Supplementary Information for

Hybrid GC Platform: A Micro Gas Chromatography System with a Simple Configuration for Low-Concentration VOCs Analysis

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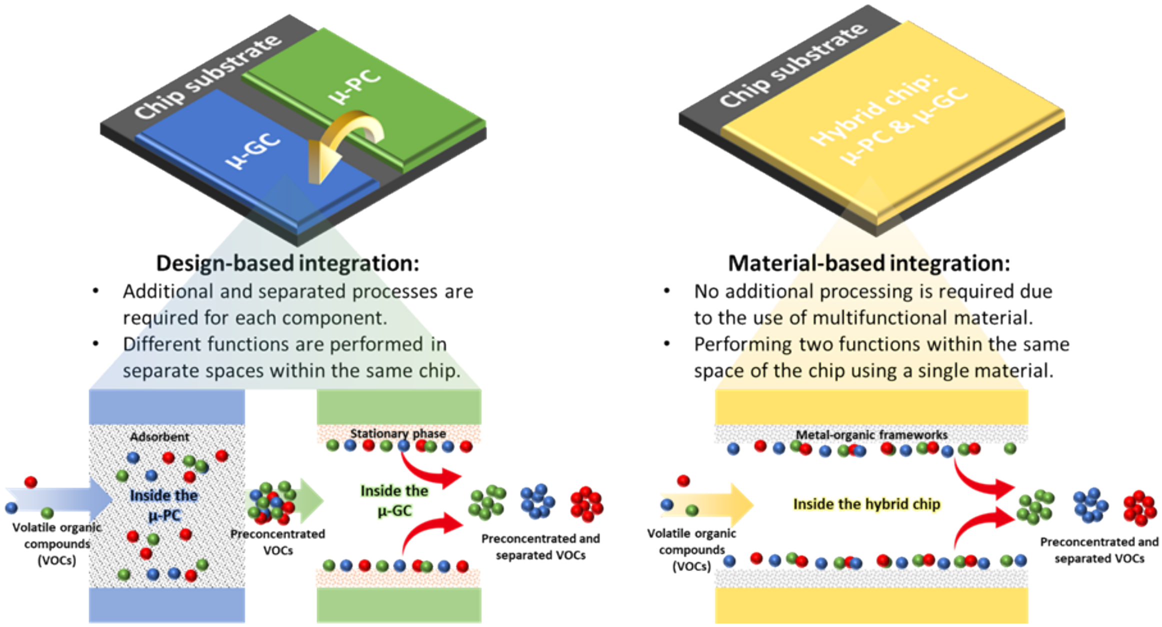
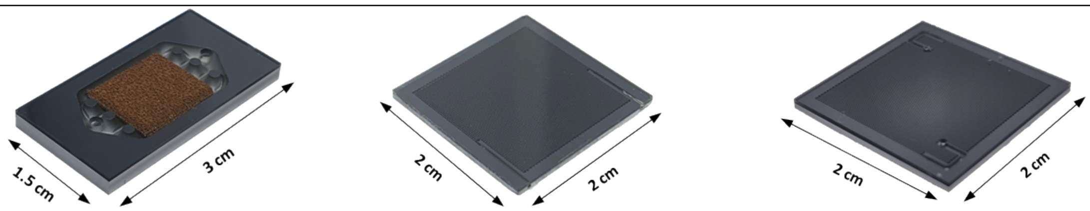


Fig. S1 Schematic illustration highlighting the difference between design-based integration and material-based integration.

Table S1 Production cost comparison between the combination of a µ-PC and a µ-GC and the hybrid chip.



µ-PC		**µ-GC**		**Hybrid chip**	
Production	Cost ($)	Production	Cost ($)	Production	Cost ($)
Microfabrication	1,400 for 4-icnh wafer	Microfabrication	2,300 for 6-icnh wafer	Microfabrication	2,500 for 6-icnh wafer
Adsorbent	Dependent	Stationary phase	Dependent	Metal-organic frameworks	Dependent
Unit price of a µ-PC	140	Unit price of a µ-GC	92	Unit price of a hybrid chip	100
µ-PC & µ-GC ($232) **> hybrid chip** ($100)					

Note: The unit prices for each chip were estimated based on the KRW-to-USD exchange rate as of April 30, 2025. Detailed microfabrication steps are not disclosed. The cost associated with the fabrication of the pattern mask has been excluded. These estimates may be inflated due to the non-mass production nature of the process, and actual costs may vary depending on labor and equipment usage.

Table S2 List of components used in the hybrid GC platform.

Component type	Name	Product	Manufacturer
Electrical components	Microprocessor	Arduino Nano	Arduino
	PID sensor	PID-AY5	Alphasense
	3-way valve	LHDA0533415H	The LEE Company
	Pump	SP 200 EC-LC	Schwarzer Precision
	Battery (4 ea) (50 × 50 × 10 mm^3, 20 g)	TW 105050	Taiwoo (Shenzen) Technology
Other components	PTFE tubing (target gas)	F300-070	Tommyheco
	Fluidic connectors	N-333, P-770, F-333N	IDEX Health & Science
	Tygon tubing (carrier gas)	ACF00001	Saint-Gobain Life Science
	Fittings	URU-0201, UFS-02, UUT-02	UNILOK
	Tedlar bag	205-2001-03	Dongbanghitech
	Hybrid chip module	Designed and fabricated in the laboratory.	
	PID module		
	Carrier gas filter pack		

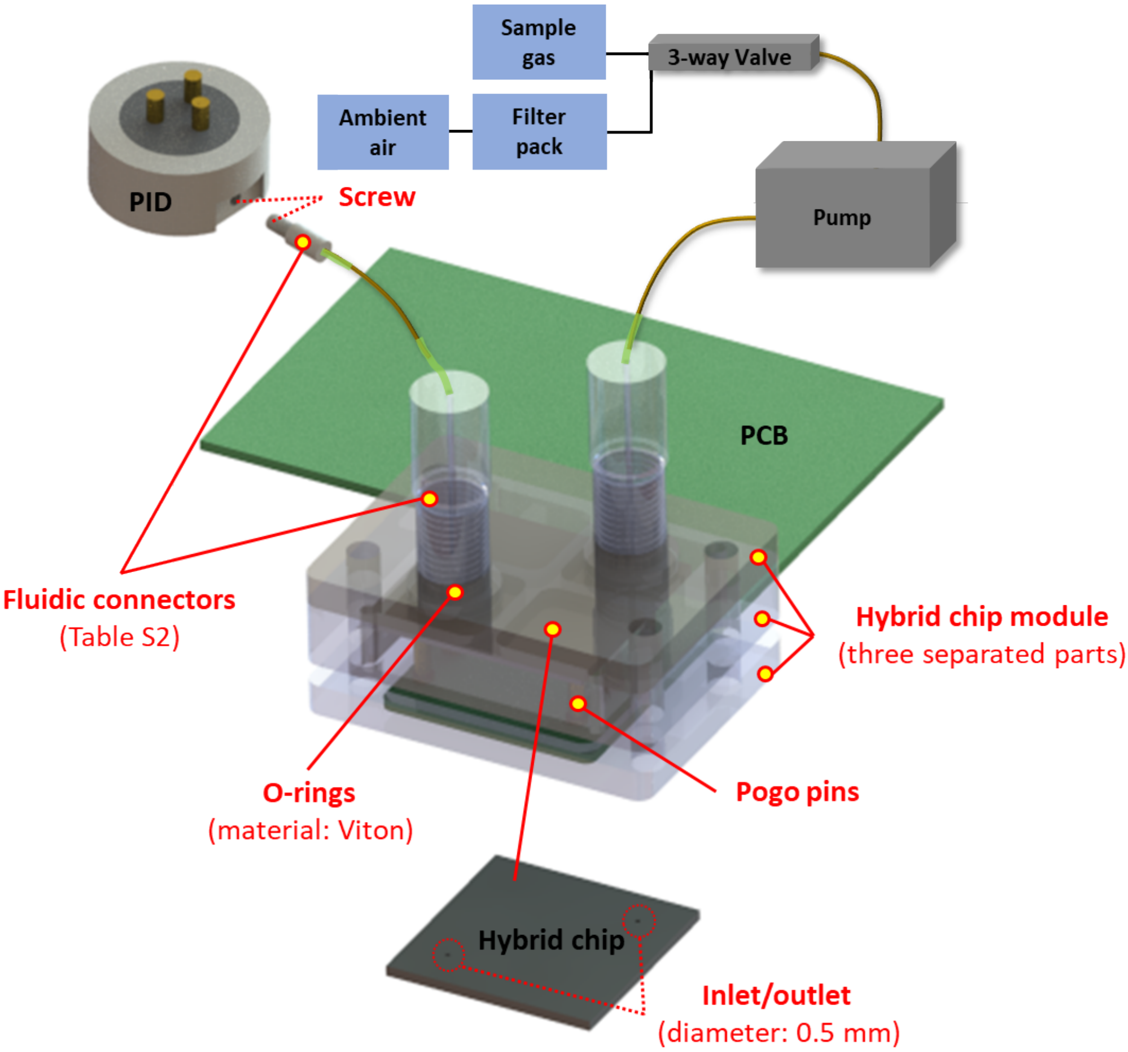


Fig. S2 Detailed interconnections between components in the hybrid GC platform.

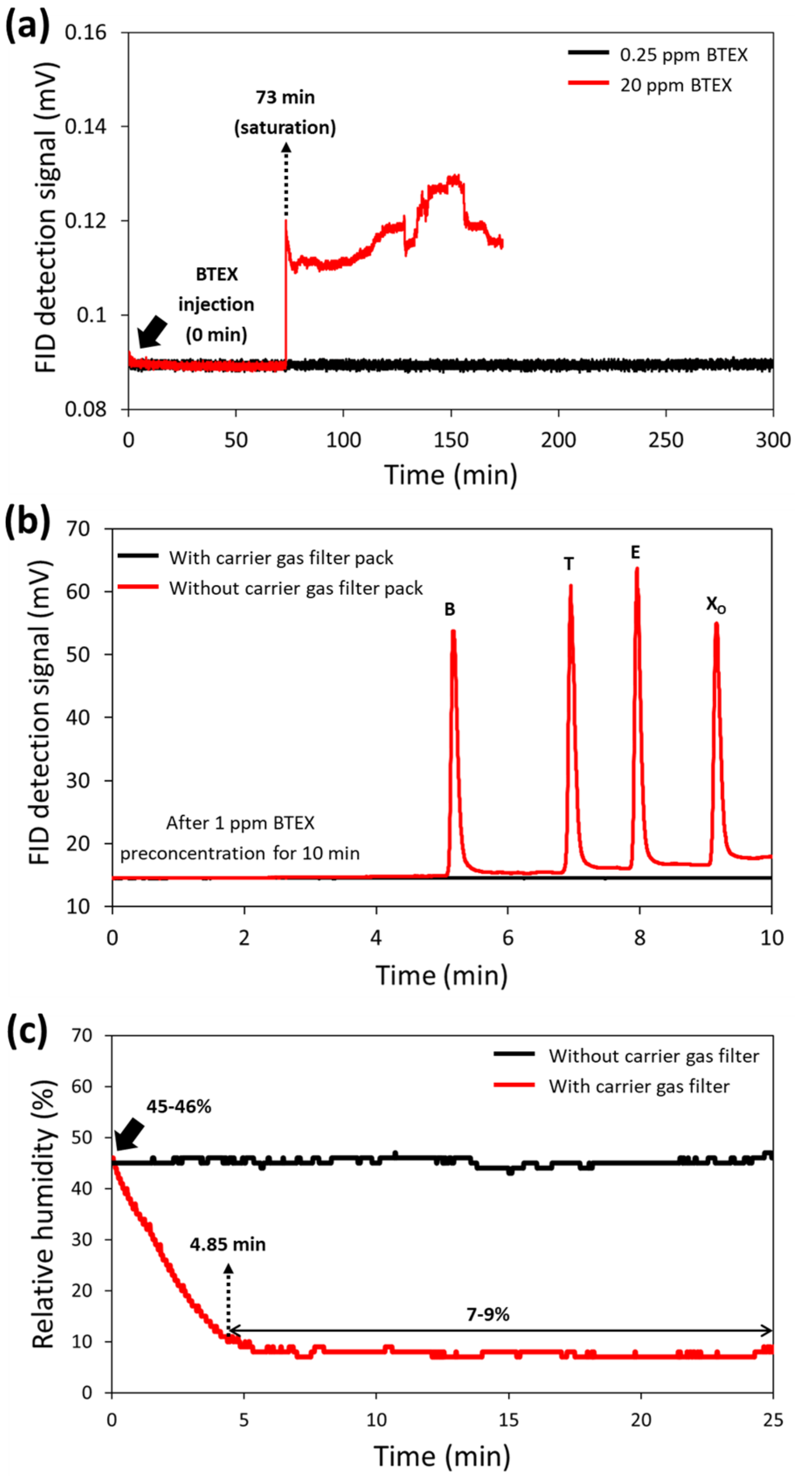


Fig. S3 Performance of the carrier gas filter pack for the removal of interfering VOCs and moisture. (a) Removal of 0.25 and 20 ppm BTEX by the filter pack using a commercial FID (fluid direction: BTEX supplied by mass flow controller → filter pack → FID), (b) BTEX removal by the filter pack connected to the hybrid chip (fluid direction: BTEX supplied by mass flow controller → filter pack → hybrid chip → GC-FID), and (c) moisture removal by the filter pack (fluid direction: ambient air → filter pack → pump → uncoated hybrid chip → humidity sensor). The flow rates were 4 mL·min^{-1} in (a, b) and 4.08 mL·min^{-1} in (c).

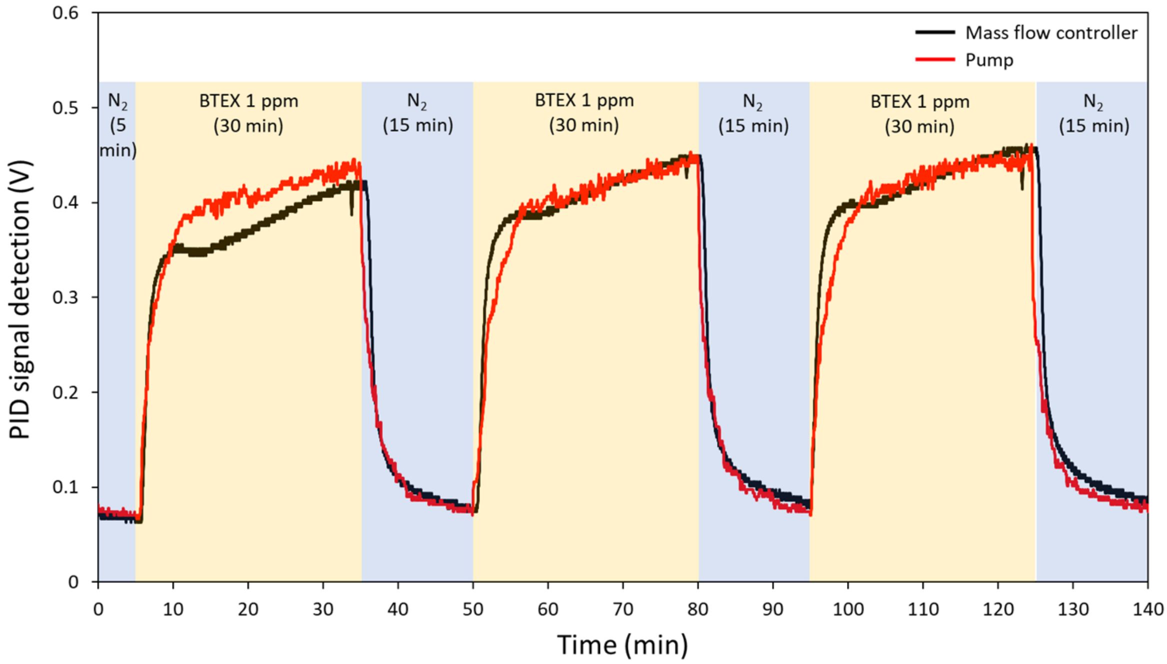


Fig. S4 Results of the pump contamination test. When using the mass flow controller (MFC), the flow direction was MFC → uncoated hybrid chip → PID (4 mL·min^{-1}). When using the pump, the flow direction was Tedlar bags → three-way valve → pump → uncoated hybrid chip → PID (4.08 mL·min^{-1}).

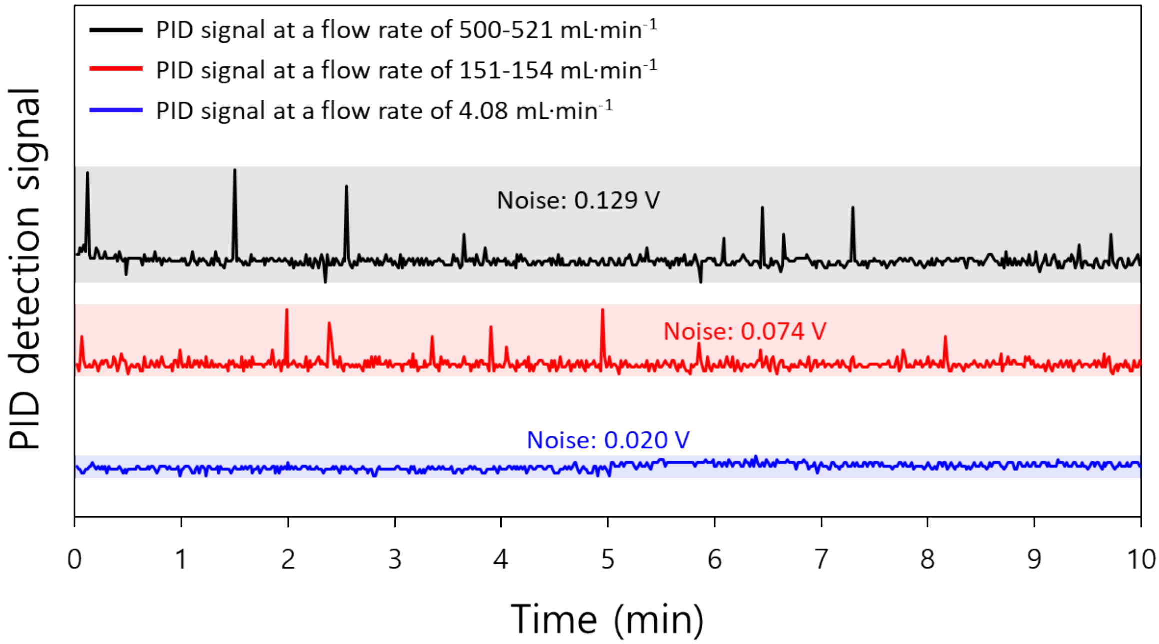


Fig. S5 Noise signals under different setups due to pump pulsation. Black colored line: PID signal obtained from a flow path consisting of a carrier gas filter pack → pump → 20 cm PTFE tubing (inner diameter: 5/32 inch) → PID sensor (flow rate: 500-521 mL·min^{-1}), red colored line: PID signal obtained from a flow path consisting of a carrier gas filter pack → pump → 20 cm uncoated capillary column (inner diameter: 0.25 mm) → PID sensor (flow rate: 151-154 mL·min^{-1}), and blue colored line: PID signal obtained from a flow path consisting of a carrier gas filter pack → pump → hybrid chip → PID sensor (flow rate: 4.08 mL·min^{-1}).

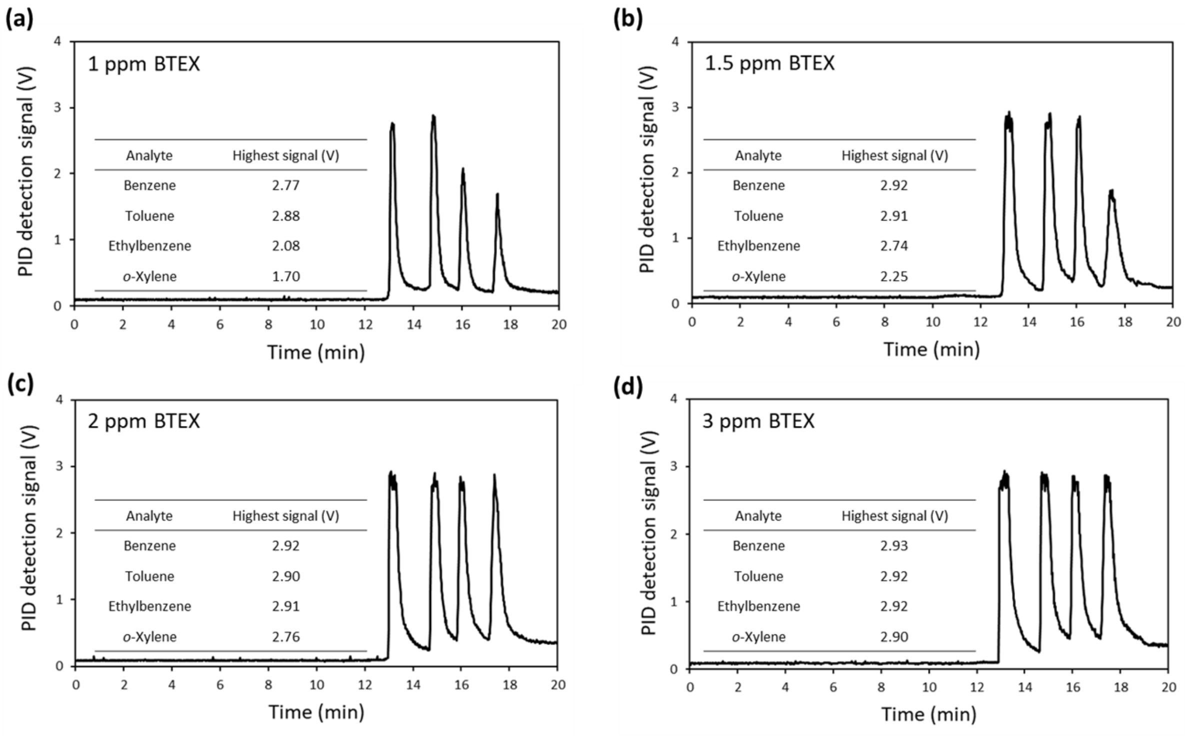


Fig. S6 Experimental results for various concentrations of BTEX to determine the linear range. (a–d) Chromatograms of 1, 1.5, 2, and 3 ppm BTEX, respectively, including the highest PID detection signal for each analyte peak.

Table S3 Peak width, full width at half height (FWHH), and peak capacity for all chromatograms.

Chromatogram	Peak number	Chemical	Peak width[a] (min)	FWHH[b] (min)	Analysis time[c] (min)	Peak capacity[d]
0.25 ppm BTEX in Fig. 4a	1	Benzene	0.61	0.27	4.5	7.87
	2	Toluene	0.54	0.27		
	3	Ethylbenzene	0.62	0.29		
	4	*o*-Xylene	0.85	0.34		
0.5 ppm BTEX in Fig. 4a	1	Benzene	0.7	0.24	4.49	8.18
	2	Toluene	0.53	0.25		
	3	Ethylbenzene	0.59	0.27		
	4	*o*-Xylene	0.68	0.32		
1 ppm BTEX in Fig. 4a	1	Benzene	0.65	0.22	4.45	8.81
	2	Toluene	0.5	0.27		
	3	Ethylbenzene	0.57	0.25		
	4	*o*-Xylene	0.56	0.25		
1.5 ppm BTEX in Fig. S6	1	Benzene	0.92	0.42	4.28	6.17
	2	Toluene	0.88	0.4		
	3	Ethylbenzene	0.58	0.27		
	4	*o*-Xylene	0.93	0.49		
2 ppm BTEX in Fig. S6	1	Benzene	1.02	0.42	4.28	6.30
	2	Toluene	0.75	0.38		
	3	Ethylbenzene	0.73	0.33		
	4	*o*-Xylene	0.73	0.35		
3 ppm BTEX in Fig. S6	1	Benzene	1.19	0.5	4.27	5.34
	2	Toluene	1.07	0.44		
	3	Ethylbenzene	0.8	0.4		
	4	*o*-Xylene	0.88	0.45		
Alkane mixture in Fig. 6	1	Pentane	0.53	0.3	3.42	9.34
	2	Hexane	0.4	0.23		
	3	Heptane	0.42	0.23		
	4	Octane	0.35	0.21		
	5	Nonane	0.35	0.22		
Alcohol mixture in Fig. 6	1	Ethanol	0.69	0.35	6.36	11.26
	2	Propanol	0.74	0.32		
	3	Butanol	0.43	0.27		
Aldehyde mixture in Fig. 6	1	Ethanal	0.38	0.2	5.29	10.35
	2	Propanal	0.47	0.3		
	3	Butanal	0.53	0.23		
	4	Pentanal	0.45	0.35		
	5	Hexanal	1	0.31		
Ketone mixture in Fig. 6	1	Propanone	0.63	0.29	4.38	8.06
	2	Butanone	0.58	0.28		
	3	Pentanone	0.65	0.32		
Mixture in Fig. 7	1	Ethanol	0.85	0.28	6.56	13.23
	2	Benzene	0.45	0.24		
	3	Heptane	0.48	0.23		
	4	Toluene	0.47	0.25		
	5	Ethylbenzene	0.67	0.33		
	6	*m*-Xylene	0.47	0.28		
	7	*o*-Xylene	0.41	0.23		
	8	Petanone	0.49	0.23		

a peak width was measured at 10% of peak height.

b FWHH was determined at 50% of peak height

c analysis time was defined as the difference between the retention times of the last and first eluted peaks.

d peak capacity was calculated as $n_p = 1 + (t_{end} - t_{start})/w$, where w is the average peak width, t_{start} is the retention time of the first eluted peak, and t_{end} is that of the last eluted peak.

Table S4 Quantitative analysis via the hybrid GC platform.

Analyte	Linear range (ppm)	Equation	Linearity (R^2 value)	SD[a] (V·min)	LOD[b] (ppm)
Benzene	0.25–1	y = 0.9073x + 0.0330	0.9978	0.00532	0.0193
Toluene	0.25–1	y = 0.9043x + 0.0681	0.9992	0.00624	0.0228
Ethylbenzene	0.25–1.5	y = 0.4892x + 0.0081	0.9957	0.00450	0.0304
Ortho-Xylene	0.25–2	y = 0.4628x – 0.0328	0.9984	0.00342	0.0244

a standard deviation (SD) of the peak areas obtained from 30 repeated experiments with 0.25 ppm BTEX.
b LOD = $3.3 \cdot SD \cdot S^{-1}$ (S is the slope of the equation).

Table S5 Limit of detection of the hybrid GC platform calculated by the signal-to-noise ratio method.

Concentration	Analyte	Peak height (V)	Peak width at half height (min)	Range for noise (min)	Noise in blank (V)	Signal-to-noise ratio
10 ppb	Benzene	0.074	0.3	10.32–16.32	0.02	3.7
	Toluene	0.121	0.233	12.49–17.15	0.02	6.05
	Ethylbenzene	0.043	0.267	13.68–19.02	0.02	2.15
	o-Xylene	0.035	0.267	15.08–20.00	0.02	1.75
5 ppb	Benzene	0.043	0.267	10.60–15.94	0.02	2.15
	Toluene	0.051	0.2	12.8–16.8	0.02	2.55
	Ethylbenzene	0.020	0.317	13.13–19.47	0.02	1
	o-Xylene	0.016	0.167	16.06–19.40	0.02	0.8

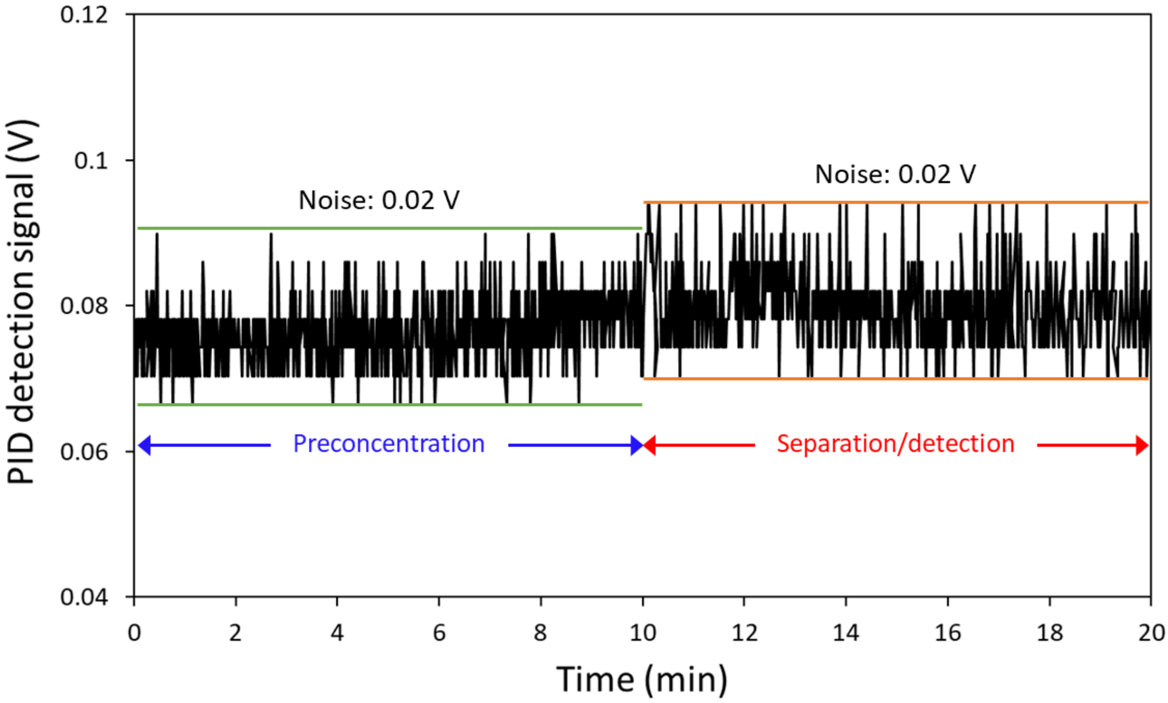


Fig. S7 Noise levels measured in the blank test.

Table S6 TD–GC–MS analysis conditions.

Preconcentration (PC) and thermal desorption (TD) conditions						
Adsorbent	PC time	PC flow rate	TD instrument	TD temperature	TD time	TD flow rate
Tenax-TA	5 min	100 mL·min^{-1}	MARKES TD100-xr	250°C	30 min	50 mL·min^{-1}
GC separation and MS detection conditions						
Column	GC instrument	Carrier gas	Oven conditions	MS instrument	Ionization	Scan range
HP-5MS	Agilent Technologies 8890 GC	Helium (1 mL·min^{-1})	Hold at 40°C for 5 min, ramp from 40°C to 150°C at a rate of 5°C·min^{-1}, and ramp from 150°C to 240°C at a rate of 10°C·min^{-1}	Agilent Technologies 5977B MSD	70 eV	50–500 m·z^{-1}

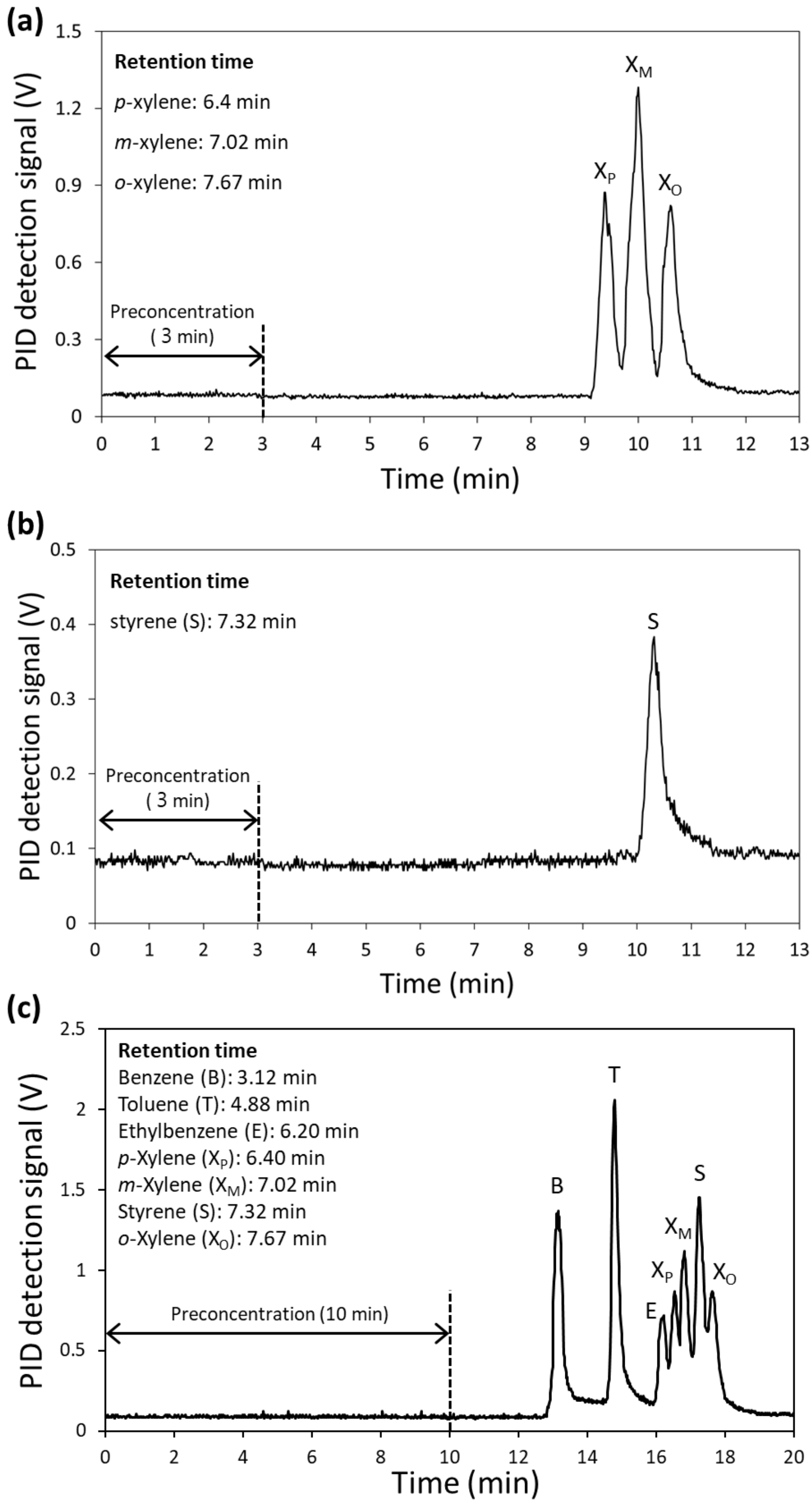


Fig. S8 Experimental results for xylene isomers, styrene and monocyclic aromatic hydrocarbons obtained using the hybrid GC platform. (a) Chromatogram of xylene isomers from a gas cylinder containing a mixture of xylene isomers, (b) chromatogram of styrene from a single gas cylinder, and (c) chromatogram of monocyclic aromatic hydrocarbons.

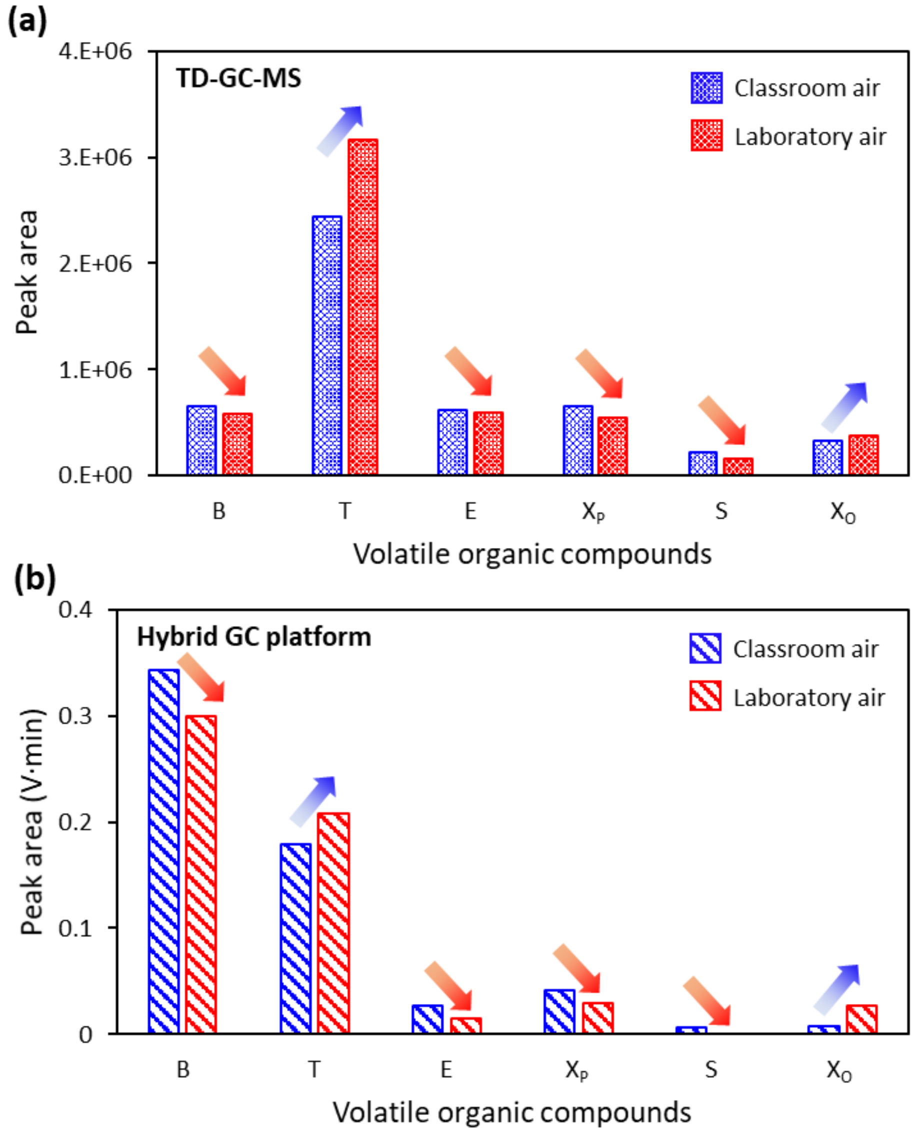


Fig. S9 Peak area variations of major VOCs detected in classroom and laboratory air samples. (a) Peak areas obtained by the TD-GC-MS and (b) peak areas obtained by the hybrid GC platform.

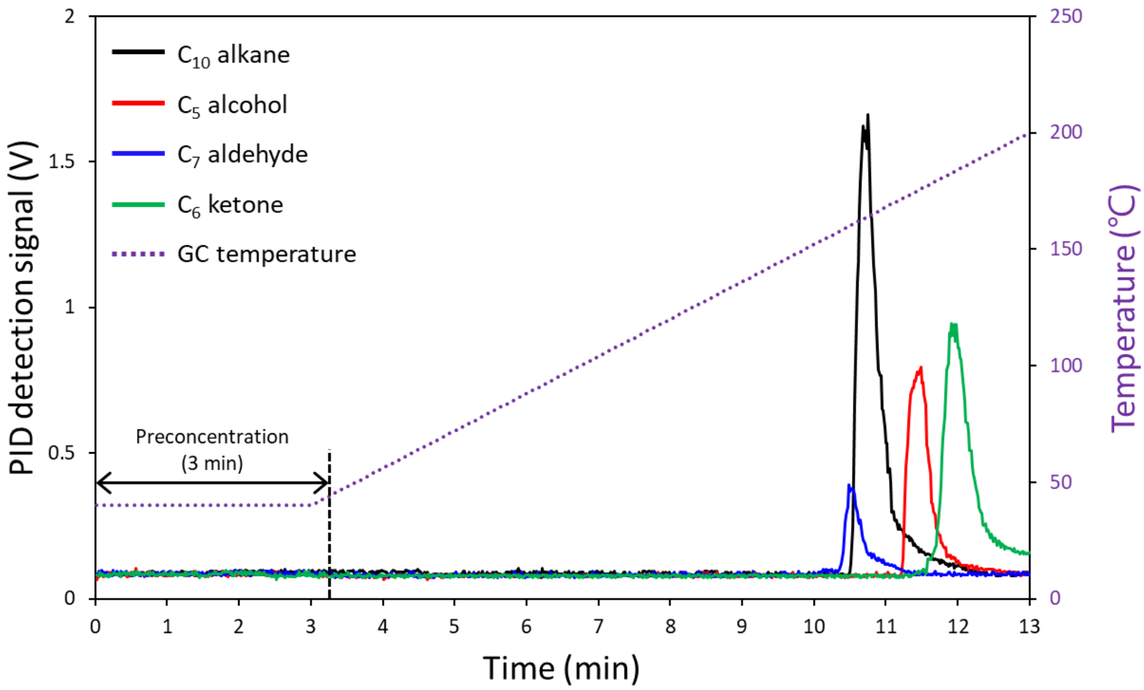


Fig. S10 Desorption and detection of analytes undetected in Fig. 6 due to insufficient TD temperature (hybrid chip temperature ramping: 40°C to 200°C).

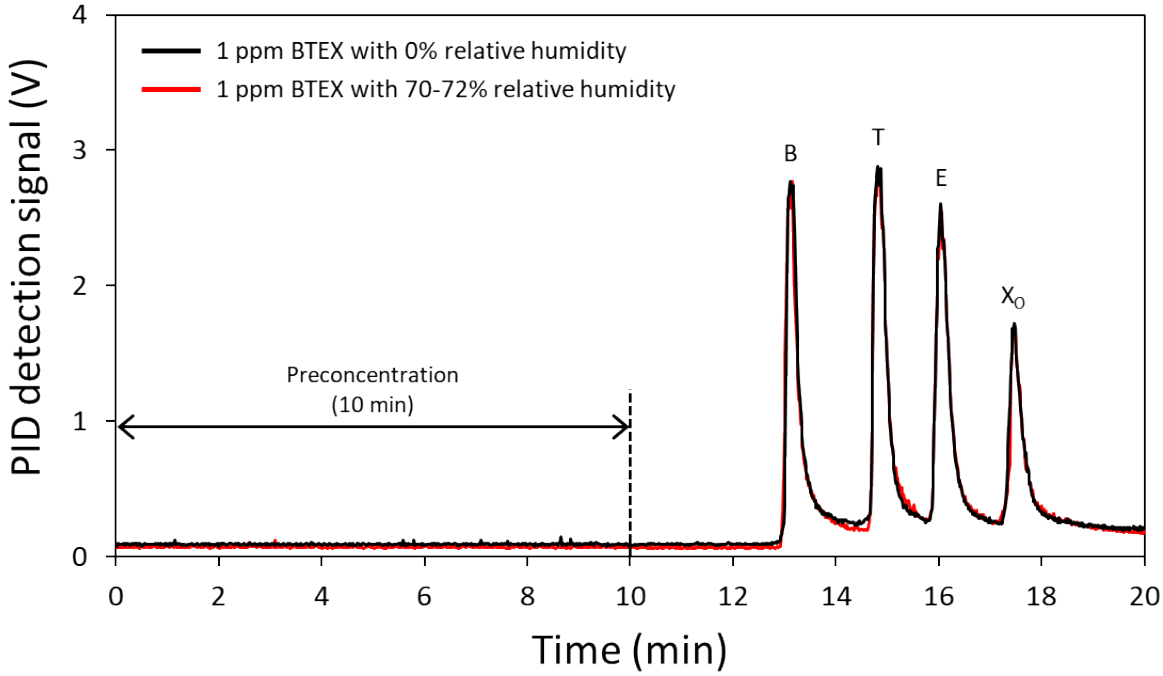


Fig. S11 Effect of relative humidity on analytical performance. The relative humidity level of 70–72% was achieved by placing a water bubbling chamber (a conical tube) between the pump and the hybrid chip.