Gas Chromatography–Triple Quadrupole Mass Spectrometry Analysis of Dioxins in Soil

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The applicability of gas chromatography–triple quadrupole mass spectrometry (GC–MS/MS) for determination of dioxins in soil was investigated. The analytical method was validated based on US Environmental Protection Agency (EPA) Method 1613 and European Union (EU) Regulation No. 709/2014 for selectivity, linearity of sensitivity, and instrumental limits of quantification (iLOQs). Method development commenced with determination of retention times for 17 native polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) and selection of characteristic ions from GC–MS/MS spectra. The linearity was measured using 1613 standard solutions (CS1–CS5) containing 0.5 to 200 ng/mL tetrachlorodibenzo-p-dioxin/furan (TCDD/F) congeners, 2.5 to 1000 ng/mL pentachlorodibenzo-p-dioxin/furan (PeCDD/F) to heptachlorodibenzo-p-dioxin/furan (HpCDD/F) congeners, and 20 to 2000 ng/mL octachlorodibenzo-p-dioxin/furan (OCDD/F) congeners. The correlation coefficient (R^2) values ranged between 0.9990 and 0.9999, and the iLOQ values ranged from 0.052 to 0.350 pg/ μ L for TCDD/F congeners, with a relative standard deviation of 2.7–9.6%. The entire analytical method was verified by analysis of certified reference materials (BCR-529 and BCR-530), and the recoveries were 71.79–103.87% and 81.50–103.12%, respectively. Thus, the GC–MS/MS system provides an alternative to GC–high-resolution MS for the simultaneous determination of TCDD/F congeners in soil.

Keywords: dioxins, GC–MS/MS, polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans, soil analysis

Introduction

Polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) are important environmental pollutants (also known as dioxins) that are classified as persistent organic pollutants (POPs) and lead to a broad range of toxic effects in humans and natural environments [1–3]. PCDD/PCDFs are unintentionally formed as by-products during a variety of industrial, manufacturing, and combustion processes [4–8]. Dioxins are chemically highly stable and persist in environmental ecosystems for many years due to a half-life in soil of 10–12 years [9]. For this reason, analytical methods for the determination of dioxins in natural environments are being actively developed.

For instrumental determination, exhaustive extraction, extensive clean-up and sensitive detection procedures are required to determine dioxins in complex matrices. High-resolution gas chromatography coupled to high-resolution mass spectrometry (HRGC/HRMS) is a powerful tool for dioxin research, which has been used successfully for analysis of PCDD/F congeners, and designated as an international reference method [10–15]. HRGC/HRMS has advantages and disadvantages in terms of the analysis process and equipment. Advantages include its high sensitivity, high selectivity, and robustness in terms of MS [16–17]. Disadvantages include its relatively high cost and difficult usage [18]. For these reasons, the development of alternative methods that are more reliable than HRMS but with similar or better reliability is ongoing.

As an alternative to HRGC/HRMS, gas chromatography–triple quadrupole mass spectrometry (GC–MS/MS) should in theory be able to determine dioxin congeners at very low concentrations, potentially providing unambiguous evidence to confirm measurements derived from HRGC/HRMS. Accuracy and sensitivity have both been recently improved due to technological and developmental advances in mass spectrometry (MS). These improvements are in accordance with the analytical criteria of HRGC/HRMS and represent enhanced selectivity. In recent years, analysis of dioxins from matrices including food, feed, fats, sewage sludge, and fly ash samples using GC–MS/MS have revealed sensitivity and accuracy comparable with HRGC/HRMS [15, 18–23]. Therefore, GC–MS/MS could, in principle, be employed for analysis of POPs, such as dioxins, and for analysis of harmful and toxic substances in various fields.

To the best of our knowledge, determination of dioxin congeners in soil using GC–MS/MS instead of HRGC/HRMS has not been reported previously. In the present study, we demonstrate the applicability of the GC–MS/MS system for analysis of PCDD/F congeners in soil containing low levels of these compounds.

Experimental

Reagents, Standards, and Materials. All reagents and solvents for dioxin analysis were of analytical grade or HPLC-grade. Toluene and nonane of dioxin analysis grade were provided by Wako Pure Chemical Industries (Tokyo, Japan), and other solvents including dichloromethane, hexane, and methanol (MeOH) were obtained from Burdick & Jackson (Muskegon, MI, USA). A multilayer silica gel column (10% silver nitrate silica gel, 44% sulfuric silica gel,

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Figure 1. Flow diagram of the sample extraction and clean-up procedures

22% sulfuric silica gel, and 2% potassium hydroxide silica gel) and activated carbon solid phase extraction (SPE) cartridges were obtained from GL Science Inc. (Tokyo, Japan) and Sigma-Aldrich (St. Louis, MO, USA). Native and $^{13}\text{C}_{12}$ -isotope-labelled standard mixtures of PCDD/Fs (EPA 1613 CS1 to CS5, LCS, and ISS) were certified purchases from Wellington Laboratories Inc. (Guelph, Ontario, Canada) and were used for the development of the analytical methodology. Certified reference material (CRM) samples including BCR 529 (sandy soil) and 530 (clay soil) were obtained from the Institute for Reference Materials and Measurements (IRMM, Geel, Belgium) for method validation.

Sample Extraction and Clean-up. Extraction procedures for determination of dioxins in soil were performed as described previously [24] with a slight modification, as shown in Figure 1. Briefly, 10 g soil was spiked with ^{13}C -labelled compounds (EPA 1613 LCS) as internal (surrogate) standards, and extraction was performed using an ASE 300 system (Dionex, Sunnyvale, CA, USA) with instrument settings as follows: 170 °C, 1500 psi, 70% flush volume, 2 static cycles of 6 min, and toluene as an extraction solvent. The aliquots were evaporated by rotary evaporation, solvent was replaced with *n*-hexane, and samples were injected into a multilayer silica gel column pre-equilibrated with 25 mL *n*-hexane. After elution of 100 mL *n*-hexane and evaporation to dryness, the samples were redissolved in 3 mL *n*-hexane and transferred to an active carbon SPE column to separate PCDD/Fs. The activated carbon SPE column was washed with 50 mL DCM-hexane (1:1, v/v) to separate the interfering material and eluted with 100 mL toluene. The eluted extract was evaporated to dryness using nitrogen gas, redissolved in 25 μL nonane, and EPA1613 ISS ($^{13}\text{C}_{12}$ -1,2,3,4- tetrachlorodibenzo-p-dioxin [TCDD] and $^{13}\text{C}_{12}$ -1,2,3,7,8,9-hexachlorodibenzo-p-dioxin [HxCDD]) were added as an internal injection standard at a final concentration of 100 ng/mL. The samples were

transferred to auto-sampling vials and analyzed by GC-MS/MS.

Instrumental Analysis (GC-MS/MS). For determination of PCDD/F congeners, we used a Bruker Scion TQ triple quadrupole mass spectrometer (Bruker, Fremont, CA, USA) coupled to a Bruker 451 GC and CP 8400 auto sampler, with a DB-5MS UI capillary column (60 m $\times$ 0.25 mm $\times$ 0.25 μm ; J&W Scientific, Folsom, CA, USA) operated in the selected ion monitoring (SIM) mode and the electron ionization (EI) positive mode at 70 eV. The temperatures of the transfer line, injector, and ion source were 280 °C and 230 °C, respectively. For analysis, a 2- μL sample was injected in the pulse splitless mode. Helium at a constant flow rate of 1 mL/min was used as the carrier gas. The program temperature was 140 °C for 1 min, increased to 220 °C at 20 °C/min (held for 1 min) and then to 320 °C at 5 °C/min (held for 14 min) for a total runtime of 35 min. Details of the GC-MS/MS operational parameters, as well as the multiple reaction monitoring (MRM) conditions for PCDD/Fs determination, are provided in Tables 1 and 2.

Results and Discussion

Analytical Validation of the GC-MS/MS Method. Analytical performance was assessed in terms of selectivity, linearity of sensitivity, and instrumental limits of quantification (iLOQs) according to the validation parameters for GC-MS/MS method development. EPA-1613 CS3 calibration standard solutions were selected to evaluate the chromatographic separation of PCDD/Fs, and the separation was acceptable for all PCDD/F congeners (Figure 2). Optimization of operational parameters was performed by selecting the two most abundant precursor ions for each target compound from full scan spectra of PCDD/Fs. Tables 2 summarizes the MRM transitions and optimum collision energy (CE) voltages for each congener and transition.

Table 1. Experimental conditions for gas chromatography–triple quadrupole mass spectrometry (GC–MS/MS) analysis of polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs)

GC conditions	
Column	DB-5MS UI
	60 m × 0.250 mm × 0.25 µm
Injection volume (µL)	2.0, splitless
Inlet temp. (°C)	280
Inlet module and mode	Pulsed splitless, 50 psi (1 min)
Carrier gas	Helium
Column flow (mL/min)	1.0
Column pneumatics	Constant flow
Oven program	140 °C (1 min) 20 °C/min to 220 °C (1 min) 5 °C/min to 320 °C (14 min)
MS conditions	
Operation mode	Electron ionisation (EI), multiple reaction monitoring (MRM)
MS system	MS WS 8.0 SPI
Transfer line temperature	280 °C
Ion source temperature	230 °C
Electron energy	–70 eV
Collision gas	1.5 mTorr

Linearity is an important factor determining the accuracy of the analytical validation process. Linearity tests were optimized and applied to five calibration standard solutions (EPA1613 CS1 to CS5) including native and $^{13}\text{C}_{12}$ -labelled tetrachlorodibenzo-p-dioxin/furan (TCDD/F) congeners at concentrations ranging from 0.5 to 2000 pg/µL and 100 pg/µL, respectively, except for $^{13}\text{C}_{12}$ -octachlorodibenzo-p-dioxin (OCDD), which was 200 pg/µL. Determination coefficient (R^2) values higher than 0.999

indicated good linearity, and the relative response factor (RRF) and relative standard deviation (RSD) values were in good agreement (RSD <15%) for PCDD/F congeners (Table 3). These excellent linearity results confirmed that method was in accordance with the criteria established earlier by the EPA 1613 method.

One of the major differences between HRGC/HRMS and GC–MS/MS is the ability to set the iLOQ value; although HRGC/HRMS is measured by the signal-to-noise (S/N) ratio for raw signals, GC–MS/MS does not allow calculation of the S/N ratio due to filtering of ions by the quadrupoles [25]. For these reasons, iLOQ values for the GC–MS/MS system were measured using a 10-fold dilution of the EPA-1613CS1 standard solution following 10 repeated injections, which were considered to be 10 times the RSD of the replicates. The iLOQ values ranged from 0.052 to 0.350 pg/µL for TCDD/F congeners. All %RSD values were below 9.6% (Table 4), suggesting that the proposed GC–MS/MS analytical method was sufficiently sensitive to easily detect low-level dioxin congeners.

Determination of Dioxins in CRMs. To assess the accuracy of the validation tests used to assess the analytical method, we evaluated the analytical efficiency using two CRMs, BCR 529 and 530, which are the same matrices as the real samples. The accuracy values obtained as recovery factors for dioxin congeners were used as reference values for quality assurance with the GC–MS/MS instrument. CRM and accuracy results are shown in Table 5. The measured total dioxin values for BCR 529 (16,865.53 pg. g^{–1}) and BCR 530 (1495.69 pg. g^{–1}) were in good agreement with the certified values for BCR 529 (20,025 ± 2981 pg/g) and BCR 530 (1575 ± 174 pg/g). The range of accuracy of values for dioxin congeners compared with certified values for BCR 529 and BCR 530 were 71.79–103.87% (average = 84%) and 81.50–

Table 2. Multiple reaction monitoring (MRM) conditions for detection of the PCDD/F congeners

Congeners	RT (min)	Precursor ion	Product ion	CE (V)	Precursor ion	Product ion	CE (V)
^{13}C -2,3,7,8-TCDF	15.40	316	252	30	318	254	30
2,3,7,8-TCDF	15.41	304	241	30	306	243	30
^{13}C -1,2,3,4-TCDD(ISS ^a)	15.46	332	268	22	334	270	22
^{13}C -2,3,7,8-TCDD	15.71	332	268	22	334	270	22
2,3,7,8-TCDD	15.71	320	257	22	322	259	22
^{13}C -1,2,3,7,8-PeCDF	17.62	350	286	32	352	288	32
1,2,3,7,8-PeCDF	17.63	338	275	30	340	277	30
^{13}C -2,3,4,7,8-PeCDF	18.18	350	286	32	352	288	32
2,3,4,7,8-PeCDF	18.21	338	275	30	340	277	30
^{13}C -1,2,3,7,8-PeCDD	18.36	368	304	22	370	306	22
1,2,3,7,8-PeCDD	18.38	354	291	25	356	293	25
^{13}C -1,2,3,4,7,8-HxCDF	20.22	386	322	32	388	324	32
1,2,3,4,7,8-HxCDF	20.24	374	311	30	376	313	30
^{13}C -1,2,3,6,7,8-HxCDF	20.33	386	322	32	388	324	32
1,2,3,6,7,8-HxCDF	20.34	374	311	30	376	313	30
^{13}C -2,3,4,6,7,8-HxCDF	20.76	386	322	32	388	324	32
2,3,4,6,7,8-HxCDF	20.77	374	311	30	376	313	30
^{13}C -1,2,3,4,7,8-HxCDD	20.90	402	338	22	404	340	22
1,2,3,4,7,8-HxCDD	20.85	388	262	40	390	327	25
^{13}C -1,2,3,6,7,8-HxCDD	21.14	402	338	22	404	340	22
1,2,3,6,7,8-HxCDD	21.16	388	262	40	390	327	25
^{13}C -1,2,3,7,8,9-HxCDD(ISS ^a)	21.13	402	338	22	404	340	22
1,2,3,7,8,9-HxCDD	21.16	388	262	40	390	327	25
^{13}C -1,2,3,7,8,9-HxCDF	21.48	386	322	32	388	324	32
1,2,3,7,8,9-HxCDF	21.48	374	311	30	376	313	30
^{13}C -1,2,3,4,6,7,8-HpCDF	22.61	420	356	35	420	358	35
1,2,3,4,6,7,8-HpCDF	22.60	408	345	35	410	347	35
^{13}C -1,2,3,4,6,7,8-HpCDD	23.46	436	372	22	438	374	22
1,2,3,4,6,7,8-HpCDD	23.48	424	361	25	426	363	25
^{13}C -1,2,3,4,7,8,9-HpCDF	23.94	420	356	35	422	358	35
1,2,3,4,7,8,9-HpCDF	23.96	408	345	35	410	347	35
^{13}C -OCDD	25.87	470	406	25	472	408	25
OCDD	25.87	458	395	25	460	397	25
OCDF	26.07	442	379	30	444	381	30

^aISS, internal standards (EPA-1613ISS).

Figure 2. Chromatographic and mass spectrometric separation of 17 polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) using gas chromatography–triple quadrupole mass spectrometry (GC–MS/MS)

Table 3. Linearity of calibration curves and relative response factors (RRFs) of PCDD/F congeners

Congeners	Concentration range (pg/ μ L)	R^2	Average RRF	RRF% RSD
2,3,7,8-TCDF	0.5–40	0.9994	1.23	8.2
2,3,7,8-TCDD	0.5–40	0.9997	1.16	3.8
1,2,3,7,8-PeCDF	2.5–1000	0.9999	1.28	2.9
2,3,4,7,8-PeCDF	2.5–1000	0.9990	1.52	1.5
1,2,3,7,8-PeCDD	2.5–1000	0.9999	0.81	9.4
1,2,3,4,7,8-HxCDF	2.5–1000	0.9991	1.38	8.5
1,2,3,6,7,8-HxCDF	2.5–1000	0.9999	1.22	3.6
2,3,4,6,7,8-HxCDF	2.5–1000	0.9996	1.03	5.2
1,2,3,4,7,8-HxCDD	2.5–1000	0.9994	1.27	5.8
1,2,3,6,7,8-HxCDD	2.5–1000	0.9999	0.95	4.7
1,2,3,7,8,9-HxCDD	2.5–1000	0.9992	1.14	10.2
1,2,3,7,8,9-HxCDF	2.5–1000	0.9999	1.09	9.4
1,2,3,4,6,7,8-HpCDF	2.5–1000	0.9995	0.91	2.5
1,2,3,4,6,7,8-HpCDD	2.5–1000	0.9999	1.22	4.8
1,2,3,4,7,8,9-HpCDF	2.5–1000	0.9991	1.05	3.8
OCDD	5.0–2000	0.9999	1.34	2.4
OCDF	5.0–2000	0.9999	1.25	7.2

103.12% (average = 95%), respectively, which was satisfactory (>90% for most congeners) according to US Environmental Protection Agency (EPA) 1613 [14] and European Union (EU) Regulation 709/2014 [26]. These results indicate that GC–MS/MS approaches were suitable for the monitoring of dioxins in soil and comparable in terms of sensitivity to HRGC/HRMS.

Conclusion

Analysis of dioxins in environmental samples is generally performed by HRGC coupled to HRMS. However, we demonstrate that a GC–MS/MS analysis could be used as an alternative method, thanks to the recent technical advances in MS. In this study, a GC–MS/MS-based analytical method was developed to detect low concentrations of dioxins in soil. The method was validated according to the US EPA Method 1613 and EU Regulations 709/2014 guidelines using EPA-1613 standard solution. The results were satisfactory in terms of

Table 4. Calibration curve data and instrumental limits of quantitation (iLOQ) values

	Retention time (min)	Lowest calibration point (pg/ μ L)	Highest calibration point (pg/ μ L)	Lowest calibration point RSD (%)	R^2 correlation coefficient	Difference RF (low)-RF (All) %	Average RF	iLOQ (pg/ μ L)
PCDDs								
2,3,7,8-TCDD	15.961	0.078	3.957	6.7	0.9991	-0.411	2.799	0.052
1,2,3,7,8-PeCDD	18.638	0.421	20.213	4.1	0.9999	-0.242	1.450	0.173
1,2,3,4,7,8-HxCDD	21.418	0.414	20.204	8.5	0.9999	2.170	1.436	0.350
1,2,3,6,7,8-HxCDD	21.425	0.394	20.067	5.7	0.9999	0.094	1.507	0.226
1,2,3,7,8,9-HxCDD	21.427	0.361	20.093	6.6	0.9999	1.498	1.546	0.239
1,2,3,4,6,7,8-HpCDD	23.750	0.391	19.995	5.1	0.9999	1.008	1.408	0.199
OCDD	26.165	0.850	40.142	3.7	0.9999	0.492	0.945	0.315
PCDFs								
2,3,7,8-TCDF	15.652	0.090	3.957	9.6	0.9995	-16.286	5.554	0.086
1,2,3,7,8-PeCDF	17.879	0.427	19.929	3.2	0.9998	-0.392	2.799	0.137
2,3,4,7,8-PeCDF	18.482	0.394	19.957	3.9	0.9997	-0.503	3.151	0.154
1,2,3,4,7,8-HxCDF	20.511	0.421	19.855	7.5	0.9999	0.869	2.926	0.317
1,2,3,6,7,8-HxCDF	20.596	0.423	20.086	6.1	0.9999	0.518	3.230	0.255
2,3,4,6,7,8-HxCDF	21.037	0.384	20.275	2.7	0.9999	1.283	3.166	0.104
1,2,3,7,8,9-HxCDF	21.736	0.405	20.179	6.4	0.9999	2.137	2.505	0.261
1,2,3,4,6,7,8-HpCDF	22.864	0.419	19.909	3.2	0.9999	-0.127	1.987	0.136
1,2,3,4,7,8,9-HpCDF	24.220	0.425	19.857	3.6	0.9999	-0.243	1.484	0.153
OCDF	26.349	0.849	40.157	3.7	0.9999	0.624	1.290	0.315

Table 5. Results of dioxin concentration analysis in the reference materials BCR 529 and BCR 530

Congeners	BCR 529			BCR 530		
	Certified (pg/g)	Analyzed (pg/g)	Ratio of analyzed /certified (%)	Certified (pg/g)	Analyzed (pg/g)	Ratio of analyzed /certified (%)
2,3,7,8-TCDD	4500 $\pm$ 600	4253.41	94.52	NA	NC	NA
1,2,3,7,8-PeCDD	440 $\pm$ 50	446.19	101.41	NA	NC	NA
1,2,3,4,7,8-HxCDD	1220 $\pm$ 210	1256.51	102.99	NA	NC	NA
1,2,3,6,7,8-HxCDD	5400 $\pm$ 900	3919.85	72.59	61 $\pm$ 11	49.72	81.50
1,2,3,7,8,9-HxCDD	3000 $\pm$ 400	2153.75	71.79	21.8 $\pm$ 2.9	18.65	85.56
1,2,3,4,6,7,8-HpCDD	NA	NC	NA	NA	NC	NA
OCDD	NA	NC	NA	NA	NC	NA
2,3,7,8-TCDF	78 $\pm$ 13	81.02	103.87	NA	NC	NA
1,2,3,7,8-PeCDF	145 $\pm$ 28	146.11	100.77	240 $\pm$ 40	217.48	90.62
2,3,4,7,8-PeCDF	360 $\pm$ 70	354.27	98.41	620 $\pm$ 70	639.37	103.12
1,2,3,4,7,8-HxCDF	3400 $\pm$ 500	2913.12	85.68	321 $\pm$ 16	311.46	97.03
1,2,3,6,7,8-HxCDF	1090 $\pm$ 150	1028.89	94.39	186 $\pm$ 23	155.04	83.35
2,3,4,6,7,8-HxCDF	370 $\pm$ 50	295.34	79.82	126 $\pm$ 12	103.96	82.51
1,2,3,7,8,9-HxCDF	22 $\pm$ 10	17.06	77.54	NA	NC	NA
1,2,3,4,6,7,8-HpCDF	NA	NC	NA	NA	NC	NA
1,2,3,4,7,8,9-HpCDF	NA	NC	NA	NA	NC	NA
OCDF	NA	NC	NA	NA	NC	NA
Total PCDD/Fs (pg/g)	20,025 $\pm$ 2981	16865.53	84.22	1575 $\pm$ 174	1495.69	94.96
Total WHO-TEQs (pg/g)	6510 $\pm$ 895	5976.82	91.80	264 $\pm$ 28	262.22	99.32

NA, data not available.
NC, data not calculated.
WHO-TEQs, World Health Organization toxic equivalent.

selectivity, linearity of sensitivity, and iLOQ. Furthermore, the accuracy of the analytical method was confirmed using CRMs BCR-529 and BCR-530, and the accuracy was successfully optimized. Thus, GC-MS/MS provides an alternative method for routine screening and quantification of dioxins in soil.

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