2010.11.052).

22 M. Danish and T. Ahmad, A review on utilization of wood biomass as a sustainable precursor for activated carbon production and application, *Renew. Sustain. Energy Rev.*, 2018, **87**, 1–21, DOI: [10.1016/j.rser.2018.02.003](https://doi.org/10.1016/j.rser.2018.02.003).

23 R. Fang, H. Huang, J. Ji, M. He, Q. Feng, Y. Zhan and D. Y. C. Leung, Efficient MnO<sub>x</sub> supported on coconut shell activated carbon for catalytic oxidation of indoor formaldehyde at room temperature, *Chem. Eng. J.*, 2018, **334**, 2050–2057, DOI: [10.1016/j.cej.2017.11.176](https://doi.org/10.1016/j.cej.2017.11.176).

24 E. Gallego, F. J. Roca, J. F. Perales and X. Guardino, Experimental evaluation of VOC removal efficiency of a coconut shell activated carbon filter for indoor air quality enhancement, *Build. Environ.*, 2013, **67**, 14–25, DOI: [10.1016/j.buildenv.2013.05.003](https://doi.org/10.1016/j.buildenv.2013.05.003).

25 X. Pang, L. Sellaoui, D. Franco, G. L. Dotto, J. Georgin, A. Bajahzar, H. Belmabrouk, A. B. Lamine, A. Bonilla-Petriciolet and Z. Li, Adsorption of crystal violet on biomasses from pecan nutshell, para chestnut husk, araucaria bark and palm cactus: experimental study and theoretical modeling via monolayer and double layer statistical physics models, *Chem. Eng. J.*, 2019, **378**, 122101, DOI: [10.1016/j.cej.2019.122101](https://doi.org/10.1016/j.cej.2019.122101).

26 P. Yao, J. Cen, M. Fang, T. Wang and Q. Wang, A study on the preparation of pitch-based high-strength columnar activated carbon and mechanism of phenol adsorption from aqueous solution, *RSC Adv.*, 2018, **8**, 17558–17568, DOI: [10.1039/C7RA13344H](https://doi.org/10.1039/C7RA13344H).

27 Y. Huang, X. Zhu, D. Wang and S. Hui, Enhanced formaldehyde oxidation over MnO<sub>2</sub> and doped manganese-based catalysts: Experimental and theoretical Insights into mechanism and performance, *Environ. Res.*, 2023, **238**, 117265, DOI: [10.1016/j.envres.2023.117265](https://doi.org/10.1016/j.envres.2023.117265).

28 A. C. Martins, A. L. Cazetta, O. Pezoti, J. R. B. Souza, T. Zhang, E. J. Pilau, T. Asefa and V. C. Almeida, Sol-gel synthesis of new TiO<sub>2</sub>/activated carbon photocatalyst and its application for degradation of tetracycline, *Ceram. Int.*, 2017, **43**, 4411–4418, DOI: [10.1016/j.ceramint.2016.12.088](https://doi.org/10.1016/j.ceramint.2016.12.088).

29 Y. An, Q. Fu, D. Zhang, Y. Wang and Z. Tang, Performance evaluation of activated carbon with different pore sizes and functional groups for VOC adsorption by molecular simulation, *Chemosphere*, 2019, **227**, 9–16, DOI: [10.1016/j.chemosphere.2019.04.011](https://doi.org/10.1016/j.chemosphere.2019.04.011).

30 K. J. Lee, J. Miyawaki, N. Shiratori, S.-H. Yoon and J. Jang, Toward an effective adsorbent for polar pollutants: Formaldehyde adsorption by activated carbon, *J. Hazard. Mater.*, 2013, **260**, 82–88, DOI: [10.1016/j.jhazmat.2013.04.049](https://doi.org/10.1016/j.jhazmat.2013.04.049).

31 M. A. Fulazzaky, Analysis of global and sequential mass transfers for the adsorption of atrazine and simazine onto granular activated carbons from a hydrodynamic column, *Anal. Methods*, 2012, **4**, 2396–2403, DOI: [10.1039/C2AY05467A](https://doi.org/10.1039/C2AY05467A).

32 J.-P. Bellat, I. Bezverkhyy, G. Weber, S. Royer, R. Averlant, J.-M. Giraudon and J. F. Lamonier, Capture of formaldehyde by adsorption on nanoporous materials, *J. Hazard. Mater.*, 2015, **300**, 711–717, DOI: [10.1016/j.jhazmat.2015.07.078](https://doi.org/10.1016/j.jhazmat.2015.07.078).

33 Q. Lang, P. Lu, X. Yang and V. Valtchev, Zeolites for the environment, *Green Carbon*, 2024, **2**, 12–32, DOI: [10.1016/j.greanca.2024.02.007](https://doi.org/10.1016/j.greanca.2024.02.007).

34 C. Giosuè, M. Pierpaoli, A. Mobili, M. L. Ruello and F. Tittarelli, Influence of binders and lightweight aggregates on the properties of cementitious mortars: from traditional requirements to indoor air quality improvement, *Materials*, 2017, **10**, 978, DOI: [10.3390/ma10080978](https://doi.org/10.3390/ma10080978).

35 A. M. de Yus, B. Rubio and M. T. Izquierdo, Influence of activation atmosphere used in the chemical activation of almond shell on the characteristics and adsorption performance of activated carbons, *Fuel Process. Technol.*, 2014, **119**, 74–80, DOI: [10.1016/j.fuproc.2013.10.024](https://doi.org/10.1016/j.fuproc.2013.10.024).



36 E. David, Production of activated biochar derived from residual biomass for adsorption of volatile organic compounds, *Materials*, 2023, **16**, 389, DOI: [10.3390/ma16010389](https://doi.org/10.3390/ma16010389).

37 A. Rezaee, H. Rangkooy, A. Khavanin and A. J. Jafari, High photocatalytic decomposition of the air pollutant formaldehyde using nano-ZnO on bone char, *Environ. Chem. Lett.*, 2014, **12**, 353–357, DOI: [10.1007/s10311-014-0453-7](https://doi.org/10.1007/s10311-014-0453-7).

38 J. Mohammed, N. S. Nasri, M. A. A. Zaini, U. D. Hamza and F. N. Ani, Adsorption of benzene and toluene onto KOH activated coconut shell-based carbon treated with NH<sub>3</sub>, *Int. Biodeter. Biodegrad.*, 2015, **102**, 245–255, DOI: [10.1016/j.ibiod.2015.02.012](https://doi.org/10.1016/j.ibiod.2015.02.012).

39 K. Yang, L. Zhu, J. Yang and D. Lin, Adsorption and correlations of selected aromatic compounds on a KOH-activated carbon with large surface area, *Sci. Total Environ.*, 2018, **618**, 1677–1684, DOI: [10.1016/j.scitotenv.2017.10.018](https://doi.org/10.1016/j.scitotenv.2017.10.018).

40 Y. Jiao, C. Wan and J. J. Li, Synthesis of carbon fiber aerogel from natural bamboo fiber and its application as a green high-efficiency and recyclable adsorbent, *Mater. Design*, 2016, **107**, 26–32, DOI: [10.1016/j.matdes.2016.06.015](https://doi.org/10.1016/j.matdes.2016.06.015).

41 D. J. Tranchemontagne, J. R. Hunt and O. M. Yaghi, Room temperature synthesis of metal-organic frameworks: MOF-5, MOF-74, MOF-177, MOF-199, and IRMOF-0, *Tetrahedron*, 2008, **64**, 8553–8557, DOI: [10.1016/j.tet.2008.06.036](https://doi.org/10.1016/j.tet.2008.06.036).

42 K. Yang, Q. Sun, F. Xue and D. Lin, Adsorption of volatile organic compounds by metal-organic frameworks MIL-101: Influence of molecular size and shape, *J. Hazard. Mater.*, 2011, **195**, 124–131, DOI: [10.1016/j.jhazmat.2011.08.020](https://doi.org/10.1016/j.jhazmat.2011.08.020).

43 A. Kundu, K. Sillar and J. Sauer, Predicting adsorption selectivities from pure gas isotherms for gas mixtures in metal-organic frameworks, *Chem. Sci.*, 2020, **11**, 643–655, DOI: [10.1039/C9SC03008E](https://doi.org/10.1039/C9SC03008E).

44 Y. Zhou and B. Yan, A responsive MOF nanocomposite for decoding volatile organic compounds, *Chem. Commun.*, 2016, **52**, 2265–2268, DOI: [10.1039/C5CC09029F](https://doi.org/10.1039/C5CC09029F).

45 C. S. L. Koh, H. K. Lee, X. Han, H. Y. F. Sim and X. Y. Ling, Plasmonic nose: integrating the MOF-enabled molecular preconcentration effect with a plasmonic array for recognition of molecular-level volatile organic compounds, *Chem. Commun.*, 2018, **54**, 2546–2549, DOI: [10.1039/C8CC00564H](https://doi.org/10.1039/C8CC00564H).

46 J. J. Richardson and K. Liang, Nano-biohybrids: in vivo synthesis of metal-organic frameworks inside living plants, *Small*, 2018, **14**, 1702958, DOI: [10.1002/smll.201702958](https://doi.org/10.1002/smll.201702958).

47 W. Chaikittisilp, K. Ariga and Y. Yamauchi, A new family of carbon materials: synthesis of MOF-derived nanoporous carbons and their promising applications, *J. Mater. Chem. A*, 2013, **1**, 14–19, DOI: [10.1039/C2TA00278G](https://doi.org/10.1039/C2TA00278G).

48 E. Barea, C. Montoro and J. A. Navarro, Toxic gas removal–metal-organic frameworks for the capture and degradation of toxic gases and vapours, *Chem. Soc. Rev.*, 2014, **43**, 5419–5430, DOI: [10.1039/C3CS60475F](https://doi.org/10.1039/C3CS60475F).

49 M. Eddaoudi, H. Li and O. Yaghi, Highly porous and stable metal-organic frameworks: structure design and sorption properties, *J. Am. Chem. Soc.*, 2000, **122**, 1391–1397, DOI: [10.1021/ja9933386](https://doi.org/10.1021/ja9933386).

50 A. J. Graham, D. R. Allan, A. Muszkiewicz, C. A. Morrison and S. A. Moggach, The effect of high pressure on MOF-5: Guest-induced modification of pore size and content at high pressure, *Angew. Chem.*, 2011, **123**, 11334–11337, DOI: [10.1002/ange.201104285](https://doi.org/10.1002/ange.201104285).

51 B. F. Hoskins and R. Robson, Infinite polymeric frameworks consisting of three dimensionally linked rod-like segments, *J. Am. Chem. Soc.*, 1989, **111**, 5962–5964, DOI: [10.1021/ja00197a079](https://doi.org/10.1021/ja00197a079).

52 O. Yaghi, G. Li and H. Li, Selective binding and removal of guests in a microporous metal-organic framework, *Nature*, 1995, **378**, 703–706, DOI: [10.1038/378703a0](https://doi.org/10.1038/378703a0).

53 G. Moore, K. M. Devos, Z. Wang and M. D. Gale, Cereal genome evolution: grasses, line up and form a circle, *Curr. Biol.*, 1995, **5**, 737–739, DOI: [10.1016/S0960-9822\(95\)00148-5](https://doi.org/10.1016/S0960-9822(95)00148-5).

54 M. Eddaoudi, J. Kim, N. Rosi, D. Vodak, J. Wachter, M. O'Keeffe and O. M. Yaghi, Systematic design of pore size and functionality in isoreticular MOFs and their application in methane storage, *Science*, 2002, **295**, 469–472, DOI: [10.1126/science.1067208](https://doi.org/10.1126/science.1067208).

55 V. K. Saini and J. Pires, Development of metal organic framework-199 immobilized zeolite foam for adsorption of common indoor VOCs, *J. Environ. Sci.*, 2017, **55**, 321–330, DOI: [10.1016/j.jes.2016.09.017](https://doi.org/10.1016/j.jes.2016.09.017).

56 V. K. Saini, M. Andrade, M. L. Pinto, A. P. Carvalho and J. Pires, How the adsorption properties get changed when going from SBA-15 to its CMK-3 carbon replica, *Separ. Purif. Technol.*, 2010, **75**, 366–376, DOI: [10.1016/j.jseppur.2010.09.006](https://doi.org/10.1016/j.jseppur.2010.09.006).

57 G. Férey, C. Mellot-Draznieks, C. Serre, F. Millange, J. Dutour, S. Surblé and I. Margiolaki, A chromium terephthalate-based solid with unusually large pore volumes and surface area, *Science*, 2005, **309**, 2040–2042, DOI: [10.1126/science.1116275](https://doi.org/10.1126/science.1116275).

58 S. H. Jhung, J.-H. Lee, J. W. Yoon, C. Serre, G. Férey and J.-S. Chang, Microwave synthesis of chromium terephthalate MIL-101 and its benzene sorption ability, *Adv. Mater.*, 2007, **19**, 121–124, DOI: [10.1002/adma.200601604](https://doi.org/10.1002/adma.200601604).

59 D. Wang, G. Wu, Y. Zhao, L. Cui, C.-H. Shin, M.-H. Ryu and J. Cai, Study on the copper(II)-doped MIL-101(Cr) and its performance in VOCs adsorption, *Environ. Sci. Pollut. Res.*, 2018, **25**, 28109–28119, DOI: [10.1007/s11356-018-2849-6](https://doi.org/10.1007/s11356-018-2849-6).

60 X. Huang, Q. Hu, L. Gao, Q. Hao, P. Wang and D. Qin, Adsorption characteristics of metal-organic framework MIL-101(Cr) towards sulfamethoxazole and its persulfate oxidation regeneration, *RSC Adv.*, 2018, **8**, 27623–27630, DOI: [10.1039/C8RA04789H](https://doi.org/10.1039/C8RA04789H).

61 E. Jangodaz, E. Alaie, A. A. Safekordi and S. Tasharofi, Adsorption of ethylbenzene from air on metal-organic



frameworks MIL-101(Cr) and MIL-53(Fe) at room temperature, *J. Inorg. Organomet. Polym. Mater.*, 2018, **28**, 2090–2099, DOI: [10.1007/s10904-018-0896-6](https://doi.org/10.1007/s10904-018-0896-6).

62 V. Finsy, H. Verelst, L. Alaerts, D. De Vos, P. A. Jacobs, G. V. Baron and J. F. M. Denayer, Pore-filling-dependent selectivity effects in the vapor-phase separation of xylene isomers on the metal-organic framework MIL-47, *J. Am. Chem. Soc.*, 2008, **130**, 7110–7118, DOI: [10.1021/ja800686c](https://doi.org/10.1021/ja800686c).

63 C.-Y. Huang, M. Song, Z.-Y. Gu, H.-F. Wang and X.-P. Yan, Probing the adsorption characteristic of metal-organic framework MIL-101 for volatile organic compounds by quartz crystal microbalance, *Environ. Sci. Technol.*, 2011, **45**, 4490–4496, DOI: [10.1021/es200256q](https://doi.org/10.1021/es200256q).

64 A. H. Mamaghani, F. Haghigheh and C.-S. Lee, Effect of titanium dioxide properties and support material on photocatalytic oxidation of indoor air pollutants, *Build. Environ.*, 2021, **189**, 107518, DOI: [10.1016/j.buildenv.2020.107518](https://doi.org/10.1016/j.buildenv.2020.107518).

65 S. Zhang, Y. Zhuo, C. I. Ezugwu, C.-c. Wang, C. Li and S. Liu, Synergetic molecular oxygen activation and catalytic oxidation of formaldehyde over defective MIL-88B (Fe) nanorods at room temperature, *Environ. Sci. Technol.*, 2021, **55**, 8341–8350, DOI: [10.1021/acs.est.1c01277](https://doi.org/10.1021/acs.est.1c01277).

66 D. Chen, G. Zhang, M. Wang, N. Li, Q. Xu, H. Li, J. He and J. Lu, Pt/MnO<sub>2</sub> nanoflowers anchored to boron nitride aerogels for highly efficient enrichment and catalytic oxidation of formaldehyde at room temperature, *Angew. Chem.*, 2021, **60**, 6377–6381, DOI: [10.1002/anie.202013667](https://doi.org/10.1002/anie.202013667).

67 L. Wang, Y. Li, J. Liu, Z. Tian and Y. Jing, Regulation of oxygen vacancies in cobalt-cerium oxide catalyst for boosting decontamination of VOCs by catalytic oxidation, *Separ. Purif. Technol.*, 2021, **277**, 119505, DOI: [10.1016/j.seppur.2021.119505](https://doi.org/10.1016/j.seppur.2021.119505).

68 R. Yang, Z. Guo, L. Cai, R. Zhu, Y. Fan, Y. Zhang, P. Han, W. Zhang, X. Zhu, Q. Zhao, Z. Zhu, C. K. Chan and Z. Zeng, Investigation into the phase–activity relationship of MnO<sub>2</sub> nanomaterials toward ozone-assisted catalytic oxidation of toluene, *Small*, 2021, **17**, 2103052, DOI: [10.1002/smll.202103052](https://doi.org/10.1002/smll.202103052).

69 R. Liu, B. Zhou, L. Liu, Y. Zhang, Y. Chen, Q. Zhang, M. Yang, L. Hu, M. Wang and Y. Tang, Enhanced catalytic oxidation of VOCs over porous Mn-based mullite synthesized by in-situ dismutation, *J. Colloid Interface Sci.*, 2021, **585**, 302–311, DOI: [10.1016/j.jcis.2020.11.096](https://doi.org/10.1016/j.jcis.2020.11.096).

70 Y. Ma, L. Wang, J. Ma, H. Wang, C. Zhang, H. Deng and H. He, Investigation into the enhanced catalytic oxidation of o-xylene over MOF-derived Co<sub>3</sub>O<sub>4</sub> with different shapes: the role of surface twofold-coordinate lattice oxygen (O<sub>2f</sub>), *ACS Catal.*, 2021, **11**, 6614–6625, DOI: [10.1021/acscatal.1c01116](https://doi.org/10.1021/acscatal.1c01116).

71 X. Zhang, L. Guo, Y. Wang, B. Lv, Z. Huang, X. Wu, H. Zhao, G. Jing and H. Shen, Y single atoms boost MnO<sub>2</sub> for efficient ambient formaldehyde catalytic oxidation, *Separ. Purif. Technol.*, 2025, **362**, 131962, DOI: [10.1016/j.seppur.2025.131962](https://doi.org/10.1016/j.seppur.2025.131962).

72 M. Humayun, F. Raziq, A. Khan and W. Luo, Modification strategies of TiO<sub>2</sub> for potential applications in photocatalysis: a critical review, *Green Chem. Lett. Rev.*, 2018, **11**, 86–102, DOI: [10.1080/17518253.2018.1440324](https://doi.org/10.1080/17518253.2018.1440324).

73 S. Weon, F. He and W. Choi, Status and challenges in photocatalytic nanotechnology for cleaning air polluted with volatile organic compounds: visible light utilization and catalyst deactivation, *Environ. Sci.: Nano*, 2019, **6**, 3185–3214, DOI: [10.1039/C9EN00891H](https://doi.org/10.1039/C9EN00891H).

74 Z. Shayegan, C.-S. Lee and F. Haghigheh, TiO<sub>2</sub> photocatalyst for removal of volatile organic compounds in gas phase–A review, *Chem. Eng. J.*, 2018, **334**, 2408–2439, DOI: [10.1016/j.cej.2017.09.153](https://doi.org/10.1016/j.cej.2017.09.153).

75 J.-L. Shie, C.-H. Lee, C.-S. Chiou, C.-T. Chang, C.-C. Chang and C.-Y. Chang, Photodegradation kinetics of formaldehyde using light sources of UVA, UVC and UVLED in the presence of composed silver titanium oxide photocatalyst, *J. Hazard. Mater.*, 2008, **155**, 164–172, DOI: [10.1016/j.jhazmat.2007.11.043](https://doi.org/10.1016/j.jhazmat.2007.11.043).

76 Z. Zhu and R.-J. Wu, The degradation of formaldehyde using a Pt@TiO<sub>2</sub> nanoparticles in presence of visible light irradiation at room temperature, *J. Taiwan Inst. Chem. Eng.*, 2015, **50**, 276–281, DOI: [10.1016/j.jtice.2014.12.022](https://doi.org/10.1016/j.jtice.2014.12.022).

77 X. Li, X. Qian, X. An and J. Huang, Preparation of a novel composite comprising biochar skeleton and “chrysanthemum” g-C<sub>3</sub>N<sub>4</sub> for enhanced visible light photocatalytic degradation of formaldehyde, *Appl. Surf. Sci.*, 2019, **487**, 1262–1270, DOI: [10.1016/j.apsusc.2019.05.195](https://doi.org/10.1016/j.apsusc.2019.05.195).

78 A. Nasriddinov, M. Rumyantseva, A. Marikutsa, A. Gaskov, J.-H. Lee, J.-H. Kim, J.-Y. Kim, S. S. Kim and H. W. Kim, Sub-ppm formaldehyde detection by n-n TiO<sub>2</sub>@SnO<sub>2</sub> nanocomposites, *Sensors*, 2019, **19**, 3182, DOI: [10.3390/s19143182](https://doi.org/10.3390/s19143182).

79 Y. Ji, T. Fan and Y. Luo, First-principles study on the mechanism of photocatalytic reduction of nitrobenzene on the rutile TiO<sub>2</sub>(110) surface, *Phys. Chem. Chem. Phys.*, 2020, **22**, 1187–1193, DOI: [10.1039/C9CP05010H](https://doi.org/10.1039/C9CP05010H).

80 C. A. Korologos, M. D. Nikolaki, C. N. Zerva, C. J. Philippopoulos and S. G. Poulopoulos, Photocatalytic oxidation of benzene, toluene, ethylbenzene and m-xylene in the gas-phase over TiO<sub>2</sub>-based catalysts, *J. Photochem. Photobiol. A: Chem.*, 2012, **244**, 24–31, DOI: [10.1016/j.jphotochem.2012.06.016](https://doi.org/10.1016/j.jphotochem.2012.06.016).

81 S. K. F. Stofela, J. R. de Andrade and M. G. A. Vieira, Adsorption of benzene, toluene, and xylene (BTX) from binary aqueous solutions using commercial organoclays, *Can. J. Chem. Eng.*, 2017, **95**, 1034–1044, DOI: [10.1002/cjce.22748](https://doi.org/10.1002/cjce.22748).

82 H. Huang, G. Liu, Y. Zhan, Y. Xu, H. Lu, H. Huang, Q. Feng and M. Wu, Photocatalytic oxidation of gaseous benzene under VUV irradiation over TiO<sub>2</sub>/zeolites catalysts, *Catal. Today*, 2017, **281**, 649–655, DOI: [10.1016/j.cattod.2016.07.005](https://doi.org/10.1016/j.cattod.2016.07.005).

83 J. Qian, K. Wang, Q. Guan, H. Li, H. Xu, Q. Liu, W. Liu and B. Qiu, Enhanced wet hydrogen peroxide catalytic oxidation performances based on CuS nanocrystals/reduced graphene oxide composites, *Appl. Surf. Sci.*, 2014, **288**, 633–640, DOI: [10.1016/j.apsusc.2013.10.086](https://doi.org/10.1016/j.apsusc.2013.10.086).



84 L. F. Liotta, Catalytic oxidation of volatile organic compounds on supported noble metals, *Appl. Catal. B: Environ.*, 2010, **100**, 403–412, DOI: [10.1016/j.apcatb.2010.08.023](https://doi.org/10.1016/j.apcatb.2010.08.023).

85 P. Liu, G. Wei, H. He, X. Liang, H. Chen, Y. Xi and J. Zhu, The catalytic oxidation of formaldehyde over palygorskite-supported copper and manganese oxides: Catalytic deactivation and regeneration, *Appl. Surf. Sci.*, 2019, **464**, 287–293, DOI: [10.1016/j.apsusc.2018.09.070](https://doi.org/10.1016/j.apsusc.2018.09.070).

86 S. Indrawirawan, H. Sun, X. Duana and S. Wang, Low temperature combustion synthesis of nitrogen-doped graphene for metal-free catalytic oxidation, *J. Mater. Chem. A*, 2015, **3**, 3432–3440, DOI: [10.1039/C4TA05940A](https://doi.org/10.1039/C4TA05940A).

87 W. Han, X. Huang, G. Lu and Z. Tang, Research progresses in the preparation of Co-based catalyst derived from Co-MOFs and application in the catalytic oxidation reaction, *Catal. Surv. Asia*, 2019, **23**, 64–89, DOI: [10.1007/s10563-018-9258-1](https://doi.org/10.1007/s10563-018-9258-1).

88 J. Peng and S. Wang, Correlation between microstructure and performance of Pt/TiO<sub>2</sub> catalysts for formaldehyde catalytic oxidation at ambient temperature: effects of hydrogen pretreatment, *J. Phys. Chem. C*, 2007, **111**, 9897–9904, DOI: [10.1021/jp070821r](https://doi.org/10.1021/jp070821r).

89 P. Liu, G. Wei, X. Liang, D. Chen, H. He, T. Chen, Y. Xi, H. Chen, D. Han and J. Zhu, Synergetic effect of Cu and Mn oxides supported on palygorskite for the catalytic oxidation of formaldehyde: Dispersion, microstructure, and catalytic performance, *Appl. Clay Sci.*, 2018, **161**, 265–273, DOI: [10.1016/j.clay.2018.04.032](https://doi.org/10.1016/j.clay.2018.04.032).

90 Y. Shi, Z. Qiao, Z. Liu and J. Zuo, Cerium doped Pt/TiO<sub>2</sub> for catalytic oxidation of low concentration formaldehyde at room temperature, *Catal. Lett.*, 2019, **149**, 1319–1325, DOI: [10.1007/s10562-019-02684-z](https://doi.org/10.1007/s10562-019-02684-z).

91 J. Wang, J. Wang, X. Wu and G. Zhang, Pt-TiO<sub>2</sub> microspheres with exposed {001} facets for degradation of formaldehyde in air: Formation mechanism and enhanced visible light photocatalytic activity, *Mater. Res. Bull.*, 2017, **96**, 262–269, DOI: [10.1016/j.materresbull.2017.01.050](https://doi.org/10.1016/j.materresbull.2017.01.050).

92 Y. Li, C. Zhang, J. Ma, M. Chen, H. Deng and H. He, High temperature reduction dramatically promotes Pd/TiO<sub>2</sub> catalyst for ambient formaldehyde oxidation, *Appl. Catal. B: Environ.*, 2017, **217**, 560–569, DOI: [10.1016/j.apcatb.2017.06.023](https://doi.org/10.1016/j.apcatb.2017.06.023).

93 C. Li, Y. Shen, M. Jia, S. Sheng, M. O. Adebajo and H. Zhu, Catalytic combustion of formaldehyde on gold/iron-oxide catalysts, *Catal. Commun.*, 2008, **9**, 355–361, DOI: [10.1016/j.catcom.2007.06.020](https://doi.org/10.1016/j.catcom.2007.06.020).

94 B.-b. Chen, X.-b. Zhu, M. Crocker, Y. Wang and C. Shi, FeO<sub>x</sub>-supported gold catalysts for catalytic removal of formaldehyde at room temperature, *Appl. Catal. B: Environ.*, 2014, **154**, 73–81, DOI: [10.1016/j.apcatb.2014.02.009](https://doi.org/10.1016/j.apcatb.2014.02.009).

95 Y. Shen, X. Yang, Y. Wang, Y. Zhang, H. Zhu, L. Gao and M. Jia, The states of gold species in CeO<sub>2</sub> supported gold catalyst for formaldehyde oxidation, *Appl. Catal. B: Environ.*, 2008, **79**, 142–148, DOI: [10.1016/j.apcatb.2007.09.042](https://doi.org/10.1016/j.apcatb.2007.09.042).

96 S. Imamura, D. Uchihori, K. Utani and T. Ito, Oxidative decomposition of formaldehyde on silver-cerium composite oxide catalyst, *Catal. Lett.*, 1994, **24**, 377–384, DOI: [10.1007/BF00811810](https://doi.org/10.1007/BF00811810).

97 Y. Sekine, Oxidative decomposition of formaldehyde by metal oxides at room temperature, *Atmos. Environ.*, 2002, **36**, 5543–5547, DOI: [10.1016/S1352-2310\(02\)00670-2](https://doi.org/10.1016/S1352-2310(02)00670-2).

98 L. Bai, F. Wyrwalski, M. Safariamin, R. Bleta, J.-F. Lamonier, C. Przybylski, E. Monflier and A. Ponchel, Cyclodextrin-cobalt (II) molecule-ion pairs as precursors to active Co<sub>3</sub>O<sub>4</sub>/ZrO<sub>2</sub> catalysts for the complete oxidation of formaldehyde: Influence of the cobalt source, *J. Catal.*, 2016, **341**, 191–204, DOI: [10.1016/j.jcat.2016.07.006](https://doi.org/10.1016/j.jcat.2016.07.006).

99 J. Sheng, C. Li, L. Zhao, X. Du, L. Gao and G. Zeng, Efficient removal of HCHO from simulated coal combustion flue gas using CuO-CeO<sub>2</sub> supported on cylindrical activated coke, *Fuel*, 2017, **197**, 397–406, DOI: [10.1016/j.fuel.2017.02.056](https://doi.org/10.1016/j.fuel.2017.02.056).

100 X. Gao and J. Xu, A new application of clay-supported vanadium oxide catalyst to selective hydroxylation of benzene to phenol, *Appl. Clay Sci.*, 2006, **33**, 1–6, DOI: [10.1016/j.clay.2005.12.002](https://doi.org/10.1016/j.clay.2005.12.002).

101 R. Molinari, T. Poerio and P. Argurio, Liquid-phase oxidation of benzene to phenol using CuO catalytic polymeric membranes, *Desalination*, 2009, **241**, 22–28, DOI: [10.1016/j.desal.2007.11.081](https://doi.org/10.1016/j.desal.2007.11.081).

102 M.-C. Lin and J.-C. Kao, Marine environmental protection: An application of the nanometer photo catalyst method on decomposition of benzene, *Mar. Pollut. Bull.*, 2016, **105**, 139–142, DOI: [10.1016/j.marpolbul.2016.02.039](https://doi.org/10.1016/j.marpolbul.2016.02.039).

103 L. Mao, Z. Chen, X. Wu, X. Tang, S. Yao, X. Zhang, B. Jiang, J. Han, Z. Wu, H. Lu and T. Nozaki, Plasma-catalyst hybrid reactor with CeO<sub>2</sub>/γ-Al<sub>2</sub>O<sub>3</sub> for benzene decomposition with synergetic effect and nano particle by-product reduction, *J. Hazard. Mater.*, 2018, **347**, 150–159, DOI: [10.1016/j.jhazmat.2017.12.064](https://doi.org/10.1016/j.jhazmat.2017.12.064).

104 H. Sun, S. Chen, P. Wang and X. Quan, Catalytic oxidation of toluene over manganese oxide octahedral molecular sieves (OMS-2) synthesized by different methods, *Chem. Eng. J.*, 2011, **178**, 191–196, DOI: [10.1016/j.cej.2011.10.047](https://doi.org/10.1016/j.cej.2011.10.047).

105 X. Chen, X. Chen, S. Cai, E. Yu, J. Chen and H. Jia, MnO<sub>x</sub>/Cr<sub>2</sub>O<sub>3</sub> composites prepared by pyrolysis of Cr-MOF precursors containing in situ assembly of MnO<sub>x</sub> as high stable catalyst for toluene oxidation, *Appl. Surf. Sci.*, 2019, **475**, 312–324, DOI: [10.1016/j.apsusc.2018.12.277](https://doi.org/10.1016/j.apsusc.2018.12.277).

106 Y. Shan, N. Gao, Y. Chen and S. Shen, Self-template synthesis of a MnCeO<sub>8</sub>/Co<sub>3</sub>O<sub>4</sub> polyhedral nanocage catalyst for toluene oxidation, *Ind. Eng. Chem. Res.*, 2019, **58**, 16370–16378, DOI: [10.1021/acs.iecr.9b00847](https://doi.org/10.1021/acs.iecr.9b00847).

107 F. Yang, J. Zhong, X. Liu and X. Zhu, A novel catalytic alkylation process of syngas with benzene over the cerium modified platinum supported on HZSM-5 zeolite, *Appl. Energy*, 2018, **226**, 22–30, DOI: [10.1016/j.apenergy.2018.05.093](https://doi.org/10.1016/j.apenergy.2018.05.093).

108 T. K. Bedi and S. P. Bhattacharya, Chapter 13 - Indoor air quality and health: An emerging challenge in Indian



megacities, *Dev. Environ. Sci.*, 2024, **15**, 269–293, DOI: [10.1016/B978-0-443-21948-1.00013-3](https://doi.org/10.1016/B978-0-443-21948-1.00013-3).

109 S. Vitaliano, S. Cascone and P. R. D'Urso, Mitigating built environment air pollution by green systems: An in-depth review, *Appl. Sci.*, 2024, **14**, 6487, DOI: [10.3390/app14156487](https://doi.org/10.3390/app14156487).

110 R. Kumar, V. Verma, M. Thakur, G. Singh and B. Bhargava, A systematic review on mitigation of common indoor air pollutants using plant-based methods: a phytoremediation approach, *Air Qual. Atmos. Health*, 2023, **16**, 1501–1527, DOI: [10.1007/s11869-023-01326-z](https://doi.org/10.1007/s11869-023-01326-z).

111 Y. Han, J. Lee, G. Haiping, K.-H. Kim, P. Wanxi, N. Bhardwaj, J.-M. Oh and R. J. C. Brown, Plant-based remediation of air pollution: A review, *J. Environ. Manage.*, 2022, **301**, 113860, DOI: [10.1016/j.jenvman.2021.113860](https://doi.org/10.1016/j.jenvman.2021.113860).

112 M.-H. Yuan, S. Kang and K.-S. Cho, A review of phyto- and microbial-remediation of indoor volatile organic compounds, *Chemosphere*, 2024, **359**, 142120, DOI: [10.1016/j.chemosphere.2024.142120](https://doi.org/10.1016/j.chemosphere.2024.142120).

113 M. J. Kwak, J. K. Lee, S. Park, H. Kim, Y. J. Lim, K.-A. Lee, J.-a. Son, C.-Y. Oh, I. Kim and S. Y. Woo, Surface-based analysis of leaf microstructures for adsorbing and retaining capability of airborne particulate matter in ten woody species, *Forests*, 2020, **11**, 946, DOI: [10.3390/f11090946](https://doi.org/10.3390/f11090946).

114 M. Weih, Intensive short rotation forestry in boreal climates: present and future perspectives, *Can. J. Forest Res.*, 2004, **34**, 1369–1378, DOI: [10.1139/x04-090](https://doi.org/10.1139/x04-090).

115 A. Maurya, D. Sharma, M. Partap, R. Kumar and B. Bhargava, Microbially-assisted phytoremediation toward air pollutants: Current trends and future directions, *Environ. Technol. Innov.*, 2023, **31**, 103140, DOI: [10.1016/j.eti.2023.103140](https://doi.org/10.1016/j.eti.2023.103140).

116 L. Molina, R.-M. Wittich, P. van Dillewijn and A. Segura, Plant-bacteria interactions for the elimination of atmospheric contaminants in cities, *Agronomy*, 2021, **11**, 493, DOI: [10.3390/agronomy11030493](https://doi.org/10.3390/agronomy11030493).

117 Y. H. K. I. Gunasinghe, I. V. N. Rathnayake and M. P. Deeyamulla, Plant and plant associated microflora: potential bioremediation option of indoor air pollutants, *Nepal J. Biotechnol.*, 2021, **9**, 63–74, DOI: [10.3126/njb.v9i1.38669](https://doi.org/10.3126/njb.v9i1.38669).

118 H. M. Weaver-Guevara, R. W. Fitzgerald, N. A. Cote and A. Greenberg, Cytochrome P450 can epoxidize an oxepin to a reactive 2,3-epoxyoxepin intermediate: Potential insights into metabolic ring-opening of benzene, *Molecules*, 2020, **25**, 4542, DOI: [10.3390/molecules25194542](https://doi.org/10.3390/molecules25194542).

119 W. Sriprapat, P. Suksabye, S. Areephak, P. Klantup, A. Waraha, A. Sawattan and P. Thiravetyan, Uptake of toluene and ethylbenzene by plants: Removal of volatile indoor air contaminants, *Ecotoxicol. Environ. Saf.*, 2014, **102**, 147–151, DOI: [10.1016/j.ecoenv.2014.01.032](https://doi.org/10.1016/j.ecoenv.2014.01.032).

120 P. Gkorezis, M. Daghio, A. Franzetti, J. D. Van Hamme, W. Sillen and J. Vangronsveld, The interaction between plants and bacteria in the remediation of petroleum hydrocarbons: An environmental perspective, *Front. Microbiol.*, 2016, **7**, 1836, DOI: [10.3389/fmicb.2016.01836](https://doi.org/10.3389/fmicb.2016.01836).

121 D. Chen, S. Yin, X. Zhang, J. Lyu, Y. Zhang, Y. Zhu and J. Yan, A high-resolution study of PM<sub>2.5</sub> accumulation inside leaves in leaf stomata compared with non-stomatal areas using three-dimensional X-ray microscopy, *Sci. Total Environ.*, 2022, **852**, 158543, DOI: [10.1016/j.scitotenv.2022.158543](https://doi.org/10.1016/j.scitotenv.2022.158543).

122 J. Dumanović, E. Nepovimova, M. Natić, K. Kuča and V. Jaćević, The Significance of reactive oxygen species and antioxidant defense system in plants: A concise overview, *Front. Plant Sci.*, 2021, **11**, 552969, DOI: [10.3389/fpls.2020.552969](https://doi.org/10.3389/fpls.2020.552969).

123 P. Zandi and E. Schnug, Reactive oxygen species, antioxidant responses and implications from a microbial modulation perspective, *Biology*, 2022, **11**, 155, DOI: [10.3390/biology11020155](https://doi.org/10.3390/biology11020155).

124 M. Lhotská, V. Zemanová, M. Pavlík, D. Pavlíková, F. Hnilička and M. Popov, Leaf fitness and stress response after the application of contaminated soil dust particulate matter, *Sci. Rep.*, 2022, **12**, 10046, DOI: [10.1038/s41598-022-13931-6](https://doi.org/10.1038/s41598-022-13931-6).

125 C. M. F. Rosales, J. Jiang, A. Lahib, B. P. Bottorff, E. K. Reidy, V. Kumar, A. Tasoglou, H. Huber, S. Dusanter, A. Tomas, B. E. Boor and P. S. Stevens, Chemistry and human exposure implications of secondary organic aerosol production from indoor terpene ozonolysis, *Sci. Adv.*, 2022, **8**, eabj9156, DOI: [10.1126/sciadv.abj9156](https://doi.org/10.1126/sciadv.abj9156).

126 S. Matheson, R. Fleck, P. J. Iriga and F. R. Torpy, Phytoremediation for the indoor environment: a state-of-the-art review, *Rev. Environ. Sci. Biotechnol.*, 2023, **22**, 249–280, DOI: [10.1007/s11157-023-09644-5](https://doi.org/10.1007/s11157-023-09644-5).

127 P. Chatakul and S. Janpathompong, Interior plants: Trends, species, and their benefits, *Build. Environ.*, 2022, **222**, 109325, DOI: [10.1016/j.buildenv.2022.109325](https://doi.org/10.1016/j.buildenv.2022.109325).

128 K. J. Kim, M. Khalekuzzaman, J. N. Suh, H. J. Kim, C. Shagol, H.-H. Kim and H. J. Kim, Phytoremediation of volatile organic compounds by indoor plants: a review, *Hortic. Environ. Biotechnol.*, 2018, **59**, 143–157, DOI: [10.1007/s13580-018-0032-0](https://doi.org/10.1007/s13580-018-0032-0).

129 H. Teiri, Y. Hajizadeh and A. Azhdarpoor, A review of different phytoremediation methods and critical factors for purification of common indoor air pollutants: an approach with sensitive analysis, *Air Qual. Atmos. Health*, 2022, **15**, 373–391, DOI: [10.1007/s11869-021-01118-3](https://doi.org/10.1007/s11869-021-01118-3).

130 A. Sawada and T. Oyabu, Purification characteristics of pothos for airborne chemicals in growing conditions and its evaluation, *Atmos. Environ.*, 2008, **42**, 594–602, DOI: [10.1016/j.atmosenv.2007.10.028](https://doi.org/10.1016/j.atmosenv.2007.10.028).

131 M. Suzuki, H. Umeda, S. Matsuo, Y. Kawasaki, D. Ahn, H. Hamamoto and Y. Iwasaki, Effects of relative humidity and nutrient supply on growth and nutrient uptake in greenhouse tomato production, *Sci. Hortic.*, 2015, **187**, 44–49, DOI: [10.1016/j.scientia.2015.02.035](https://doi.org/10.1016/j.scientia.2015.02.035).

132 N.-X. Feng, J. Yu, H.-M. Zhao, Y.-T. Cheng, C.-H. Mo, Q.-Y. Cai, Y.-W. Li, H. Li and M.-H. Wong, Efficient phytoremediation of organic contaminants in soils using



plant-endophyte partnerships, *Sci. Total Environ.*, 2017, **583**, 352–368, DOI: [10.1016/j.scitotenv.2017.01.075](https://doi.org/10.1016/j.scitotenv.2017.01.075).

133 K. Sheoran, S. S. Siwal, D. Kapoor, N. Singh, A. K. Saini, W. F. Alsanie and V. K. Thakur, Air pollutants removal using biofiltration technique: a challenge at the frontiers of sustainable environment, *ACS Eng. Au.*, 2022, **2**, 378–396, DOI: [10.1021/acsengineeringau.2c00020](https://doi.org/10.1021/acsengineeringau.2c00020).

134 R. Tang and C. Pfrang, Indoor particulate matter (PM) from cooking in UK students' studio flats and associated intervention strategies: evaluation of cooking methods, PM concentrations and personal exposures using low-cost sensors, *Environ. Sci.: Atmos.*, 2023, **3**, 537–551, DOI: [10.1039/D2EA00171C](https://doi.org/10.1039/D2EA00171C).

135 I. Diarra, K. K. Kotra and S. Prasad, Application of phytoremediation for heavy metal contaminated sites in the South Pacific: strategies, current challenges and future prospects, *Appl. Spectrosc. Rev.*, 2021, **57**, 490–512, DOI: [10.1080/05704928.2021.1904410](https://doi.org/10.1080/05704928.2021.1904410).

136 H. Ullah, C. Treesubsuntorn and P. Thiravetyan, Enhancing mixed toluene and formaldehyde pollutant removal by *Zamioculcas zamiifolia* combined with *Sansevieria trifasciata* and its CO<sub>2</sub> emission, *Environ. Sci. Pollut. Res.*, 2021, **28**, 538–546, DOI: [10.1007/s11356-020-10342-w](https://doi.org/10.1007/s11356-020-10342-w).

137 K. Natarajan, M. P. Sugumaran, G. Porkodi, H. Kumar, S. Radhakrishnan, G. Gayathry, J. Jayakumar, K. Kalaichelvi, K. Suganya and S. Thangeswari, Screening urban tree species for air quality enhancement: A review, *Asian J. Soil Sci. Plant Nutr.*, 2024, **10**, 511–518, DOI: [10.9734/ajsspn/2024/v10i3363](https://doi.org/10.9734/ajsspn/2024/v10i3363).

138 L. Wang, H. Gong, W. Liao and Z. Wang, Accumulation of particles on the surface of leaves during leaf expansion, *Sci. Total Environ.*, 2015, **532**, 420–434, DOI: [10.1016/j.scitotenv.2015.06.014](https://doi.org/10.1016/j.scitotenv.2015.06.014).

139 Y. Shao, Y. Wang, R. Zhao, J. Chen, F. Zhang, R. J. Linhardt and W. Zhong, Biotechnology progress for removal of indoor gaseous formaldehyde, *Appl. Microbiol. Biotechnol.*, 2020, **104**, 3715–3727, DOI: [10.1007/s00253-020-10514-1](https://doi.org/10.1007/s00253-020-10514-1).

140 S. Sivasamy, S. Rajangam, T. Kanagasabai, D. Bisht, R. Prabhakaran and S. Dhandayuthapani, Biocatalytic potential of *pseudomonas* species in the degradation of polycyclic aromatic hydrocarbons, *J. Basic Microbiol.*, 2025, **65**, e2400448, DOI: [10.1002/jobm.202400448](https://doi.org/10.1002/jobm.202400448).

141 S. Bisht, P. Pandey, B. Bhargava, S. Sharma, V. Kumar and K. D. Sharma, Bioremediation of polycyclic aromatic hydrocarbons (PAHs) using rhizosphere technology, *Braz. J. Microbiol.*, 2015, **46**, 7–21, DOI: [10.1590/S1517-838246120131354](https://doi.org/10.1590/S1517-838246120131354).

142 M. S. Montaluisa-Mantilla, P. García-Encina, R. Lebrero and R. Muñoz, Botanical filters for the abatement of indoor air pollutants, *Chemosphere*, 2023, **345**, 140483, DOI: [10.1016/j.chemosphere.2023.140483](https://doi.org/10.1016/j.chemosphere.2023.140483).

143 K. J. Kim, M. I. Jeong, D. W. Lee, J. S. Song, H. D. Kim, E. H. Yoo, S. J. Jeong, S. W. Han, S. J. Kays, Y. Lim and H. Kim, Variation in formaldehyde removal efficiency among indoor plant species, *HortScience*, 2010, **45**, 1489–1495, DOI: [10.21273/HORTSCI.45.10.1489](https://doi.org/10.21273/HORTSCI.45.10.1489).

144 S. Matheson, R. Fleck, P. J. Iriga and F. R. Torpy, Phytoremediation for the indoor environment: a state-of-the-art review, *Rev. Environ. Sci. Biotechnol.*, 2023, **22**, 249–280, DOI: [10.1007/s11157-023-09644-5](https://doi.org/10.1007/s11157-023-09644-5).

145 M. Dela Cruz, R. Müller, B. Svensmark, J. S. Pedersen and J. H. Christensen, Assessment of volatile organic compound removal by indoor plants-a novel experimental setup, *Environ. Sci. Pollut. Res.*, 2014, **21**, 7838–7846, DOI: [10.1007/s11356-014-2695-0](https://doi.org/10.1007/s11356-014-2695-0).

146 M. Dela Cruz, J. H. Christensen, J. D. Thomsen and R. Müller, Can ornamental potted plants remove volatile organic compounds from indoor air? - a review, *Environ. Sci. Pollut. Res.*, 2014, **21**, 13909–13928, DOI: [10.1007/s11356-014-3240-x](https://doi.org/10.1007/s11356-014-3240-x).

147 C. M. F. Rosales, E. G. Tamayo, D. L. Babela and M. P. Benjamin, Indoor penetration of ambient particulate pollution in a hospital maternity ward in Manila, Philippines: perspectives towards holistic city-level air quality management, *Environ. Sci.: Atmos.*, 2025, **5**, 563–573, DOI: [10.1039/D4EA00160E](https://doi.org/10.1039/D4EA00160E).

148 A. Mazzeo, C. Pfrang and Z. A. Nasir, Towards developing an indoor emissions inventory for the UK: challenges and future directions, *Environ. Sci.: Atmos.*, 2025, **5**, 151–170, DOI: [10.1039/D4EA00121D](https://doi.org/10.1039/D4EA00121D).

149 P. Sheehan, A. Singhal, K. T. Bogen, D. MacIntosh, R. M. Kalmes and J. McCarthy, Potential exposure and cancer risk from formaldehyde emissions from installed Chinese manufactured laminate flooring, *Risk Anal.*, 2018, **38**, 1128–1142, DOI: [10.1111/risa.12926](https://doi.org/10.1111/risa.12926).

150 A. Talaiekhozani, S. Rezania, K.-H. Kim, R. Sanaye and A. M. Amani, Recent advances in photocatalytic removal of organic and inorganic pollutants in air, *J. Clean. Prod.*, 2021, **278**, 123895, DOI: [10.1016/j.jclepro.2020.123895](https://doi.org/10.1016/j.jclepro.2020.123895).

151 A. Jarrahi, A. Aflaki, M. Khakpour and M. Esfandiari, Enhancing indoor air quality: Harnessing architectural elements, natural ventilation and passive design strategies for effective pollution reduction - A comprehensive review, *Sci. Total Environ.*, 2024, **954**, 176631, DOI: [10.1016/j.scitotenv.2024.176631](https://doi.org/10.1016/j.scitotenv.2024.176631).

152 R. Shi, X. Zhang, G. I. N. Waterhouse, Y. Zhao and T. Zhang, The journey toward low temperature, low pressure catalytic nitrogen fixation, *Adv. Energy Mater.*, 2020, **10**, 2000659, DOI: [10.1002/aenm.202000659](https://doi.org/10.1002/aenm.202000659).

153 J. Xu, Y. Bian, W. Tian, C. Pan, C.-e. Wu, L. Xu, M. Wu and M. Chen, The structures and compositions design of the hollow micro-nano-structured metal oxides for environmental catalysis, *Nanomaterials*, 2024, **14**, 1190, DOI: [10.3390/nano14141190](https://doi.org/10.3390/nano14141190).

154 A. James, E. R. Rene, A. M. Bilyaminu and P. V. Chellam, Advances in amelioration of air pollution using plants and associated microbes: An outlook on phytoremediation and other plant-based technologies, *Chemosphere*, 2024, **358**, 142182, DOI: [10.1016/j.chemosphere.2024.142182](https://doi.org/10.1016/j.chemosphere.2024.142182).

155 N. Liu, J. Zhao, J. Du, C. Hou, X. Zhou, J. Chen and Y. Zhang, Non-phytoremediation and phytoremediation technologies of integrated remediation for water and soil



heavy metal pollution: A comprehensive review, *Sci. Total Environ.*, 2024, **948**, 174237, DOI: [10.1016/j.scitotenv.2024.174237](https://doi.org/10.1016/j.scitotenv.2024.174237).

156 K. Kujundzic, S. Stamatovic Vuckovic and A. Radivojević, Toward regenerative sustainability: A passive design comfort assessment method of indoor environment, *Sustainability*, 2023, **15**, 840, DOI: [10.3390/su15010840](https://doi.org/10.3390/su15010840).

157 T. M. Mata, A. A. Martins, C. S. C. Calheiros, F. Villanueva, N. P. Alonso-Cuevilla, M. F. Gabriel and G. V. Silva, Indoor air quality: A review of cleaning technologies, *Environments*, 2022, **9**, 118, DOI: [10.3390/environments9090118](https://doi.org/10.3390/environments9090118).

158 I. L. Niza, A. M. Bueno, M. G. da Silva and E. E. Broday, Air quality and ventilation: Exploring solutions for healthy and sustainable urban environments in times of climate change, *Results Eng.*, 2024, **24**, 103157, DOI: [10.1016/j.rineng.2024.103157](https://doi.org/10.1016/j.rineng.2024.103157).

159 Z. Li, Y. Li, S. Li, J. Ma, Q. Ma, Z. Wang, J. Wang, K. Long and X. Liu, Enhanced and sustainable removal of indoor formaldehyde by naturally porous bamboo activated carbon supported with  $MnO_x$ : Synergistic effect of adsorption and oxidation, *Molecules*, 2024, **29**, 663, DOI: [10.3390/molecules29030663](https://doi.org/10.3390/molecules29030663).

160 Z. Liu, T. Lu and Q. Chen, Intermolecular interaction characteristics of the all-carboatomic ring, cyclo[18]carbon: Focusing on molecular adsorption and stacking, *Carbon*, 2021, **171**, 514–523, DOI: [10.1016/j.carbon.2020.09.048](https://doi.org/10.1016/j.carbon.2020.09.048).

161 C. K. Law, J. H. K. Lai, X. D. Ma and G. N. Sze-To, Enhancing indoor air quality: Examination of formaldehyde adsorption efficiency of portable air cleaner fitted with chemically-treated activated carbon filters, *Build. Environ.*, 2024, **263**, 111823, DOI: [10.1016/j.buildenv.2024.111823](https://doi.org/10.1016/j.buildenv.2024.111823).

162 Y.-S. Kim, H.-G. Kim, L.-K. Kwac and S.-C. Ko, A study on the improvement of filter performance to remove indoor air pollution, *Appl. Sci.*, 2023, **13**, 2561, DOI: [10.3390/app13042561](https://doi.org/10.3390/app13042561).

163 J. Jiang, J. Liu, C. Wang, Y. Yin, J. Pei, Y. Gao, Y. Wang, O. Hyun and H. Park, Exploring the long-term performance of air purifiers in removing particulate matter and formaldehyde across different residential environments, *Environ. Res.*, 2024, **263**, 120194, DOI: [10.1016/j.envres.2024.120194](https://doi.org/10.1016/j.envres.2024.120194).

164 Y. Nosaka and A. Y. Nosaka, Generation and detection of reactive oxygen species in photocatalysis, *Chem. Rev.*, 2017, **117**, 11302–11336, DOI: [10.1021/acs.chemrev.7b00161](https://doi.org/10.1021/acs.chemrev.7b00161).

165 S. K. Sahu, A. Palai and D. Sahu, Photocatalytic applications of metal oxide-based nanocomposites for sustainable environmental remediation, *Sustain. Chem. Environ.*, 2024, **8**, 100162, DOI: [10.1016/j.scen.2024.100162](https://doi.org/10.1016/j.scen.2024.100162).

166 C. Dong, W. Fang, Q. Yi and J. Zhang, A comprehensive review on reactive oxygen species (ROS) in advanced oxidation processes (AOPs), *Chemosphere*, 2022, **308**, 136205, DOI: [10.1016/j.chemosphere.2022.136205](https://doi.org/10.1016/j.chemosphere.2022.136205).

167 F. He, W. Jeon and W. Choi, Photocatalytic air purification mimicking the self-cleaning process of the atmosphere, *Nat. Commun.*, 2021, **12**, 2528, DOI: [10.1038/s41467-021-22839-0](https://doi.org/10.1038/s41467-021-22839-0).

168 S. Pal, A. Kaitheri, S. K. Padmanabhan, M. Catalano, S. Perbonid and A. Licciullia,  $WO_3/Pt$  photocatalyst supported by a ceramic filter for indoor air purification under visible light irradiation, *Environ. Sci.:Adv.*, 2024, **3**, 1775–1787, DOI: [10.1039/D4VA00188E](https://doi.org/10.1039/D4VA00188E).

169 R. Kumar, V. Verma, M. Thakur, G. Singh and B. Bhargava, A systematic review on mitigation of common indoor air pollutants using plant-based methods: a phytoremediation approach, *Air Qual. Atmos. Health*, 2023, **16**, 1501–1527, DOI: [10.1007/s11869-023-01326-z](https://doi.org/10.1007/s11869-023-01326-z).

170 K. T. Han and L. W. Ruan, Effects of indoor plants on air quality: a systematic review, *Environ. Sci. Pollut. Res. Int.*, 2020, **27**, 16019–16051, DOI: [10.1007/s11356-020-08174-9](https://doi.org/10.1007/s11356-020-08174-9).

171 Y. Pan, J. Zheng, F. Fang, F. Liang, M. Yang, L. Tong and H. Xiao, Unveiling  $PM_{2.5}$  transport pathways: A trajectory-channel model framework for spatiotemporally quantitative source apportionment, *Atmosphere*, 2025, **16**, 883, DOI: [10.3390/atmos16070883](https://doi.org/10.3390/atmos16070883).

172 B. Bhargava, S. Malhotra, A. Chandel, A. Rakwal, R. R. Kashwari and S. Kumar, Mitigation of indoor air pollutants using Areca palm potted plants in real-life settings, *Environ. Sci. Pollut. Res. Int.*, 2021, **28**, 8898–8906, DOI: [10.1007/s11356-020-11177-1](https://doi.org/10.1007/s11356-020-11177-1).

173 H.-T. Bui, J. Park, E. Lee, W. Cho, H. Kwon and B.-J. Park, Assessment of the air cleaning performance and humidity and temperature control by five evergreen woody plants, *Atmosphere*, 2023, **14**, 1819, DOI: [10.3390/atmos14121819](https://doi.org/10.3390/atmos14121819).

