- Effects of gas phase composition on competitive adsorption properties of formaldehyde on titanium
 dioxide-supported platinum in single and mixture compositions
- 3

Yongbiao Hua^a, Swati Verma^a, Sherif A. Younis^{a,b}, Philippe M. Heynderickx^{c,d}, Ki-Hyun Kim^{a,*}

- ^a Department of Civil and Environmental Engineering, Hanyang University, 222 Wangsimni-Ro, Seoul 04763, Republic of Korea; ^b Analysis and Evaluation Department, Egyptian Petroleum Research Institute (EPRI), Nasr City, Cairo 11727, Egypt; ^c Center for Environmental and Energy Research (CEER) –
 ^g Engineering of Materials via Catalysis and Characterization, Ghent University Global Campus, 119-5
 <sup>songdomunhwa-Ro, Yeonsu-Gu, Incheon, 406-840 South Korea; ^d Department of Green Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, Ghent, B-9000, Belgium
 </sup>
- 13

14 * Corresponding author: <u>kkim61@hanyang.ac.kr</u> (K.-H.K.)

15

16 Abstract

17 Titanium dioxide-supported platinum (Pt@TiO₂) is regarded as a highly efficient catalyst to degrade various 18 volatile organic compounds (VOCs). To learn more about the hybrid adsorption/catalysis process of Pt@TiO₂, the adsorption behavior of FA onto Pt@TiO₂ was studied both as single and as multicomponent 19 20 phases (FA plus four aromatic compounds of benzene, toluene, m-xylene, and styrene (BTXS) through the 21 control of key process variables (e.g., VOCs concentration, relative humidity (RH) levels, and dosage). Moreover, the adsorption performance of Pt@TiO₂ against FA was evaluated in terms of key performance 22 metrics such as breakthrough volume (BTV), partition coefficient (PC), and adsorption capacity (Q). The 23 doping of TiO₂ with Pt metal ions was demonstrated as an efficient option to enhance the FA adsorption 24 capacity (e.g., by 50% higher than pristine TiO₂) with increased OH (O_{II}) surface active sites and surface 25 26 porosity. However, the co-presence of BTXS and water vapor greatly reduced its adsorption affinity for FA vapor (e.g., by 2 to 3 folds of magnitude) due to their competitive inhibition on the adsorption interaction. 27 According to the kinetic and isotherms analysis, a complex, multilayered physicochemical process appears 28

29	to govern the overall adsorption of FA molecules onto Pt@TiO ₂ surface. Overall, the outcomes of this work
30	are helpful to verify the enhanced removal potential of Pt@TiO2 against FA through sequential adsorption
31	and catalytic reaction mechanisms.
32	
33	Keywords: Titanium oxide (TiO ₂): Platinum metal catalyst: Volatile organic compounds (VOCs):
34	Gaseous formaldehyde: Adsorption mechanism
35	
36	
37	
38	
39	
40	
41	
42	
43	
44	
45 46	
47	
48	
49	
50	
51	
52	
53	
54	
55	
50 57	
58	
59	
60	
61	
62	
63	
64	
65	
66 07	
0/ 69	
00	

70 Abbreviations

В	Benzene
BTV	Breakthrough volume
BT	Breakthrough
BET	Brunauer-Emmet-Teller
ВЈН	Barrett - Joyner - Halenda
BE	Binding energies
CE	Ethylenediamine functionalized covalent organic polymers
DI	Deionized
EDS	Energy dispersive spectrometry
FA	Formaldehyde
FESEM	Field-emission scanning electron microscope
GPS	Gaseous primary standard
GWS	Gaseous working standards
GC-FID	Gas chromatography-flame ionization detector
ICP-OES	Inductively coupled plasma optical emission spectrometry
IPD	Intraparticle diffusion
LVI	Large volume injection
MDL	Method detection limit
MOF	Metal organic framework
OV	Oxygen vacancies
Pt@TiO ₂	Titanium dioxide-supported platinum
PXRD	Powder X-ray diffractometer
PEA	Polyester aluminum
PFO	Pseudo-first-order
PSO	Pseudo-second-order
PC	Partition coefficient
PPCPs	Pharmaceuticals and personal care products
Q	Adsorption capacity
RH	Relative humidity
RSE	Relative standard error
S	Styrene
Т	Toluene
VOCs	Volatile organic compounds
Х	M-xylene
XPS	X-ray photoelectron spectroscopy
χ^2	Chi-squared value
R ²	Correlation coefficient of determination

73 1. Introduction

Air pollution control, especially the emission of volatile organic compounds (VOCs), has attracted great 74 attention in recent years with the growing recognition of their detrimental effects on climate (e.g., key 75 precursors of ozone formation) and human health (Bai et al., 2023; Liu et al., 2023). Among the many 76 VOCs, formaldehyde (FA) is identified as one of the most hazardous VOCs with high toxicity (gene 77 mutation) upon direct contact with skin (i.e., allergic dermatitis, spots, and necrosis) (Lou et al., 2022) or if 78 exposed for long durations (Bellat et al., 2015; Zhang, 2018). Various sources contribute to the emission of 79 FA in indoor air such as anthropogenic activities (e.g., cooking or smoking) and building and furnishing 80 materials (e.g., glue, varnishes, plastic castings, rubber, and wooden furniture) (Salthammer et al., 2010). 81 As people spend more of their time indoors, proper control of FA levels in indoor air is necessary to avoid 82 83 adverse effects on human health.

84 To date, various methods have been developed and introduced to remove VOCs from indoor air such as thermal catalysis (Zhang et al., 2017), photocatalysis (Na et al., 2019; Liu et al., 2022a), spray tower-85 86 photocatalysis technique (Chen et al., 2017b), biological/botanical filtration (Wang et al., 2014), and adsorption (Robert and Nallathambi, 2021). Among these methods, adsorption is a cost-effective method 87 for the removal of toxic VOCs form air due to its multiple advantages (e.g., facile operation, low energy 88 consumption, good regeneration/reuse cycle feasibility, and high adaptability) (Dutta et al., 2019; González 89 90 et al., 2019; Khan et al., 2019; Vikrant et al., 2020a). However, a plethora of VOCs (such as aromatic hydrocarbons (e.g., BTXS) and aldehydes (FA)) exist together in the indoor air environment in residential 91 complexes and offices (Guo et al., 2004; Gallego et al., 2009). Hence, it is highly desirable to develop 92 advanced adsorbent materials that can treat VOCs with diverse properties for proper control of air quality. 93 Recently, numerous types of advanced adsorbent materials (such as biochar, activated carbon, and metal 94

95 oxides) have been developed for the removal of environmental pollutants (e.g., pharmaceuticals, heavy metals, and VOCs) (Wang et al., 2020; Xiang et al., 2020; Zhu et al., 2022). The utility of various metal 96 oxides (e.g., TiO₂, Fe₂O₃, Al₂O₃, MnO₂, ZnO, and ZrO₂) has been recognized due to their great capturing 97 potential of VOCs (e.g., high thermo-chemical stability and abundant surface-active sites for 98 adsorption)(Batault et al., 2015; Wang et al., 2020). Among them, titanium dioxide (TiO₂)-based materials 99 (e.g., TiO₂/graphene, TiO₂/SiO₂, Cu/TiO₂ and TiO₂ hollow sphere) have been used broadly for the catalytic 100 oxidation of environmental pollutants (e.g., VOCs and CO) due to their high photoactivity, chemical 101 stability, and redox potential (Chen et al., 2011; Chen et al., 2013; Dong et al., 2015; Chen et al., 2021; 102 103 Khan et al., 2021). For instance, the Cu/TiO₂ showcased good CO catalytic oxidation ability with the aid of its high dispersion of Cu species, large surface area, and abundant active sites (Khan et al., 2021). 104 However, the indigent adsorption capacity of TiO₂ for polar and nonpolar VOCs was one of the main 105 reasons for its lower catalytic performance in both laboratory and industry (Shayegan et al., 2018a). It 106 should be noted that the adsorption process is an essential step in the activation of VOC molecules on the 107 surface active sites, as photogenerated radicals could oxidize only surface-bound molecules during the 108 heterogeneous catalytic reaction. Therefore, various modification strategies were pursued to enhance the 109 110 adsorption of VOCs on the surface of TiO₂ to promote its adsorption/catalytic performance (Shayegan et al., 2018a). In this respect, doping TiO₂ with Pt nanoparticles (Pt@TiO₂) is a highly effective modification 111 strategy to accelerate the catalytic oxidation of VOCs (e.g., benzene, cyclohexane, and m-xylene). As such, 112 113 the high catalytic reactivity of Pt active sites provide an electron reservoir to accelerate the catalytic reaction with adsorbed molecules (Korologos et al., 2012; Murcia et al., 2013; Shayegan et al., 2018b). In another 114 study, doping Pt catalyst on the TiO₂ support was also reported to generate surface defects and oxygen 115 vacancies (OV) (Xiao et al., 2020). Such defects of TiO₂ could cause strong electronic modification of the 116

117 Pt catalyst, leading to an increase in its adsorption strength against VOCs (e.g., CO) (Xiao et al., 2020).

Due to heterogeneous catalytic reactions, the face defects and OV sites of catalysts help promote 118 photo/thermal catalytic reactivity for various target species (Xiao et al., 2020; Khan et al., 2023). It is also 119 well known that the role of adsorption is particularly critical in the advanced heterogeneous oxidation 120 process for VOC treatment (Batault et al., 2015; Thevenet et al., 2015). To date, Pt@TiO₂ has been 121 employed broadly for catalytic degradation of VOCs (e.g., BTX) at room temperature (Liu et al., 2022b; 122 Zhang et al., 2022a; Zhang et al., 2022b). However, relatively little is known about its adsorption behavior 123 while being commonly employed for the sequential adsorption and catalytic treatment of air streams laden 124 125 with polar and non-polar VOC pollutants. Accordingly, it would be of significant interest to study the effects of metallic Pt active sites doped onto TiO₂ surfaces with respect to their adsorption capacities against 126 different types of target gas compositions such as FA only (as aldehyde VOCs) and their mixture with other 127 common VOCs (i.e., in the presence of non-polar aromatic VOCs like BTXS). 128

In this study, the adsorption of Pt@TiO₂ (relative to pure TiO₂) was investigated towards the dynamic 129 removal of FA vapor under controlled process variables (e.g., adsorbent mass, inlet vapor concentration, 130 and relative humidity (RH) levels). To simulate the complex composition of VOCs (e.g., mixture) under 131 132 real-world conditions, the competitive adsorption breakthrough (BT) profile of VOCs onto Pt@TiO₂ was studied by comparing (i) a gas stream laden with FA (as model target VOC pollutants) only and (ii) a multi-133 component system of FA plus BTXS. Various kinetic (e.g., pseudo-first-order, pseudo-second-order, and 134 135 intraparticle diffusion models) and isotherm models (e.g., Freundlich, Temkin, and Langmuir models) were also used account for the BT adsorption data and the associated adsorption mechanism of target VOCs on 136 the Pt@TiO₂ adsorbent. Furthermore, the adsorption performances of Pt@TiO₂ were assessed and 137 compared with pure TiO₂ in terms of the key performance metrics (e.g., PC, BTV, and adsorption capacity 138

(Q)). As such, this study is expected to offer valuable insights into the basic removal mechanism of
Pt@TiO₂ in the sequential adsorption and catalysis reactions of FA between single and multicomponent
VOC systems.

142

143 2. Materials and methods

144 **2.1 Materials and chemicals**

All chemicals (such as chloroplatinic acid hexahydrate (H₂PtCl₆·6H₂O; \geq 37.5% Pt basis), paraformaldehyde (pFA (HO(CH₂O)_nH); 95%), TiO₂ (P25) nanopowder (~21 nm, \geq 99.5% trace metal basis)) and liquid analytical reagents (e.g., benzene (B), toluene (T), m-xylene (X), and styrene (S)) were purchased from Sigma-Aldrich (USA). Nitrogen (N₂; 99.999%) cylinders were procured from Union Gas Co., Ltd. (Yong-in, Republic of Korea). All synthesis experiments related to material preparation were carried out in deionized (DI) water.

151

152 2.2 Preparation of Pt@TiO₂

The Pt@TiO₂ was prepared by a facile wet impregnation method (Kim et al., 2021a). In this procedure, TiO₂ nanopowder (500 mg) was suspended in an aqueous platinum (Pt, 1% wt./wt.) solution (19 mg of H₂PtCl₆·6H₂O in 100 mL DI) under continuous stirring for 24 h at room temperature. The obtained suspension was left for evaporation and drying at 100°C for 12 h. Then, Pt@TiO₂ adsorbent (Pt = $1\%_{wt./wt.}$) was finally obtained via annealing the above dried powder at 450°C for 3 h under ambient air in a muffle furnace. Pure TiO₂ (as a pristine adsorbent) was thermally treated in the same way to assess the role of doped platinum in the adsorption of VOCs.

161 **2.3 Characterization**

A powder X-ray diffractometer (PXRD) (MiniFlex600, Rigaku co., Japan) was employed to analyze 162 the crystal phase of the as-prepared materials. Surface morphology and elemental composition of Pt@TiO₂ 163 were evaluated using the field-emission scanning electron microscope coupled with energy dispersive 164 165 spectrometry (FESEM-EDS: Nova Nano SEM 450; FEI Co., USA), X-ray photoelectron spectroscopy (XPS: K-alpha TM system, ThermoFisher Scientific Co., USA), and inductively coupled plasma optical 166 emission spectrometry (ICP-OES: SPECTRO ARCOS, SPECTRO Analytical Instruments Co., 167 Germany). The textural features (i.e., surface area, pore volume, and surface pore size) were measured by 168 recording N₂ adsorption-desorption isotherms at 77K (3Flex, Micromeritics Instruments Co., USA), 169 following Brunauer-Emmet-Teller (BET) and Barrett - Joyner - Halenda (BJH) methods. 170

171

172 **2.4 Adsorption experimental procedures**

173 2.4.1. Preparation of single and multicomponent VOCs gaseous working standards

A fresh gaseous primary standard (GPS) of FA was prepared by the thermal cracking paraformaldehyde 174 at 130°C in the presence of N₂ (99.99%) flow as an inert gas carrier by following the procedure of our 175 176 previous study (Vikrant et al., 2023). The individual GPS of B, T, X, or S (each ~1000 ppm = 100 Pa) were prepared by injecting a certain volume of their liquid reagents into a separate 10 L polyester aluminum 177 (PEA) (Top trading Eng., Korea) bag with N₂ gas (99.99%) and then kept further at ambient conditions for 178 179 24 h to achieve diffusion equilibrium. The pre-prepared GPS of B, T, X, S, and FA were used to prepare a single and multicomponent gaseous working standards (GWS; 50 L PEA bags) of B, T, X, and S (BTXS: 180 at 0.5, 1, 5, 10, and 14 ppm each) with FA at different concentration levels (e.g., 25, 50, 250, 500, and 700 181 ppm). The dry GWS samples (at RH= 0%) were prepared by diluting the respective GPS to the desired 182

concentration with N₂ gas. To assess the humidity effect, the humidified GWS samples (e.g., at RH = 20, 50, 80, and 100%) were obtained through injecting 230, 575, 920, and 1150 μ L of DI water into the corresponding PEA bags (50 L) filled with the gaseous VOCs (single or mixed) at a pre-determined concentration level. The humidified PEA bags containing target VOCs were then stored overnight under ambient conditions to ensure the complete volatilization/vaporization and equilibration of humidified components before the adsorption experiments (Liu et al., 2021b).

189

190 **2.4.2.** Adsorption study

191 For the adsorption study, packed-bed adsorbent tubes were prepared by packing Pt@TiO₂ (10, 20, and 40 mg) into quartz tubes (90 mm length × 4 mm inner diameter × 1 mm thickness) containing quartz wools 192 (5 mg) at both ends to secure the adsorbent. The prepared packed-bed adsorbent tubes were thermally 193 conditioned (CT2000 Tube Cleaner) at 150°C for 2 h under N₂ (99.999%) flow (200 mL min⁻¹) to remove 194 possibly adsorbed moisture and atmospheric gases on the adsorbent surface. For the adsorption study, a 195 packed-bed adsorbent tube covered by aluminum foil was placed in between the GWS bags and a large 196 volume injection (LVI: 315 mL min⁻¹), which was attached to an online gas chromatography-flame 197 198 ionization detector (GC-FID; Shimadzu Model GC-2010, Japan), as shown in Fig. 1. During the experiments, the LVI system pulls the VOCs gaseous streams (single or mixed) from the dry and humidified 199 GWS bags through the adsorbent material, while the effluent gas (treated stream) was simultaneously 200 201 analyzed using the GC-FID system. The detailed operations and parameters used for VOC analysis using the LVI-GC-FID system are listed in Table S1. 202

203 2.4.3 Regeneration/ reusability study

204 The ability of Pt@TiO₂ adsorbent to be regenerated and reused for adsorption removal of VOCs

multiple cycles is important from a practical perspective. Accordingly, the spent Pt@TiO₂ adsorbent
collected after the VOCs adsorption process was subjected to thermal regeneration at 150°C for 2 h under
N₂ gas flow (200 mL/min). The regenerated Pt@TiO₂ (20 mg) was tested again to remove 50 ppm FA vapor
in single and multicomponent VOC-laden (e.g., in the presence of diluted BTXS vapors, at 1 ppm each)
dry gas (i.e., at 0% RH level).

210

211 2.5 Data analysis

In this work, the basic quality assurance and quality control parameters (e.g., method detection limit (MDL) and relative standard error (RSE)) for the GC-FID system were determined based on the fixed standard volume method (Ha et al., 2021; Liu et al., 2021a). Using the data obtained from seven consecutive runs, the MDL values for B, T, X, S, and FA by the GC-FID analysis were 0.01, 0.04, 0.03, 0.03, and 1.76 ng, respectively. Similarly, based on three experiment runs, their RSE values were 0.25, 0.12, 0.48, 0.20, and 0.50%, respectively.

Several adsorption performance metrics were also computed to evaluate the affinity of $Pt@TiO_2$ for VOC removal, including breakthrough (BT: C_{out}/C_{in} , Eq. 1) ratio, BT volume (BTV: L atm g⁻¹, Eq. 2), adsorption capacity (Q: mg/g, Eq. 3), and partition coefficient (PC: mol kg⁻¹Pa⁻¹, Eq. 4) (Vikrant et al., 2020c; Wang et al., 2023).

222
$$\frac{C_{out}}{C_{in}} = \frac{[(outet \quad conc \ entration \quad)_n + (outet \quad concentration \quad)_{n-1}]/2}{intet \quad concentration}$$
(1)
223
$$BTV = \frac{\mathbb{E} \Delta V_n}{M}$$
(2)

where C_{out} and C_n are the outlet and inlet concentrations of target VOCs. C_{out}/C_n is obtained by considering the average value of the outlet concentrations of target VOCs for the *n*-1 run and *n* run and further normalized by the inlet concentration. $\Box \Delta V_n$ stands for the loaded G-WS volume (L) during the adsorption process.

228
$$Q = \frac{\mathbb{Z}_{i=0}^{m} \Delta m_{n}}{M}$$
(3)

229 Based on the determined Q values, the PC metric was calculated as follows:

$$PC = \frac{Q}{P_{out}*M_w} \tag{4}$$

Where M (g) stands for the adsorbent mass, while $\mathbb{Z}_{i=0}^{m} \Delta m_{n}$ represents the total mass of adsorbed VOCs (mg) vapor during adsorption. P_{out} is the outlet partial pressure (Pa). M_{w} is molecular weight (g/mol) of target VOCs.

Pseudo-first-order (PFO, Eq. 5), pseudo-second-order (PSO, Eq. 6), and intraparticle diffusion (IPD,
Eq. 7) models (Liu et al., 2021a; Wang et al., 2022) were utilized to study the rate-controlling adsorption
mechanism for Pt@TiO₂ against FA in single and multicomponent VOCs systems.

237
$$q_t = q_e(1 - e^{-k_1 t})$$
(5)

238
$$q_t = \frac{k_2 q_e^2 t}{1 + k_2 q_e t}$$
(6)

239
$$q_t = k_i t^{0.5} + C$$

Here, the $q_e (mg g^{-1})$ and $q_t (mg g^{-1})$ represent the equilibrium adsorption capacities at equilibrium (BT=100%) and varying BT time (t, min), respectively. The k_1 (min⁻¹) is the for PFO models. k_2 (g mg⁻¹ min⁻¹) is the kinetic rate constants for PSO models. In the IPD model, k_i (mg g⁻¹ min^{-0.5}) and C, stand for the diffusion rate constant and boundary layer thickness, respectively.

(7)

To investigate the adsorption mechanism of Pt@TiO₂ against FA between single and mixed phases,
the adsorption isotherm of FA was analyzed by non-linear expressions of Freundlich (Eq. 8), Temkin (Eq.
9), and Langmuir (Eq. 10) isotherm models(Wang et al., 2018; Tran et al., 2022).

247
$$q_e = K_F P^{1/n}$$
 (8)

$$q_e = Bh \ (A * P) \qquad (9)$$

$$q_e = \frac{q_m K_L P}{1 + K_L} \tag{10}$$

where $q_e (mg g^{-1})$ and P (Pa) are the equilibrium adsorption capacity and the partial pressure of target VOC vapor, respectively. $K_F (mg g^{-1} Pg^{-(1/n)})$ and *n* are the Freundlich constants related to the adsorption intensity and surface heterogeneity, respectively, depending on the nature of the adsorbent at a given temperature. The B and A Temkin isotherm constants represent the adsorption heat (J mol⁻¹) and maximum binding energy (L g^{-1}) of target VOCs on the surface of Pt@TiO₂, respectively. For the Langmuir model, the $q_m (mg g^{-1})$ represents the maximum theoretical adsorption capacity with monolayer coverage, while K_L (Pa⁻¹) indicates the extent of interactions between VOC adsorbates and the Pt@TiO₂ surface.

The fitting adequacy of isotherm and kinetic models to the obtained adsorption capacity data of FA over Pt@TiO₂ adsorbent was evaluated based on the error analysis between the experimental and theoretical data obtained from the applied models using the reduced chi-squared value (χ^2 , Eq. 11) and the correlation coefficient of determination (R², Eq. 12) formula (Aykın-Dinçer and Erbaş, 2018).

262
$$x^2 = \frac{\mathbb{Z}(Q_e - Q_m)^2}{n - z}$$
 (11)

263
$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}}$$
 (12)

264
$$SS_{res} = \mathbb{P}(Q_{exp} - Q_{at})^2$$
(13)

265
$$S_{tot} = \mathbb{Z}(Q_{exp} - Q_{m ean})^2$$
(14)

where *n* is the number of observations, and z is the number of constants in the model. For the R^2 determination, the SS_{res} and SS_{tot} represent the residual sum of square errors (Eq. 13) and the total sum of square errors (Eq. 14) between experimental and theoretical adsorption capacities, respectively. The Q_{exp}, Q_{calc}, and Q_{mean} (mg g⁻¹) are the experimental, theoretical, and mean experimental adsorption capacities, respectively.

271 3. Results and discussion

272 **3.1** Physicochemical characteristics of Pt@TiO₂ adsorbent

The PXRD data obtained from Pt@TiO₂ and pristine TiO₂ (P25) are shown in Fig. 2(a). As can be 273 seen, the PXRD pattern of Pt@TiO₂ was similar to that of TiO₂ (P25), with major characteristic peaks at 274 2 Θ = 25.4°, 38.1°, 48.3°, 54.2°, 55.2°, 62.9°, 69.1°, 70.5°, and 75.3°. These diffraction peaks correspond to 275 the (101), (004), (200), (105), (211), (204), (116), (220), and (215) lattice planes of TiO₂ anatase phase 276 (JCPDS Card No. 21-1272), respectively (Lee et al., 2021). Note that the Pt@TiO₂ showed no characteristic 277 diffraction peaks for doped Pt active sites (e.g., 39.2° (111) and 45.7° (200)) due to the low concentration 278 (1%wt./wt.) and uniform dispersion of Pt species on the surface of TiO₂ particles, as verified by the FE-279 SEM (Fig. S1) (Guo et al., 2019). The FE-SEM analysis with the corresponding EDS mapping images (Fig. 280 S1 a-f) for Pt@TiO₂ (in reference to pristine TiO₂) revealed that the Pt species were deposited uniformly 281 throughout the TiO₂ surface without altering its spherical morphology (Chen et al., 2007). 282 Debye-Scherrer formula $(D_{hkl} = 0.9\lambda/B_{hkl}Cos\theta)$ was used to determine the alteration in the 283

crystallite size of TiO₂ after Pt impregnation (Pt@TiO₂), where D_{hkl} is crystallite size in the direction 284 perpendicular to the lattice planes, λ (= 1.54 Å) is the wavelength of the X-ray source used, B_{hkl} is the full 285 width at half maximum of the diffraction peak at the (101) lattice plane, and θ is diffraction angle 286 287 (Holzwarth and Gibson, 2011). From the PXRD pattern (Fig. 2a), the crystallite sizes of pure TiO₂ and Pt@TiO2 were estimated to be 22.4 and 20.0 nm, respectively. Such a slight decrease in the crystallite size 288 of Pt@TiO₂ implies a decrease in the anatase phase crystallinity after Pt doping to reflect the stress 289 generated in the TiO₂ lattice as a result of the discrepancy between Ti and Pt ionic radii (Ti⁴⁺_{ionic radius} = 0. 290 $61 \text{ Å}, \text{Pt}^{2+}_{\text{ionic radius}} = 0.80 \text{ Å}, \text{ and } \text{Pt}^{4+}_{\text{ionic radius}} = 0.65 \text{ Å}) (\text{Ahrens, 1952; Li and Li, 2002; Aboud et al., 2019}).$ 291 From the ICP-OES analysis, the Pt content (wt.%) in Pt@TiO₂ was 1.21%, which agrees with the theoretical 292

293 prediction of 1%. These above findings confirm the successful formation of Pt @TiO₂.

The effect of Pt loading on the texture properties of TiO2 was investigated based on the N2 adsorption-294 desorption isotherm (Fig. 2b). Accordingly, both TiO₂ and Pt@TiO₂ exhibited a typical type-IV isotherm 295 with a H3 type hysteresis loop (Fig. 2b), which might be ascribable to their mesoporous structure with a 296 complex pore network because of the aggregation of the nanoparticles (Pierotti and Rouquerol, 1985; 297 Giannakoudakis et al., 2020). As shown in Fig. 2c, similar pore size distribution curvatures, ranging from 298 around 9 to 40 Å, were observed for both TiO₂ and Pt@TiO₂. However, the pristine P25 (TiO₂) has a slightly 299 lower BET surface area and pore volume (40 m² g⁻¹ and 0.05 cm³ g⁻¹) than that of Pt@TiO₂ (43 m² g⁻¹ and 300 $0.07 \text{ cm}^3 \text{ g}^{-1}$). This might be attributed to the formation of complex pore network caused by the synergistic 301 role of doped Pt species and reallocation (and/or rearrangement) of the nanoparticles after thermal 302 calcination at high temperature (Giannakoudakis et al., 2020). 303

The XPS analysis was also carried out to study the chemical and electronic state of elements on the 304 surface of Pt@TiO₂ relative to pure TiO₂ (Fig. 3). As shown in Fig. 3 (b- e), there was no change or track 305 shift in the binding energies (BE) of Ti 2p and O1s core-level spectra for TiO₂ after the Pt impregnation. 306 The core level of Ti 2p (Fig. 3b and d) in pure and Pt-doped TiO₂ showed the same spin-orbit doublet peaks 307 for Ti⁴⁺ species at BE values of 459.3 eV (Ti 2p_{3/2}) and 465.1 eV (Ti 2p_{1/2}), indicating that Pt loading does 308 not influence the chemical state of Ti in the TiO₂ crystal (Zhang et al., 2022a). The core level of O1s in both 309 pure TiO₂ and Pt@TiO₂ (Fig. 3c and e) also revealed the existence of two types of oxygen species including 310 311 lattice oxygen (OI: 530.5 eV) and surface hydroxyls (-OH (OII): BEs of 531.6 and 531.7 eV in TiO2 and Pt@TiO2, respectively) (Lee et al., 2019; Zhang et al., 2022a). Additionally, the increase in the content of 312 OH (O_{II}) species (e.g., from 35.8% (pristine P25) to 43.4% in the Pt-doped TiO₂) supports the possibility 313 that the impregnation of Pt species might change the electronic environment for surface hydroxyl groups. 314

Similar phenomena were also observed after introducing other metallic components (e.g., Ag and Er) 315 into the TiO₂ crystal lattice (Chen et al., 2017a; Rao et al., 2019). From Fig. 3(f), the deconvoluted spectrum 316 of Pt 4f in Pt@TiO₂ reflects the existence of Pt⁰ (metallic Pt), Pt²⁺, and Pt⁴⁺ (Kim et al., 2016; Zhang et al., 317 2022a). Among these, the metallic Pt (39.5% Pt^0) and cationic Pt^{2+} (44.6%) species are the major forms in 318 Pt@TiO₂, while the existence of Pt⁴⁺ was minor (around 15.6%). From Fig. 3(f), the metallic Pt⁰ peaks were 319 observed at BEs of 72.6 and 75.0 eV, which were assigned to $Pt^{0+} 4f_{7/2}$ and $4f_{5/2}$, respectively(Lee et al., 320 321 2021). Similarly, the deconvoluted peaks at about 74.3 and 75.9 eV implied the presence of Pt^{2+} species (Pt-O), while that observed at 78.2 eV was attributed to the Pt⁴⁺ species (O-Pt-O (PtO₂)) in the prepared 322 Pt@TiO₂ composite (Zhang et al., 2022a). These results consistently confirmed the successful doping of Pt 323 active sites on the TiO₂ crystal surface. 324

325

326 **3.2** Adsorption study of VOCs onto TiO₂ and Pt@TiO₂

As a simple means to assess the synergistic role of Pt impregnation in the adsorption of aldehyde and 327 aromatic VOCs, the BT adsorption profiles established for the removal of multi-component VOCs system 328 (FA (50 ppm) and BTXS (1 ppm each) at RH level= 0%) were compared between pristine TiO₂ and 329 Pt@TiO₂ (20 mg mass) (Fig. 4). Accordingly, all of them showcased a higher affinity for FA uptake as 330 compared to non-polar targets (B, T, X, S), with the roll-up effect in the BT profiles of BTX components 331 (i.e., C_{out}/C_{in}>1). The roll-up phenomenon is caused by the partial displacement of adsorbed BTX molecules 332 (i.e., weaker adsorbates) from the TiO₂ or Pt@TiO₂ surfaces by polar FA molecules (i.e., a stronger 333 334 adsorbate) as a result of competitive adsorption effects in the multi-component gas stream (Samaddar et al., 2019). 335

336 In general, the maximum obtainable performance for a tested adsorbent is achieved at the saturation

status (100% BT level (BTV100)). However, 10% BT values (BTV10) also have been recommended as a 337 proper metric for evaluating adsorbent performance and service lifetime (Liu et al., 2021a; Liu et al., 2021b). 338 Table 1 summarizes the adsorption performance of $Pt@TiO_2$ adsorbent (relative to pure TiO₂ adsorbent) 339 for the selective uptake of FA (50 ppm) from a multi-component VOCs gaseous stream containing BTXS 340 vapor mixture (1 ppm each). Note that because of very rapid adsorption of benzene and toluene in the very 341 initial stage of a run, their adsorption affinity at the 10% BTV level could not be determined from a Pt@TiO₂ 342 (and TiO₂) packed bed. The BT adsorption times to achieve 100% BT for benzene/toluene were 0.6±0.2 343 min (Pt@TiO₂) and 0.4±0.2 min (TiO₂) (Fig. 4). At a 100% BT level, the equilibrium capacity of BTXS 344 and FA molecules over TiO₂ adsorbent bed was significantly improved by 0.5 to 2.6-fold after impregnation 345 with Pt species. The BTV100 values increased from 5.84 to 11.13 L atm g⁻¹ (for B), from 11.73 to 31.27 L 346 atm g^{-1} (for T), from 18.44 to 67.43 L atm g^{-1} (for X), from 809.41 to 1290.09 L atm g^{-1} (for S), and from 347 818.85 to 1381.15 L atm g⁻¹ (for FA) after the impregnation of TiO₂ with Pt species. These data revealed 348 349 that $Pt(a)TiO_2$ should possess a higher adsorption affinity for polar FA molecules, followed by S > X > T >B targets. The same ranking was also observed in the BTV10, PC value, and adsorption capacities (Table 350 1). Such above findings revealed that Pt impregnation on the TiO₂ surface enhances the adsorption affinity 351 352 towards VOCs capture, specifically polar FA molecules.

The higher affinity for FA adsorption could be ascribed to the formation of hydrogen bonding as a result of interactions between the FA aldehyde group (H-CHO) and the surface hydroxyl group of TiO₂ or Pt@TiO₂ (Ao et al., 2004; Nie et al., 2013). On this basis, the improved capacity of Pt@TiO₂ for FA adsorption could be accounted for by the increased fraction (43.4%) of OH (O_{II}) species in Pt@TiO₂ than that of pure TiO₂ (35.8%), as is evident from XPS analysis. As the van der Waal force could act as the ratelimiting adsorption mechanism for BTXS on the Pt@TiO₂ surface, it was noted that the van der Waal

interaction force is directly proportional to the number of carbon atoms in the aliphatic/aromatic 359 hydrocarbons (Allinger and Lii, 1987; Samaddar et al., 2019). In this case, VOCs with the lower volatility 360 (higher boiling points: e.g., m-xylene and styrene) should exhibit stronger adsorption on the Pt@TiO₂ 361 surface relative to lighter (benzene and toluene) aromatic ones (Samaddar et al., 2019; Vikrant et al., 2020a). 362 Furthermore, styrene (boiling point: 145°C) showed more competitive adsorption onto a Pt@TiO₂ surface 363 as compared to that of m-xylene (boiling point: 139°C) (Fig. 4). The excellent performance of Pt@TiO₂ 364 towards all VOCs adsorption (e.g., relative to the pristine TiO₂) could be ascribed to its higher surface area 365 and pore volume than pure TiO₂. The increased BET surface area and surface porosity accelerated the 366 adsorption diffusion mechanism and raised the number of free available sorption sites available for 367 interactions with VOC molecules (Tran et al., 2022). In the recognition of the high affinity of Pt@TiO₂ 368 towards FA from a multiple VOC mixture (e.g., compared with pure TiO₂), the selectivity of Pt@TiO₂ was 369 explored mainly towards FA uptake (from single and multi-component VOCs mixtures) in the next stage 370 371 under varying operating conditions.

372

373 3.3. Effect of operating variables on FA adsorption by Pt@TiO2 adsorbent

374 3.3.1 Fixed-bed mass

The effect of $Pt@TiO_2$ bed mass on the BT adsorption profiles of FA molecules from the single (FA: 50 ppm) and multicomponent (FA: 50ppm + BTXS each: 1ppm) gas phases was evaluated at RH = 0%, as seen in Fig. S2. The corresponding performance data are presented in Tables 2-3 and Table S2. Since the initial BT point of BTXS components over $Pt@TiO_2$ adsorbent was higher than 10%, the adsorption performance metrics of $Pt@TiO_2$ for FA and BTXS at varying mass loads were calculated and compared at 100% BT (equilibrium/saturation phase). As summarized in Table 2-3, the adsorption affinity for FA capture

from both single and mixed VOC gas phases increased by 2 - 2.8 fold upon increasing the loaded Pt@TiO₂ 381 adsorbent bed mass from 5 to 20 mg. However, the adsorption capacity of FA onto Pt@TiO2 declined by 382 1.4 to 1.8 times upon introducing the BTXS mixture simultaneously in the gas stream. At the highest bed 383 mass (20 mg), the adsorption capacity of FA onto Pt@TiO₂ increased by 11250, 1125, 233, and 26 times as 384 compared to benzene, toluene, m-xylene, and styrene, respectively (Table 3, Fig. S3a). It was noted that the 385 adsorption performance of Pt@TiO₂ for aromatic VOC (i.e., BTX molecules) capture slightly decreased 386 with increasing packed bed masses from 5 to 20 mg (Table 3). In particular, the BTV100 values of B, T, 387 and X components (i.e., aromatic/non-polar VOCs) decreased from 31.87 to 11.13, 69 to 31.27, and 125.62 388 to 67.43 L atm g⁻¹ upon increasing Pt@TiO₂ bed mass from 5 to 20 mg, respectively. This phenomenon 389 could be explained based on the factors influencing the extent of the adsorption process, such as surface 390 reactivity and nature of the adsorbate. Due to the preferable Pt@TiO2 surface active sites for interactions 391 with polar FA (H-bond formation), an increase in the Pt@TiO2 bed mass increases the number of free 392 393 available active sites for FA adsorption. In this case, the higher occupation of FA onto the Pt@TiO₂ surface could reduce the bed porosity and the mass transfer zone to suppress the adsorption probability of non-polar 394 VOCs (BTX molecules) with increasing bed mass. This is verified by the adsorption capacity of FA with 395 396 increasing Pt@TiO₂ bed mass. At the 100% BT level, the BTV100 values of FA (i.e., polar VOCs) from single/mixed VOC gas phases increased as the packed Pt@TiO2 bed masses increased such as 397 976.41/685.67, 1085.74/995.93, and 1466.53/1381.15 L atm g⁻¹ at 5, 10, and 20 mg of Pt@TiO₂ adsorbent 398 399 bed mass, respectively. The corresponding maximum adsorption capacities of FA onto Pt@TiO2 adsorbent from single/multi-component gas phases also increased to 4.26/2.35, 8.64/5.19, and 9.61/6.75 mg g⁻¹ at 5, 400 10, and 20 mg bed mass, respectively (Tables 2 and 3, Fig. S3a). Likewise, at 100% BT, the Q and BTV 401 values of styrene (polar VOCs) significantly increased by 1.7 and 1.3 times upon increasing Pt@TiO₂ bed 402

mass from 5 to 20 mg, respectively (Table 3). The reduction of FA uptake on the Pt@TiO₂ might be
attributed to the competitive adsorption due to the co-presence of BTXS in the mixed gas phase (relative to
the single gas phase). In contrast, the improved adsorption capacity at a higher bed mass load was caused
by an increased number of active theoretical plates and adsorption sites within the fixed-bed adsorbent tube
with increased adsorbent mass (Kim et al., 2022).

408

409 **3.3.1 Inlet VOC concentration**

To further understand the surface reactivity of Pt@TiO₂, the adsorption performance of Pt@TiO₂ for 410 FA capture was studied from single and multicomponent VOC gas streams by varying the inlet 411 concentrations of FA (25-700 ppm) and BTXS (0.5-14 ppm) components. At higher bed mass (20 mg), the 412 respective adsorption performance data of Pt@TiO2 for FA and BTXS capture are summarized in Tables 2-413 3 and S2. Notably, the adsorption performance of $Pt@TiO_2$ was 1.1 - 2 fold higher for FA uptake in the 414 single system than in the multicomponent VOCs system (Tables 2-3 and S2) for all studied concentration 415 levels. Although the adsorption capacity of FA increased with increasing inlet vapor concentrations, the 416 overall adsorption performance of Pt@TiO₂ (in terms of BTV and PC metrics) decreased. Specifically, the 417 BTV100 values of single FA were 2331, 1466.5, 451.02, 213.96, and 149.11 L atm g⁻¹ at inlet concentrations 418 of 25, 50, 250, 500, and 700 ppm, respectively. In the case of multicomponent VOCs, the counterpart 419 BTV100 values of FA significantly declined to 1330.9, 1381.15, 276.58, 97.1, and 70.23 L atm g⁻¹ when 420 the inlet FA/BTXS concentrations were 25/0.5, 50/1, 250/5, 500/10, and 700/14 ppm, respectively. In 421 422 contrast, we observed that the presence of 0.5ppm BTXS had little effect on the maximum adsorption capacity of FA at lower inlet concentrations of 25 ppm. Compared to the Q value of single FA, the maximum 423 Q values of FA decreased by 6.8, 42.3, 28.4, 31.6, and 27.7% when switching the inlet gas phase from 424

single FA to multicomponent VOC mixture with increasing FA/BTXS inlet concentrations of 25/0.5, 50/1, 250/5, 500/10, and 700/14 ppm, respectively. According to the Q metric at saturation state (100% BT), the adsorption performance ranking of Pt@TiO₂ in VOCs capturing was as follows: FA (Q = 6.29 - 11.76 mg g^{-1}) > styrene (Q= 0.16 - 0.34 mg g^{-1}) > m-xylene (Q = 0.062 - 0.14 mg g^{-1}) > toluene (Q= 0.019 - 0.052mg g^{-1}) > benzene (Q=0.0072 - 0.021 mg g^{-1}) at all tested concentrations (Fig. S3b).

In the fixed bed column, the increased adsorption capacity of VOCs can be attributed to the larger 430 mass transfer coefficient and higher adsorption rate with increasing inlet VOC concentration. In this case, 431 the Pt@TiO₂ surface adsorption sites were quickly saturated by VOCs (BTXS and/or FA) at the highest 432 433 inlet concentrations, allowing a faster BT time for more VOCs molecules in the outlet gaseous streams due to the limited surface active sites available for adsorption on the adsorbent surface. Such a phenomenon 434 causes a decrease in the performance of Pt@TiO2 adsorbent for FA capture in both single and 435 multicomponent gas phases (Zhang et al., 2020). As a result, the decrease in the capturing capacity of FA 436 in the multicomponent phase (e.g., relative to the single phase) was apparent, which should be ascribable 437 to the competitive adsorption of BTXS species in the multicomponent phase. 438

439 **3.3.2** Relative humidity (RH)

Relative humidity (RH) is a vital real-air condition parameter that affects the adsorption capacity of VOCs onto metal oxides. Thus, the effect of RH levels (0-100%) on the BT profile of Pt@TiO₂ packed bed adsorbent are shown for FA adsorption from single and multicomponent VOC mixture in Fig. 5. Early in the BT profile, the adsorption affinity of Pt@TiO₂ for FA from single and multicomponent gas mixture decreased by more than 80% (from 0.6 to 0.1 L) and 85% (from 0.2 to 0.03) with an increased RH level from 0 to 100%, respectively (Fig. 5a -b). At higher RH levels (>50%), a fast BT point of FA was observed after 0.3/0.03 L feeding volume of single/mixed gaseous systems. Obviously, the BTV100 values of FA

from single and multicomponent gas phases significantly declined from 1466.53/1381.15 to 802.43/518.66 447 L atm g⁻¹ as the RH level rose from 0% to 100%, respectively. Similarly, the adsorption capabilities of 448 Pt@TiO₂ for BTX components showed a descending trend with increasing RH levels (Table 3, Fig. S3c). 449 When the gaseous RH level increased from 0 to 100%, the BTV100 value of benzene, toluene, and xylene 450 over Pt@TiO₂ bed sorbent declined by 71%, 72%, and 36%, respectively. Compared to dry conditions 451 (RH = 0%), the maximum adsorption capacities (Q values) of FA, B, T, X, and S onto $Pt@TiO_2$ were 452 significantly lowered by about 70, 99, 95, 83, and 74% upon introducing a humidified gas stream (RH = 20453 -100%) (Fig. S3c). 454

455 Among VOCs, the adsorption capacity of Pt@TiO₂ for non-polar BTX molecules is more susceptible to the presence of water vapor than polar VOCs (FA components). In the case of polar VOCs adsorption, 456 the water vapor had a higher negative impact on the adsorption ability of Pt@TiO₂ for S capture than FA 457 from the multicomponent gas phase. The water vapor exhibited more intensely competitive inhibition effect 458 on FA adsorption onto Pt@TiO2 adsorbent in the presence of BTXS components as compared to that in a 459 single gas phase, as verified by the BTV, Q, and PC metrics (Tables 2 and 3). Compared with the adsorption 460 data in the dry phase (RH=0%), the maximum adsorption capacities of FA onto Pt@TiO₂ at 100% RH levels 461 462 declined by 66 and 70% in single and mixed phases, respectively (Table 2-3 and S2). Such observations might be attributed to the combined inhibition effects of both BTXS and water vapor molecules on FA 463 adsorption by Pt@TiO₂ surface active sites. 464

In light of the above findings, we inferred that the relative humidity adversely affected the adsorption capability of $Pt@TiO_2$ for polar and non-polar VOCs. More specifically, as the relative humidity increases, the increased water clusters in the gas phase might compete with VOC molecules for surface/pore diffusion within porous $Pt@TiO_2$ adsorbent are accompanied by the formation of H-bonds between two or more

469	neighboring water molecules. Also, the layer (e.g., monolayer) of water molecules might be generated on
470	the surface of TiO_2 through the formation of $HO \cdots H_2O$ in the presence of moisture (Patrick and Giustino,
471	2014). As such, the reduction in the adsorption capacity may become apparent as the clustered water on the
472	Pt@TiO2 surface diminishes the number of binding sites available for capturing FA molecules (Zhang et
473	al., 2020). A similar antagonistic effect of moisture on FA removal was also observed from other materials
474	such as activated carbon and covalent organic polymers with water molecules blocking the surface-active
475	sites (Pei and Zhang, 2011; Lee et al., 2013; Vikrant et al., 2020c).

477 3.5 Adsorption mechanism of FA onto Pt@TiO₂

478 3.5.1 Adsorption kinetic modeling

The effects of gas phase composition (single vs. mixed VOCs) on the surface and pore diffusion 479 mechanisms were investigated using FA over Pt@TiO₂ packed bed adsorbent based on three kinetic models 480 such as pseudo-first-order (PFO), pseudo-second-order (PSO), and intraparticle diffusion (IPD) models 481 (Tan and Hameed, 2017; Vellingiri et al., 2018). It is demonstrated that the use of non-linear fitting modes 482 should be more reliable and free from the statistical/mathematical side effects (e.g., alteration of the error 483 484 distribution) than those of linear fitting modes (Tan and Hameed, 2017; Xiao et al., 2018). The obtained experimental adsorption data of FA in single and multicomponent phases onto Pt@TiO₂ were fitted by the 485 non-linear expression of PFO and PSO models (Fig. 6). The corresponding kinetic results are expressed in 486 terms of kinetic rate constants and fitting results (e.g., R^2 and χ^2) for both single and multicomponent VOC 487 phases as summarized in Table 4. 488

As is evident from the compilation of R² values in Table 4, the experimental adsorption of FA onto Pt@TiO₂ from single and multicomponent VOC gas streams can be explained by PFO and PSO kinetic

models, with high fitting accuracy between experimental and predicted capacities ($R^2 > 0.9$). However, the 491 PSO kinetic model yielded a better fit ($R^2 = 0.989-0.999$) for describing FA adsorption by Pt@TiO₂ 492 adsorbent (for both single and multi-component gas phase), with lower error values ($\chi^2 = 0.0345 - 0.181$) in 493 comparison to the PFO model ($R^2 = 0.978-0.992$, $\chi^2 = 0.122-0.192$). These observations imply that a 494 complex physical and chemical adsorption mechanisms might govern the FA adsorption process onto the 495 surface of Pt@TiO₂ (Ha et al., 2020). Note that the estimated PSO kinetic rate of FA (k₂ value= 0.0131 g 496 mg^{-1} min⁻¹) from a single gas system was lower than that of the mixed VOC system (k₂ value= 0.0232 g 497 mg⁻¹ min⁻¹). Moreover, the initial adsorption rate ($h_0=K_2Q_e^2$ (mg g⁻¹ min⁻¹)) of FA declined from 1.42 to 498 1.38 mg g⁻¹ min⁻¹ when feeding gas stream composition was altered from a single FA to its mixture with 499 BTXS. As such, it can be inferred that FA and BTXS components should actively compete for Pt@TiO2 500 surface active sites, which should be accompanied by the rapid saturation of packed bed adsorbent. 501

Note that the enhancement of adsorption process for target adsorbate species can be assessed in terms 502 of surface interaction and pore diffusion mechanisms (Figaro et al., 2009; Kim et al., 2022). In this respect, 503 the IPD model has been used for studying the rate-limiting adsorption diffusion mechanism (e.g., pore-504 505 diffusion or surface diffusion mechanisms) onto porous adsorbents (Kim et al., 2021b; Liu et al., 2021a; 506 Kim et al., 2022). As displayed in Fig. 6(b) and (d), the IPD profiles of FA adsorption by Pt@TiO₂ studied herein consist of three linear curvature stages (R^2 values= 0.975-0.993) in single and multi-component gas 507 systems such as the surface/pore diffusion stage (first/second stage) and micropore diffusion stage (third 508 509 stage). Note that none of these linear regions in the IPD plots pass through the origin point (C \neq 0) (Verma and Dutta, 2015). This implies that surface/pore-diffusion as well as chemical interaction mechanisms 510 might exert the control on the adsorption rate of FA onto Pt@TiO₂ (Shikuku et al., 2018; Liu et al., 2021a). 511 In the IPD model, the FA uptake rate in all three regions followed the order: K_{id2} = 2.268 mg g⁻¹ min^{-1/2} 512

(Region II) > K_{id1} =0.964 mg g⁻¹ min^{-1/2} (Region I) > K_{id3} = 0.467 mg g⁻¹ min^{-1/2} (Region III) for a single 513 component, while those of the mixed system were in the order of K_{id2} = 1.825 mg g⁻¹ min^{-1/2} (Region II) > 514 $K_{id1}=0.961 \text{ mg g}^{-1} \min^{-1/2}$ (Region I) > $K_{id3}=0.361 \text{ mg g}^{-1} \min^{-1/2}$ (Region III). It is apparent that the IPD 515 rates for the first and second regions in both single and mixed systems were higher than those estimated for 516 the third region. As such, surface/pore diffusion in Pt@TiO₂ may be proactive for controlling the FA 517 adsorption. It can thus be inferred that the increased surface porosity and surface hydroxyl (O_{II}) fraction in 518 Pt@TiO₂ should significantly contribute to the enhancement of adsorption capacity for FA in both single 519 and multicomponent systems. 520

521 3.5.2 Adsorption isotherm modeling

522 To provide better insight into the nature and properties of adsorbate-adsorbent interactions, our adsorption data were fit using Freundlich, Langmuir, and Temkin isotherm models (Aziz et al., 2018; 523 Vikrant et al., 2019). The Freundlich model was used based on the assumption that a reversible uptake 524 phenomena commonly appears in the multilayered adsorption of adsorbate onto heterogeneous surface sites. 525 In contrast, the Langmuir model assumes that the monolayer coverage of adsorbate molecules can reach 526 the dynamic equilibrium on those microporous sorbents with isoenergetic surface active sites. In the case 527 528 of the Temkin isotherm model, the decrease in the heat of adsorption is accompanied by the increased coverage of the adsorbent surface (Foo and Hameed, 2010; Tran et al., 2022). In light of such conditions, 529 the obtained adsorption experimental data were non-linearly fitted using Freundlich (Eq. 8), Temkin(Eq. 9), 530 and Langmuir (Eq. 10) isotherm models, as shown in Fig. 7. Table 5 summarizes the fitting results (e.g., 531 isotherm constants, R^2 , and χ^2) for the applied isotherm models . 532

533 According to the fitting metrics, the fitting adequacy of FA adsorption isotherm models can be ranked as 534 follows: Freundlich ($R^2 = 0.986-0.991$) > Temkin ($R^2 = 0.963-0.971$) > Langmuir ($R^2 = 0.852-0.927$). Such 24

an observation suggests the higher surface heterogeneity of Pt@TiO₂ for the multi-layer adsorption 535 mechanism of FA molecules from single/multicomponent systems. Due to the poor fitting adequacy of the 536 537 Temkin isotherm model (relative to Freundlich isotherm), it can be inferred that the adsorption heat of FA does not linearly decrease with the increased monolayer coverage of the Pt@TiO₂ adsorbent surface with 538 VOC molecules (Foo and Hameed, 2010). In Table 5, the higher Freundlich intensity constant (n) values 539 (i.e., n = 4.771 to 4.812 and n > 1) may imply favorable multi-layer coverage of Pt@TiO₂ surface with FA 540 molecules via a complex physicochemical adsorption mechanism (e.g., surface interactions and diffusion 541 processes) (Ha et al., 2020). However, the binding coefficient value of FA in single mode (K_F:6.262 mg g⁻ 542 ¹ Pa^{-(1/n)}) was higher than that in a multicomponent system (K_F: 4.924 mg g⁻¹ Pa^{-(1/n)})(Table 5) because of 543 the competitive inhibition effects of BTXS molecules in a multi-component gas phase. This observation 544 was also in line with our previously mentioned findings (Section 3.5.1) in that the feed gas composition 545 significantly influences the adsorption performance of Pt@TiO₂ toward FA capture. 546

547

548 3.5.3 Assessment of regeneration and performance comparison

The reusability of an adsorbent is an important factor to consider for the assessment of practical 549 applications. As seen in Fig. 8, Pt@TiO₂ could be easily regenerated with an appreciable adsorption 550 performance against gaseous FA in both single and multi-component systems (e.g., up to three adsorption-551 desorption cycles). The Pt@TiO₂ system exhibited good adsorption performance stability for FA capture 552 over three reuse cycles, with a negligible decline in the maximum adsorption capacities by 1.3% and 4.9% 553 554 for single and multicomponent VOC systems, respectively (Fig. 8). It is thus suggested that the Pt@TiO₂ can be easily subject to thermal regeneration (e.g., at 150°C for 2 h under nitrogen gas flow of 50 mL min⁻ 555 ¹). The results of this study also reveal that the thermal regeneration process exerted almost no effect on the 556

FA adsorption affinity of Pt@TiO2 over reuse cycles. Similarly, the adsorption capacity value of 557 aminosilane-functionalized activated carbon was noted to have a negligible decline of 2% (from 1.43 to 1.4 558 mg g⁻¹) after three regeneration cycles (at 300°C for 3h at the nitrogen flow of 200 mL min⁻¹) (Vikrant et 559 al., 2020b). These results might be accounted for by the dominance of physisorption (e.g., pore diffusion) 560 of FA onto aminosilane-functionalized activated carbon (Vikrant et al., 2020b). In contrast, the 561 ethylenediamine functionalized covalent organic polymers (CE) could not be completely regenerated at 562 150°C for 3h under nitrogen gas flow of 50 mL min⁻¹ (Vikrant et al., 2020c). This CE showed a significant 563 decrease in its capacity by 60% (from 105 to 42 mg g⁻¹) for the first regeneration cycle due to the strong 564 interactions (e.g., formation of imine) between FA molecules and the amine functionalities of CE (Vikrant 565 et al., 2020c). Likewise, the adsorbed FA cannot significantly desorb from UiO-66-NH₂ after regeneration 566 (e.g., 150°C for 3 h under nitrogen gas flow of 200 mL min⁻¹) because of strong chemical linkages (e.g., 567 imine formation) between FA molecule and amine groups of UiO-66-NH₂. As a result, the adsorption 568 capacity of UiO-66-NH₂ toward FA dropped significantly after each cycle to record a 77.7% reduction of 569 the performance in the third cycle (from around 76 to 18 mg g^{-1}) (Tran et al., 2022). 570

The FA adsorption performance of Pt@TiO₂ was assessed and compared with other commonly used 571 572 adsorbents (e.g., metal organic frameworks (MOFs)) in terms of key performance metrics such as adsorption capacity (Q) and partition coefficient (PC) (Table S3). If the Q values are compiled for 573 performance comparison, the ethylenediamine functionalized covalent organic polymers (CE) achieved the 574 highest Q values (105 mg g⁻¹) for FA adsorption followed by $Pt@TiO_2$ (single phase system, 9.61 mg g⁻¹) > 575 Pt@TiO₂ (multicomponent phase system, 6.75 mg g⁻¹) > UiO-66 (4.3 mg g⁻¹) > MOF-5 (prepared at 25°C, 576 4.1 mg g⁻¹) (Table S3) (Vikrant et al., 2020c; Vikrant et al., 2020d). However, the performance evaluation 577 based on adsorption capacity alone can be biased considerably because of the arbitrary selection of the 578

operation conditions (e.g., inlet VOC concentration) (Na et al., 2019; Ahmadi and Kim, 2022). To reduce 579 such biases, the use of PC concept has been recommended for evaluating the adsorption performance of 580 materials, as it can help the lower the biases stemming from large differences in the initial feeding 581 concentration of target species (Vikrant et al., 2020b; Tran et al., 2022). In terms of the PC (mol kg⁻¹ Pa⁻¹), 582 their relative order is slightly altered such as ethylenediamine functionalized covalent organic polymers 583 (CE) $(0.35 \text{ mol kg}^{-1} \text{ Pa}^{-1}) > \text{Pt}(@\text{TiO}_2 \text{ (single phase system, 0.061 mol kg}^{-1} \text{ Pa}^{-1}) > \text{Graphene (0.06 mol kg}^{-1} \text{ Pa}^{-1})$ 584 ¹ Pa⁻¹) > UiO-66 (0.054 mol kg⁻¹ Pa⁻¹) > MOF-5 (prepared at 25°C, 0.047 mol kg⁻¹ Pa⁻¹) (Wu et al., 2017; 585 Vikrant et al., 2020c; Vikrant et al., 2020d). The superior adsorption performance (Q/PC, 105 mg g⁻¹/0.35 586 mol kg⁻¹ Pa⁻¹) of CE should be attributable to the reasons as follows: (i) the formation of chemical 587 interaction (non-covalent interaction) between carbonyl groups of FA and the amine functional group of 588 CE. (ii) The physical interaction (van der Waals interactions) between FA and the surface of CE (Vikrant et 589 al., 2020c). However, the complex synthesis process for CE might limit its practical application (Vikrant et 590 591 al., 2020c). Among all adsorbents listed in Table S3, the Pt@TiO2 had the second highest Q/PC values (9.61 mg g⁻¹ and 0.061 mol kg⁻¹ Pa⁻¹) at single FA phase system (Table S3). The good performance of Pt@TiO₂ 592 may reflect the effects of interaction between the FA aldehyde group (H-CHO) and the surface hydroxyl 593 594 group of Pt@TiO2. As such, Pt@TiO2 can be considered as one of the recommendable options for FA adsorption. 595

596

597 4 Conclusion

In this study, platinized titanium dioxide (Pt@TiO₂) was prepared and utilized as an adsorbent for the enhanced removal of formaldehyde (FA) as a single component or as a mixture with aromatic compounds (BTXS). The FA adsorption affinity of Pt@TiO₂ was also investigated under the control of various operation 601 variables (e.g., relative humidity (RH), adsorbent dosage, and inlet VOC concentration) in the absence and presence of BTXS components (FA+BTXS). Doping of TiO₂ with Pt metal ions likely increased OH (O_{II}) 602 surface active sites and surface porosity (relative to that of pristine TiO₂) to lead to the enhancement of 603 adsorption capacity against FA (through hydrogen bonding formation with the aldehyde group of FA 604 molecules). As such, the maximum adsorption capacities (6.75 mg g⁻¹) of Pt@TiO₂ was around 50% larger 605 than that of its pristine form, i.e., TiO_2 (4.62 mg g⁻¹). Moreover, the higher surface porosity of Pt@TiO₂ 606 607 accelerated the adsorption diffusion of smaller FA molecules (compared with larger, nonpolar BTX molecules) to interact with free available sorption sites in the micropore volume. The maximum adsorption 608 609 capacities of Pt@TiO2 towards FA in single/multicomponent phase systems were found to increase from 4.32/2.35 to 9.61/6.75 mg g⁻¹ with the increases in utilized bed-masses (i.e., 5, 10, and 20 mg). Such 610 improved adsorption capacity at higher bed mass load should be associated with the increased number of 611 active sites for FA molecules. Further, it was observed that the increased water vapor (RH: 20-100%) greatly 612 diminished the adsorption performance of Pt@TiO₂ for FA molecules, especially from the multi-component 613 VOC gas phase (due possibly to the enhancement in competitive inhibition effects toward FA adsorption 614 on the surface active site of the Pt@TiO₂ adsorbent). In addition, the adsorbed water molecules might 615 616 interfere with hydrogen bonding formation between the FA aldehyde group and surface OH groups of the 617 Pt@TiO₂ to weaken the adsorption interactions between FA and surface active sites. Such competition, if it occurs, can also lower the number of adsorption sites available for capturing FA molecules. Consequently, 618 619 maximum adsorption capacities of Pt@TiO2 in single/multicomponent phase system were reduced from 9.61/6.75 mg g⁻¹ to 3.15/2.03 mg g⁻¹ with the increase in RH level from 0 to 100%. According to the 620 isotherms and kinetics modeling, the FA adsorption process over Pt@TiO2 might involve complex 621 physicochemical adsorption such as surface/pore diffusion with multi-layer adsorption mechanisms. 622

623	Moreover, the reusability study revealed the good adsorption stability of Pt@TiO2 adsorbent in
624	single/multicomponent gas phases (only 1.3%/4.9% reduction in adsorption capacity) for FA capture (e.g.,
625	over three consecutive reuse cycles), confirming its potential for a real-world application. Further
626	researches should be made to address the effects of different variables such as temperature and presence of
627	more polar VOCs (relative to FA) on its adsorption activity. Overall, this study is expected to help broaden
628	the utility of noble metal-impregnated TiO2 nanoparticles, especially in the sequential adsorption and
629	catalytic abatement of VOCs.
630	
631	
632	Acknowledgements
633	This work was supported by a grant from the National Research Foundation of Korea (NRF) funded
634	by the Ministry of Science and ICT (MSIT) of the Korean government (Grant No: 2021R1A3B1068304).
635	P.M.H. would like to thank the Research and Development Program of Ghent University Global Campus
636	(GUGC), Korea.
637	
638	
639	References
640	Aboud, A.A., Shaban, M., Revaprasadu, N., 2019. Effect of Cu, Ni and Pb doping on the photo-electrochemical activity
641	of ZnO thin films. RSC advances 9, 7729-7736.
642	Ahmadi, Y., Kim, KH., 2022. Recent Progress in the Development of Hyper-Cross-Linked Polymers for Adsorption of
643	Gaseous Volatile Organic Compounds. Polymer Reviews, 1-29.
644	Ahrens, L.H., 1952. The use of ionization potentials Part 1. Ionic radii of the elements. Geochimica et cosmochimica
645	Acta 2, 155-169.

- Allinger, N.L., Lii, J.H., 1987. Benzene, aromatic rings, van der Waals molecules, and crystals of aromatic molecules in
 molecular mechanics (MM3). Journal of computational chemistry 8, 1146-1153.
- Ao, C., Lee, S., Yu, J., Xu, J., 2004. Photodegradation of formaldehyde by photocatalyst TiO₂: effects on the presences
- of NO, SO₂ and VOCs. Applied catalysis B: environmental 54, 41-50.
- 650 Aykın-Dinçer, E., Erbaş, M., 2018. Drying kinetics, adsorption isotherms and quality characteristics of vacuum-dried beef
- 651 slices with different salt contents. Meat science 145, 114-120.
- Aziz, A., Sajjad, M., Kim, M., Kim, K., 2018. An efficient Co-ZSM-5 catalyst for the abatement of volatile organics in air:
- effect of the synthesis protocol. International journal of environmental science and technology 15, 707-718.
- Bai, X., Liu, W., Wu, B., Liu, S., Liu, X., Hao, Y., Liang, W., Lin, S., Luo, L., Zhao, S., 2023. Emission characteristics and
- inventory of volatile organic compounds from the Chinese cement industry based on field measurements. Environmental
 Pollution 316, 120600.
- Batault, F., Thevenet, F., Hequet, V., Rillard, C., Le Coq, L., Locoge, N., 2015. Acetaldehyde and acetic acid adsorption
- on TiO₂ under dry and humid conditions. Chemical Engineering Journal 264, 197-210.
- Bellat, J.-P., Bezverkhyy, I., Weber, G., Royer, S., Averlant, R., Giraudon, J.-M., Lamonier, J.-F., 2015. Capture of
- 660 formaldehyde by adsorption on nanoporous materials. Journal of hazardous materials 300, 711-717.
- 661 Chen, C., Lei, X., Xue, M., 2017a. A simple method to synthesise Ag-doped TiO₂ photocatalysts with different Ag₀: Ag₂O
- atomic ratios for enhancing visible-light photocatalytic activity. Journal of Chemical Research 41, 475-483.
- 663 Chen, H.-W., Ku, Y., Kuo, Y.-L., 2007. Effect of Pt/TiO₂ characteristics on temporal behavior of o-cresol decomposition
- by visible light-induced photocatalysis. Water Research 41, 2069-2078.
- 665 Chen, J., Li, G., He, Z., An, T., 2011. Adsorption and degradation of model volatile organic compounds by a combined
- titania–montmorillonite–silica photocatalyst. Journal of Hazardous Materials 190, 416-423.
- 667 Chen, J., Liu, R., Gao, Y., Li, G., An, T., 2017b. Preferential purification of oxygenated volatile organic compounds than

- 668 monoaromatics emitted from paint spray booth and risk attenuation by the integrated decontamination technique.
 669 Journal of Cleaner Production 148, 268-275.
- 670 Chen, J., Nie, X., Shi, H., Li, G., An, T., 2013. Synthesis of TiO₂ hollow sphere multimer photocatalyst by etching titanium
- 671 plate and its application to the photocatalytic decomposition of gaseous styrene. Chemical engineering journal 228, 834-
- 672 842.
- 673 Chen, J., Zhang, Z., Zhu, W., Zhang, L., Zhao, B., Ji, Y., Li, G., An, T., 2021. Superoxide radical enhanced photocatalytic
 674 performance of styrene alters its degradation mechanism and intermediate health risk on TiO₂/graphene surface.
 675 Environmental Research 195, 110747.
- Dong, H., Zeng, G., Tang, L., Fan, C., Zhang, C., He, X., He, Y., 2015. An overview on limitations of TiO₂-based particles
- 677 for photocatalytic degradation of organic pollutants and the corresponding countermeasures. Water research 79, 128-678 146.
- Dutta, T., Kim, T., Vellingiri, K., Tsang, D.C., Shon, J., Kim, K.-H., Kumar, S., 2019. Recycling and regeneration of
- 680 carbonaceous and porous materials through thermal or solvent treatment. Chemical Engineering Journal 364, 514-529.
- Figaro, S., Avril, J., Brouers, F., Ouensanga, A., Gaspard, S., 2009. Adsorption studies of molasse's wastewaters on
- activated carbon: Modelling with a new fractal kinetic equation and evaluation of kinetic models. Journal of hazardous
 materials 161, 649-656.
- Foo, K.Y., Hameed, B.H., 2010. Insights into the modeling of adsorption isotherm systems. Chemical engineering journal
 156, 2-10.
- 686 Gallego, E., Roca, X., Perales, J.F., Guardino, X., 2009. Determining indoor air quality and identifying the origin of odour
 687 episodes in indoor environments. Journal of Environmental Sciences 21, 333-339.
- 688 Giannakoudakis, D.A., Farahmand, N., Łomot, D., Sobczak, K., Bandosz, T.J., Colmenares, J.C., 2020. Ultrasound-
- 689 activated TiO₂/GO-based bifunctional photoreactive adsorbents for detoxification of chemical warfare agent surrogate

- 690 vapors. Chemical Engineering Journal 395, 125099.
- 691 González, D., Guerra, N., Colón, J., Gabriel, D., Ponsá, S., Sánchez, A., 2019. Filling in sewage sludge biodrying gaps:
- 692 Greenhouse gases, volatile organic compounds and odour emissions. Bioresource technology 291, 121857.
- 693 Gu, Z.-Y., Wang, G., Yan, X.-P., 2010. MOF-5 metal organic framework as sorbent for in-field sampling and
- 694 preconcentration in combination with thermal desorption GC/MS for determination of atmospheric formaldehyde.
- 695 Analytical chemistry 82, 1365-1370.
- 696 Guo, H., Lee, S., Chan, L., Li, W., 2004. Risk assessment of exposure to volatile organic compounds in different indoor
- 697 environments. Environmental Research 94, 57-66.
- Guo, Y., Sun, Y., Yang, D.-P., Dai, J., Liu, Z., Chen, Y., Huang, J., Li, Q., 2019. Biogenic Pt/CaCO₃ nanocomposite as
 a robust catalyst toward benzene oxidation. ACS applied materials & interfaces 12, 2469-2480.
- 700 Ha, S.-H., Kim, K.-H., Younis, S.A., Dou, X., 2020. The interactive roles of space velocity and particle size in a
- 701 microporous carbon bed system in controlling adsorptive removal of gaseous benzene under ambient conditions.
- 702 Chemical Engineering Journal 401, 126010.
- Ha, S.-H., Younis, S.A., Vikrant, K., Szulejko, J.E., Kim, K.-H., 2021. Evidence of the dominant role of particle size in
- 704 controlling the dynamic adsorption breakthrough behavior of gaseous benzene in a microporous carbon bed system.
- 705 Chemical Engineering Journal, 130977.
- Holzwarth, U., Gibson, N., 2011. The Scherrer equation versus the Debye-Scherrer equation'. Nature nanotechnology
 6, 534-534.
- Khan, A., Szulejko, J.E., Kim, K.-H., Sammadar, P., Lee, S.S., Yang, X., Ok, Y.S., 2019. A comparison of figure of merit
- (FOM) for various materials in adsorptive removal of benzene under ambient temperature and pressure. Environmental
 research 168, 96-108.
- 711 Khan, S., Park, J.-S., Ishihara, T., 2023. A Review of the Single-Step Flame Synthesis of Defective and Heterostructured

- 712 TiO₂ Nanoparticles for Photocatalytic Applications. Catalysts 13, 196.
- 713 Khan, W.U., Iris, K., Sun, Y., Polson, M.I., Golovko, V., Lam, F.L., Ogino, I., Tsang, D.C., Yip, A.C., 2021. Size-activity
- threshold of titanium dioxide-supported Cu cluster in CO oxidation. Environmental Pollution 279, 116899.
- 715 Kim, G.J., Kwon, D.W., Hong, S.C., 2016. Effect of Pt particle size and valence state on the performance of Pt/TiO₂
- catalysts for CO oxidation at room temperature. The Journal of Physical Chemistry C 120, 17996-18004.
- 717 Kim, J.-M., Vikrant, K., Kim, T., Kim, K.-H., Dong, F., 2021a. Thermocatalytic oxidation of gaseous benzene by a titanium
- 718 dioxide supported platinum catalyst. Chemical Engineering Journal, 131090.
- 719 Kim, W.-K., Younis, S.A., Kim, K.-H., 2021b. A strategy for the enhancement of trapping efficiency of gaseous benzene
- on activated carbon (AC) through modification of their surface functionalities. Environmental Pollution 270, 116239.
- 721 Kim, W.-K., Younis, S.A., Kim, K.-H., 2022. The control on adsorption kinetics and selectivity of formaldehyde in relation
- to different surface-modification approaches for microporous carbon bed systems. Separation and Purification
 Technology 283, 120178.
- Korologos, C.A., Nikolaki, M.D., Zerva, C.N., Philippopoulos, C.J., Poulopoulos, S.G., 2012. Photocatalytic oxidation of
- 525 benzene, toluene, ethylbenzene and m-xylene in the gas-phase over TiO₂-based catalysts. Journal of Photochemistry
- and Photobiology A: Chemistry 244, 24-31.
- Lee, K.J., Miyawaki, J., Shiratori, N., Yoon, S.-H., Jang, J., 2013. Toward an effective adsorbent for polar pollutants:
- Formaldehyde adsorption by activated carbon. Journal of hazardous materials 260, 82-88.
- Lee, S.H., Jang, Y.H., Nguyen, D.D., Chang, S.W., Kim, S.C., Lee, S.M., Kim, S.S., 2019. Adsorption properties of
 arsenic on sulfated TiO₂ adsorbents. Journal of Industrial and Engineering Chemistry 80, 444-449.
- 731 Lee, Y.-J., Vikrant, K., Szulejko, J.E., Kim, K.-H., Dong, F., 2021. Thermocatalytic oxidation of a three-component
- 732 mixture of volatile organic compounds by a titanium dioxide-supported platinum catalyst. Journal of Cleaner Production
- 733 325, 129279.

- Li, F., Li, X., 2002. The enhancement of photodegradation efficiency using Pt–TiO₂ catalyst. Chemosphere 48, 11031111.
- Liu, B., Yang, Y., Yang, T., Dai, Q., Zhang, Y., Feng, Y., Hopke, P.K., 2023. Effect of photochemical losses of ambient
- volatile organic compounds on their source apportionment. Environment International, 107766.
- Liu, B., Younis, S.A., Kim, K.-H., 2021a. The dynamic competition in adsorption between gaseous benzene and moisture
- on metal-organic frameworks across their varying concentration levels. Chemical Engineering Journal 421, 127813.
- Liu, B., Younis, S.A., Lee, J., Szulejko, J.E., Dou, X., Kim, K.-H., 2021b. The competing role of moisture in adsorption
- of gaseous benzene on microporous carbon. Separation and Purification Technology 277, 119487.
- Liu, Q., Wang, Y., Wen, M., Guo, Y., Wei, Y., Li, G., An, T., 2022a. Catalytic oxidation of formaldehyde over a Au@Co₃O₄
- 743 nanocomposite catalyst enhanced by visible light: moisture indispensability and reaction mechanism. Environmental
 744 Science: Nano 9, 4162-4176.
- Liu, R., Tian, M., Shang, W., Cui, J., Zhao, D., Liu, S., Zhao, Y., Ding, H., Fu, J., 2022b. Normal temperature catalytic
 degradation of toluene over Pt/TiO2. Environmental Technology 43, 2047-2058.
- Lou, C., Lei, G., Liu, X., Xie, J., Li, Z., Zheng, W., Goel, N., Kumar, M., Zhang, J., 2022. Design and optimization
 strategies of metal oxide semiconductor nanostructures for advanced formaldehyde sensors. Coordination Chemistry
 Reviews 452, 214280.
- 750 Ma, C., Li, X., Zhu, T., 2011. Removal of low-concentration formaldehyde in air by adsorption on activated carbon
- modified by hexamethylene diamine. Carbon 49, 2873-2875.
- 752 Murcia, J., Hidalgo, M., Navío, J., Vaiano, V., Sannino, D., Ciambelli, P., 2013. Cyclohexane photocatalytic oxidation on
- 753 Pt/TiO₂ catalysts. Catalysis Today 209, 164-169.
- Na, C.-J., Yoo, M.-J., Tsang, D.C., Kim, H.W., Kim, K.-H., 2019. High-performance materials for effective sorptive
- removal of formaldehyde in air. Journal of hazardous materials 366, 452-465.

- Nie, L., Yu, J., Li, X., Cheng, B., Liu, G., Jaroniec, M., 2013. Enhanced performance of NaOH-modified Pt/TiO₂ toward
- room temperature selective oxidation of formaldehyde. Environmental science & technology 47, 2777-2783.
- 758 Patrick, C.E., Giustino, F., 2014. Structure of a water monolayer on the anatase TiO₂ (101) surface. Physical Review
- 759 Applied 2, 014001.
- Pei, J., Zhang, J.S., 2011. On the performance and mechanisms of formaldehyde removal by chemi-sorbents. Chemical
- 761 Engineering Journal 167, 59-66.
- Pierotti, R., Rouquerol, J., 1985. Reporting physisorption data for gas/solid systems with special reference to the
 determination of surface area and porosity. Pure Appl Chem 57, 603-619.
- Rao, Z., Xie, X., Wang, X., Mahmood, A., Tong, S., Ge, M., Sun, J., 2019. Defect chemistry of Er³⁺-doped TiO₂ and its
- photocatalytic activity for the degradation of flowing gas-phase VOCs. The Journal of Physical Chemistry C 123, 1232112334.
- Robert, B., Nallathambi, G., 2021. Indoor formaldehyde removal by catalytic oxidation, adsorption and nanofibrous
 membranes: a review. Environmental Chemistry Letters 19, 2551-2579.
- Salthammer, T., Mentese, S., Marutzky, R., 2010. Formaldehyde in the indoor environment. Chemical reviews 110,
 2536-2572.
- Samaddar, P., Kim, K.-H., Yip, A.C., Zhang, M., Szulejko, J.E., Khan, A., 2019. The unique features of non-competitive
- vs. competitive sorption: Tests against single volatile aromatic hydrocarbons and their quaternary mixtures.
- Environmental research 173, 508-516.
- Shayegan, Z., Haghighat, F., Lee, C.-S., Bahloul, A., Huard, M., 2018a. Effect of surface fluorination of P25-TiO₂ on
- adsorption of indoor environment volatile organic compounds. Chemical Engineering Journal 346, 578-589.
- 776 Shayegan, Z., Lee, C.-S., Haghighat, F., 2018b. TiO₂ photocatalyst for removal of volatile organic compounds in gas
- phase–A review. Chemical Engineering Journal 334, 2408-2439.

- 778 Shikuku, V.O., Zanella, R., Kowenje, C.O., Donato, F.F., Bandeira, N.M., Prestes, O.D., 2018. Single and binary
- adsorption of sulfonamide antibiotics onto iron-modified clay: linear and nonlinear isotherms, kinetics, thermodynamics,
- 780 and mechanistic studies. applied water science 8, 1-12.
- 781 Tan, K., Hameed, B., 2017. Insight into the adsorption kinetics models for the removal of contaminants from aqueous
- solutions. Journal of the Taiwan Institute of Chemical Engineers 74, 25-48.
- 783 Thevenet, F., Olivier, L., Batault, F., Sivachandiran, L., Locoge, N., 2015. Acetaldehyde adsorption on TiO₂: Influence
- of NO₂ preliminary adsorption. Chemical Engineering Journal 281, 126-133.
- 785 Tran, T.Y., Younis, S.A., Heynderickx, P.M., Kim, K.-H., 2022. Validation of two contrasting capturing mechanisms for
- gaseous formaldehyde between two different types of strong metal-organic framework adsorbents. Journal of Hazardous
 Materials 424, 127459.
- 788 Vellingiri, K., Deng, Y.-X., Kim, K.-H., Jiang, J.-J., Kim, T., Shang, J., Ahn, W.-S., Kukkar, D., Boukhvalov, D.W., 2018.
- 789 Amine-functionalized metal-organic frameworks and covalent organic polymers as potential sorbents for removal of
- formaldehyde in aqueous phase: experimental versus theoretical study. ACS applied materials & interfaces 11, 1426-
- 791 1439.
- Verma, S., Dutta, R.K., 2015. A facile method of synthesizing ammonia modified graphene oxide for efficient removal of
- ranyl ions from aqueous medium. RSC advances 5, 77192-77203.
- Vikrant, K., Kim, K.-H., Kumar, V., Giannakoudakis, D.A., Boukhvalov, D.W., 2020a. Adsorptive removal of an eight-
- component volatile organic compound mixture by Cu-, Co-, and Zr-metal-organic frameworks: Experimental and
 theoretical studies. Chemical Engineering Journal 397, 125391.
- 797 Vikrant, K., Lim, D.-H., Younis, S.A., Kim, K.-H., 2020b. An efficient strategy for the enhancement of adsorptivity of
- 798 microporous carbons against gaseous formaldehyde: Surface modification with aminosilane adducts. Science of The
- 799 Total Environment 743, 140761.

- Vikrant, K., Na, C.-J., Younis, S.A., Kim, K.-H., Kumar, S., 2019. Evidence for superiority of conventional adsorbents in
 the sorptive removal of gaseous benzene under real-world conditions: Test of activated carbon against novel metal organic frameworks. Journal of Cleaner Production 235, 1090-1102.
- 803 Vikrant, K., Qu, Y., Kim, K.-H., Boukhvalov, D.W., Ahn, W.-S., 2020c. Amine-functionalized microporous covalent
- 804 organic polymers for adsorptive removal of a gaseous aliphatic aldehyde mixture. Environmental Science: Nano 7, 3447805 3468.
- Vikrant, K., Qu, Y., Szulejko, J.E., Kumar, V., Vellingiri, K., Boukhvalov, D.W., Kim, T., Kim, K.-H., 2020d. Utilization of
- 807 metal–organic frameworks for the adsorptive removal of an aliphatic aldehyde mixture in the gas phase. Nanoscale 12,
- 808 8330-8343.
- Vikrant, K., Yang, H., Chung, M., Kim, K.-H., Dong, F., Weon, S., He, C., Heynderickx, P., 2023. Two-dimensional
 titanium carbide (MXene)-supported Pt₃Ti intermetallic compound catalysts for efficient room-temperature oxidative
 removal of gaseous formaldehyde. Materials Today Nano 21, 100283.
- 812 Wang, L., Shi, C., Pan, L., Zhang, X., Zou, J.-J., 2020. Rational design, synthesis, adsorption principles and applications
- 813 of metal oxide adsorbents: a review. Nanoscale 12, 4790-4815.
- 814 Wang, X., Anand, B., Kim, K.-H., Younis, S.A., 2022. Insights into the performance of the two contrasting dynamic
- adsorption platforms in the removal of gaseous benzene on microporous carbon materials. Journal of Cleaner
 Production, 132520.
- 817 Wang, X., Kukkar, D., Younis, S.A., Vikrant, K., Ahmadi, Y., Boukhvalov, D., Kim, K.-H., 2023. The co-adsorption
- 818 potential of metal-organic framework/activated carbon composites against both polar and non-polar volatile organic
- 819 compounds in air. Separation and Purification Technology 306, 122594.
- 820 Wang, Y., Tao, H., Yu, D., Chang, C., 2018. Performance assessment of ordered porous electrospun honeycomb fibers
- for the removal of atmospheric polar volatile organic compounds. Nanomaterials 8, 350.

- Wang, Z., Pei, J., Zhang, J.S., 2014. Experimental investigation of the formaldehyde removal mechanisms in a dynamic
 botanical filtration system for indoor air purification. Journal of hazardous materials 280, 235-243.
- Wu, L., Qin, Z., Zhang, L., Meng, T., Yu, F., Ma, J., 2017. CNT-enhanced amino-functionalized graphene aerogel
 adsorbent for highly efficient removal of formaldehyde. New Journal of Chemistry 41, 2527-2533.
- Xiang, W., Zhang, X., Chen, K., Fang, J., He, F., Hu, X., Tsang, D.C., Ok, Y.S., Gao, B., 2020. Enhanced adsorption
- 827 performance and governing mechanisms of ball-milled biochar for the removal of volatile organic compounds (VOCs).
- 828 Chemical Engineering Journal 385, 123842.
- Xiao, Q., Wang, Y., Zhao, Z.-J., Pei, C., Chen, S., Gao, L., Mu, R., Fu, Q., Gong, J., 2020. Defect-mediated reactivity of
- 830 Pt/TiO₂ catalysts: the different role of titanium and oxygen vacancies. Science China Chemistry 63, 1323-1330.
- Xiao, Y., Azaiez, J., Hill, J.M., 2018. Erroneous application of pseudo-second-order adsorption kinetics model: ignored
- assumptions and spurious correlations. Industrial & Engineering Chemistry Research 57, 2705-2709.
- 833 Zhang, G., Peyravi, A., Hashisho, Z., Sun, Z., Liu, Y., Zheng, S., Zhong, L., 2020. Integrated adsorption and
- 834 photocatalytic degradation of VOCs using a TiO₂/diatomite composite: effects of relative humidity and reaction
- 835 atmosphere. Catalysis Science & Technology 10, 2378-2388.
- 836 Zhang, J., Vikrant, K., Kim, K.-H., Dong, F., 2022a. Photocatalytic destruction of volatile aromatic compounds by
- 837 platinized titanium dioxide in relation to the relative effect of the number of methyl groups on the benzene ring. Science
- 838 of The Total Environment 822, 153605.
- Zhang, J., Vikrant, K., Kim, K.-H., Dong, F., Chung, M.W., Weon, S., 2022b. Unveiling the collective effects of moisture
- 840 and oxygen on the photocatalytic degradation of m-Xylene using a titanium dioxide supported platinum catalyst.
- 841 Chemical Engineering Journal 439, 135747.
- 842 Zhang, L., 2018. Formaldehyde: exposure, toxicity and health effects. Royal Society of Chemistry.
- 843 Zhang, X., Gao, B., Creamer, A.E., Cao, C., Li, Y., 2017. Adsorption of VOCs onto engineered carbon materials: A

- 844 review. Journal of hazardous materials 338, 102-123.
- 845 Zhu, X., He, M., Sun, Y., Xu, Z., Wan, Z., Hou, D., Alessi, D.S., Tsang, D.C., 2022. Insights into the adsorption of
- 846 pharmaceuticals and personal care products (PPCPs) on biochar and activated carbon with the aid of machine learning.
- 847 Journal of Hazardous Materials 423, 127060.

854 Tables

855

		Benzene (B)		Toluene (T)		m-Xylene (X)		Styrene (S)			Formaldehyde (FA)					
Order	Materials	BTV ^a	Qb	PC ^c	BTV	Q	РС	BTV	Q	РС	BTV	Q	РС	BTV	Q	PC
		(L atm g ⁻¹)	mg g ⁻¹	mol kg ⁻¹ Pa ⁻¹	(L atm g ⁻¹)	mg g ⁻¹	mol kg ⁻¹ Pa ⁻¹	(L atm g ⁻¹)	mg g ⁻¹	mol kg ⁻¹ Pa ⁻¹	(L atm g ⁻¹)	mg g ⁻¹	mol kg ⁻¹ Pa ⁻¹	(L atm g ⁻¹)	mg g ⁻¹	mol kg ⁻¹ Pa ⁻¹
a. 10% BT																
1	TiO ₂	-	-	-	-	-	-	-	-	-	2.06	0.008	0.007	15.98	0.91	0.002
2	Pt@TiO ₂	-	-	-	-	-	-	4.13	0.016	0.016	9.98	0.038	0.040	23.77	1.48	0.021
b. 100% BT																
3	TiO ₂	5.84	0.0004	0.00001	11.73	0.001	0.0001	18.44	0.019	0.002	809.41	0.043	0.004	818.85	4.62	0.031
4	Pt@TiO ₂	11.13	0.0006	0.00008	31.27	0.006	0.0006	67.43	0.029	0.003	1290.09	0.26	0.024	1381.15	6.75	0.043

856 Table 1. The performance comparison against BTXS (1 ppm each) + FA (50 ppm) between pure TiO₂ and Pt@TiO₂.

857 ^aBTV: breakthrough volume

858 ^bQ: adsorption capacity

859 °PC: partition coefficient

860

861

862

868	Table 2. Summary	of FA adsorption	experiments onto	Pt@TiO ₂ acro	ss varying sorbent mass,	, formaldehyde (FA)	concentration, and relative
-----	------------------	------------------	------------------	--------------------------	--------------------------	---------------------	-----------------------------

869 humidity (RH) levels.

	Va	riablas		ртуа (\mathbf{I} at \mathbf{m} \mathbf{a}^{-1}	Partition	coefficient	Adsorption capacity (Q:		
Qudan	variables			DIV	DIV (L'atting)		l kg ⁻¹ Pa ⁻¹)	mg g ⁻¹)		
Order	Sorbent	FA	RH	10%	100%	10%	100%	10%	100%	
	mg	ppm	%							
1	5	50	0%	18.85	976.41	0.009	0.027	1.13	4.32	
2	10	50	0%	20.11	1085.74	0.088	0.054	1.27	8.64	
3	20	50	0%	32.17	1466.53	0.13	0.061	2.01	9.61	
4	20	25	0%	44.86	2331.00	0.23	0.086	1.40	6.72	
5	20	250	0%	7.90	451.02	0.041	0.016	2.34	11.93	
6	20	500	0%	9.95	213.96	0.045	0.010	5.43	14.33	
7	20	700	0%	11.55	149.11	0.065	0.007	9.28	15.01	
8	20	50	20%	19.31	1024.68	0.11	0.037	1.01	4.98	
9	20	50	50%	20.65	1140.08	0.12	0.034	1.08	4.57	
10	20	50	80%	11.04	997.29	0.051	0.027	0.56	3.51	
11	20	50	100%	6.95	802.43	0.032	0.021	0.45	3.15	

870 ^aBTV: breakthrough volume

Table 3. Summary of BTXS + FA adsorption experiments onto Pt@TiO2 across varying process variables (e.g., sorbent mass, FA+BTXS

	Variables (unit)			Benzene (B)	Toluene	Toluene (T)		m-Xylene (X)		Styrene (S)		Formaldehyde (FA)	
Order	Sorbent	FA	BTXS	RH	Q ^b	BTV ^a	Q	BTV	Q	BTV	Q	BTV	Q	BTV
	mg	ppm	ppm	%	(mg g ⁻¹)	(L atm g ⁻¹)	(mg g ⁻¹)	(L atm g ⁻¹)	(mg g ⁻¹)	(L atm g ⁻¹)	(mg g ⁻¹)	(L atm g ⁻¹)	(mg g ⁻¹)	(L atm g ⁻¹)
1	5	50	1	0%	0.001	31.87	0.007	69.00	0.039	125.62	0.15	992.03	2.35	685.67
2	10	50	1	0%	0.001	21.44	0.006	56.37	0.025	53.78	0.11	841.71	5.19	995.93
3	20	50	1	0%	0.0006	11.13	0.006	31.27	0.029	67.43	0.26	1290.09	6.75	1381.15
4	20	25	0.5	0%	0.0072	12.60	0.019	29.28	0.062	153.83	0.16	799.42	6.29	1330.88
5	20	250	5	0%	0.004	4.55	0.012	7.39	0.045	20.97	0.29	603.88	9.30	276.58
6	20	500	10	0%	0.005	11.23	0.028	15.40	0.12	15.45	0.34	221.05	10.89	97.09
7	20	700	14	0%	0.021	4.02	0.052	5.58	0.14	11.26	0.34	31.52	11.76	70.23
8	20	50	1	20%	0.0005	4.28	0.002	11.12	0.011	63.25	0.10	798.12	4.47	916.00
9	20	50	1	50%	0.0002	4.54	0.001	8.06	0.005	43.76	0.10	704.52	3.49	882.43
10	20	50	1	80%	0.0002	4.57	0.001	9.58	0.003	47.15	0.077	658.48	2.68	833.28
11	20	50	1	100%	0.0000009	3.19	0.0003	8.08	0.005	43.18	0.067	494.26	2.03	518.66

881 ^aBTV: breakthrough volume

882 ^bQ: adsorption capacity

883

Table 4. Results of pseudo-first-order (PFO), pseudo-second-order (PSO), and intraparticle diffusion (IPD)
kinetic model for FA adsorption over Pt@TiO₂ between single (FA) and multicomponent (FA+BTXS) gas
phases.

Order	Model	Parameter	Single	Multicomponent
		q _e , experimental (mg g	9.61	6.75
1	PFO	$Q_{m,1} (mg g^{-1})$	9.03	6.61
2		$k_1 (min^{-1})$	0.110	0.155
3		χ^2	0.122	0.192
4		R^2	0.992	0.978
5	PSO	$Q_{m,2} (mg g^{-1})$	10.41	7.71
6		$K_2 (g mg^{-1} min^{-1})$	0.0131	0.0232
7		χ^2	0.034	0.181
8		R^2	0.999	0.989
9	IPD	$K_{id1} (mg g^{-1} min^{-1/2})$	0.964	0.961
10		$C_{id1}(mg g^{-1})$	-0.211	-0.212
11		R_{id1}^2	0.985	0.985
12		$K_{id2} \ (mg \ g^{-1} \ min^{-1/2})$	2.269	1.825
13		$C_{id2} (mg g^{-1})$	-1.144	-0.707
14		R_{id2}^2	0.991	0.986
15		$K_{id3} (mg g^{-1} min^{-1/2})$	0.467	0.361
16		$C_{id3}(mg g^{-1})$	5.543	3.717
17		R_{id3}^2	0.975	0.993

891	$Pt@TiO_2$ from	single and multice	omponent gas phases.		
	Order	Model	Parameter	Single	Multicomponent
	1	Langmuir	$Q_m (mg g^{-1})$	14.899	11.321
	2		K_{L} (Pa ⁻¹)	0.327	0.378
	3		χ^2	0.855	0.869
	4		R^2	0.927	0.852
	5	Freundlich	$K_{\rm F} ({\rm mg \ g}^{-1} {\rm Pa}^{-1/n})$	6.262	4.924
	6		n	4.812	4.771

 χ^2

 R^2

A (L Pa⁻¹)

B (J mol⁻¹)

 χ^2

 R^2

Table 5. Summary of the Langmuir, Freundlich, and Temkin isotherm constants for FA adsorption onto 890

0.143

0.986

14.517

1.647

0.168

0.971

0.440

0.991

8.820

2.323

0.432

0.963

891	Pt@TiO ₂	from	single	and	multicon	nponent	gas	phases.	
-----	---------------------	------	--------	-----	----------	---------	-----	---------	--

Temkin

892

7

8

9

10

11

12

889

893

894

896 Figure



Fig. 1. Schematic of the adsorption unit for FA and BTXS in this study.



Fig. 2. Characterization of TiO₂ and Pt@TiO₂ materials: (a) PXRD patterns of Pt@TiO₂ (red) and TiO₂

905 (black), (b) N_2 adsorption-desorption isotherms of TiO₂ and Pt@TiO₂, and (c) their pore size distributions.

- _ _ _

-



Fig. 3. XPS analysis of TiO₂ and Pt@TiO₂ materials: (a) full survey scan, (b) and (d) deconvoluted Ti 2p,

^{918 (}c) and (e) deconvoluted O 1s, and (f) deconvoluted Pt 4f.





Fig. 4. Adsorption breakthrough profiles of multicomponent VOCs: (a) TiO₂ and (b) Pt@TiO₂ adsorbents
(concentration of benzene, toluene, m-xylene, and styrene (BTXS) = 1 ppm each, formaldehyde (FA) = 50
ppm, RH = 0%, and adsorbent mass = 20 mg).



Fig. 5. Dynamic BT profiles for the adsorption of FA at different relative humidity (RH: 0%, 20%, 50%, 80%, and 100%) onto Pt@TiO₂: (a) single phase formaldehyde (FA) and (b) multi-component phase FA
(FA 50 ppm in single phase system, FA 50 ppm + BTXS 1 ppm (each) in multicomponent phase systems, adsorbent mass = 20 mg, and RH = 0%).



Fig. 6. Non-linearly fitted kinetic models for formaldehyde (FA) adsorption by Pt@TiO₂ in varying gas compositions: (a-b) single FA gas system (fitting profiles with (a) pseudo-first-order (PFO)/pseudo-second-order (PSO) models and (b) intraparticle diffusion (IPD) model) and (c-d) multicomponent VOC gas mixture (fitting profiles with (c) PFO/PSO models and (d) IPD model) (conditions: VOC concentration = FA 50 ppm for single component system, FA 50 ppm + BTXS 1 ppm (each) for multicomponent systems, adsorbent mass = 20 mg, and RH = 0%).



Fig. 7. Non-linear isotherm fitting profiles of Langmuir, Freundlich, and Temkin isotherm models for formaldehyde (FA) adsorption by $Pt@TiO_2$: (a) single FA gas phase and (b) multicomponent VOC gas phase (conditions: VOC concentration = FA 50 ppm in single phase system, FA 50 ppm + BTXS 1 ppm (each) in multicomponent phase systems, adsorbent mass = 20 mg, and RH = 0%).



Fig. 8. Regeneration performance of $Pt@TiO_2$ against gaseous formaldehyde (FA) from single and multicomponent VOC gas phases (Conditions: VOC concentration = FA 50 ppm in single phase system, FA 50 ppm + BTXS 1 ppm (each) in multicomponent phase systems, adsorbent mass = 20 mg, and RH = 0%).

1001 Supporting information

Table S1. Operating conditions/parameters of the LVI-GC-FID system used to analyze FA+BTXSadsorption.

Order	Condition/Parameter	Value					
Column (DB-	1)						
1	Length	30 m					
2	Inner diameter	0.32 mm					
3	Film thickness	5 µm					
4	Temperature	$80^\circ\mathrm{C}$ hold for 1.3 min, then increased to 150 $^\circ\mathrm{C}$					
		with 30 °C/min and hold for 2min					
LVI							
1	Temperature	240 °C					
2	Injection mode	Split					
3	Carrier gas	N_2					
4	Flow control mode	Pressure					
5	Pressure	128.7 kPa					
6	Total flow rate	27 mL min ⁻¹					
7	Column flow rate	4 mL min ⁻¹					
8	Linear velocity	60.9 cm sec ⁻¹					
9	Purge flow rate	3 mL min ⁻¹					
10	Split ratio	5					
Detector and miscellaneous							
1	Detector type	FID					
2	Detector temperature	250 °C					
3	Makeup gas	N_2					
4	Makeup flow rate	30 mL min ⁻¹					
5	H ₂ flow rate	30 mL min ⁻¹					
6	Air flow rate	300 mL min ⁻¹					

Table S2. The partition coefficient (PC) values for BTXS + FA adsorption onto Pt@TiO₂ for changes in sorbent mass, BTXS+FA concentration, and relative humidity (RH) levels at 100% BT level.

	Variables (unit)				Bonzono (B)	Toluona (T)	m Vylono (V)	Styrong (S)	Formaldehyde
Order	Sorbent	FA	BTXS	RH	Denzene (D)			Styrene (S)	(FA)
	mg	ppm	ppm	%					
1	5	50	1	0%	0.00011	0.001	0.003	0.013	0.016
2	10	50	1	0%	0.00012	0.001	0.003	0.011	0.034
3	20	50	1	0%	0.00008	0.0006	0.003	0.024	0.043
4	20	25	0.5	0%	0.00182	0.0013	0.011	0.032	0.084
5	20	250	5	0%	0.00010	0.0001	0.0009	0.006	0.010
6	20	500	10	0%	0.00006	0.0003	0.0011	0.003	0.007
7	20	700	14	0%	0.00021	0.0004	0.0010	0.003	0.006
8	20	50	1	20%	0.00006	0.0002	0.001	0.010	0.031
9	20	50	1	50%	0.00002	0.0001	0.000	0.010	0.024
10	20	50	1	80%	0.00003	0.0001	0.000	0.009	0.019
11	20	50	1	100%	0.0000001	0.00003	0.0004	0.007	0.015

Ordon	Mataviala	FA concentration	A concentrationPartial pressureTemperatureMaximum adsort(ppm)(Pa)(°C)capacity (mg		Maximum adsorption	Partition coefficient	Doforonao
Oruer	Ivraterials	(ppm)			capacity (mg g-1)	(mol kg-1 Pa-1)	Kelerence
1	Activated carbon	1	0.1	25	0.11	0.04	(Vikrant et al., 2020b)
2	Activated carbon	2.18	0.218	25	0.08	0.012	(Ma et al., 2011)
3	Activated carbon	14	1.4	ambient	0.02	0.04	(Vikrant et al., 2020d)
4	Nitrogen and sulfur heteroatom modified activated carbon by solvothermal method	1	0.1	25	0.13	0.04	(Vikrant et al., 2020b)
5	MOF-5 (prepared at 120°C)	22.7	2.27	20	0.11	0.002	(Gu et al., 2010)
6	MOF-5 (prepared at 25°C)	14	1.4	ambient	4.1	0.047	(Vikrant et al., 2020d)
7	UiO-66	14	1.4	ambient	4.3	0.054	(Vikrant et al., 2020d)
8	CE	100	10	25	105	0.35	(Vikrant et al., 2020c)
9	Graphene	3.7	0.37	-	0.62	0.06	(Wu et al., 2017)
10	Pt@TiO ₂	50 (single phase system)	5	RT	9.61	0.061	This work
11	Pt@TiO ₂	50 (multicomponent phase system)	5	RT	6.75	0.043	This work

1028 Table S3. Performance comparison of $Pt@TiO_2$ and other commonly used adsorbents for the removal of gaseous FA.

Figure S1. FE-SEM images of analyzed materials: (a) TiO₂ and (b) Pt@TiO₂; EDS elemental mapping of
the Pt@TiO₂: (c) Pt@TiO₂, (d) O, (e) Pt, and (f) Ti.

Figure S2. Dynamic BT profiles for the effect of Pt@TiO₂ bed mass on FA adsorption: (a) single FA gas
phase at 5 -20 mg bed masses and (b-d) multicomponent VOC gas phase system ((b) 5 mg bed mass, (c) 10
mg bed mass, and (d) 20 mg bed mass). Experimental setups: VOC concentration = FA 50 ppm for single
phase system, FA 50 ppm + BTXS 1 ppm (each) for multicomponent phase systems, and RH = 0%.

Figure S3. The equilibrium adsorption capacities of BTXS+FA onto $Pt@TiO_2$ in multicomponent VOC gas phase system at varying experimental parameters: (a) adsorbent masses (Experimental conditions: BTXS 1 ppm each + FA 50 ppm and RH = 0%), (b) BTXS + FA concentrations (Experimental conditions: adsorbent mass = 20 mg and RH = 0%), and (c) RH levels (Experimental conditions: BTXS 1 ppm each + FA 50 ppm and adsorbent mass = 20 mg).