Review Article

Oliver Vaye, Rafael Sarji Ngumbu*, and Dan Xia

A review of the application of comprehensive two-dimensional gas chromatography MS-based techniques for the analysis of persistent organic pollutants and ultra-trace level of organic pollutants in environmental samples

https://doi.org/10.1515/revac-2022-0034
received January 27, 2021; accepted November 22, 2021

Abstract: Analysis of complex samples in environmental matrices poses extreme challenge for analytical chemists as the number of known and unknown compounds are numerous and have varying physical and chemical properties. The introduction, over the past decade, of comprehensive two-dimensional (2D) gas chromatography (GC × GC) paired with mass spectrometry (MS) has tremendously changed the analytical profiles of ultra-trace levels of organic pollutants from different environmental media. This review article provides a summary of selected articles using comprehensive 2D GC/MS-based methodologies from January 2014 to August 2019. The applications of various MS detectors, such as single (Q) and triple (QqQ) quadrupole, low resolution and high resolution time-of-flight (TOF), and the hybrid (quadrupole TOF-MS), coupled to GC × GC, and their benefits for analyzing persistent and emerging organic pollutants when applied to different environmental matrices were discussed. Emphasis was given to reviewing some applications of GC × GC-electron capture detector (ECD) and GC × GC-μECD within the specified period as these detectors have improved selectivity and sensitivity toward halogenated (bromine and chloride) compounds found in ultra-trace levels of environmental media.

Keywords: comprehensive two-dimensional gas chromatography, mass spectrometry, persistent organic pollutants, environmental media

1 Introduction

There is a huge global demand for chemicals used in the production of different household, agriculture, industrial, and pharmaceutical products. Most of these chemicals are eventually introduced in the environment via different exposure route (air, water, soil, and food) during production. Humans are especially vulnerable to these chemicals via dietary intake and other exposure routes [1]. One of such dangerous chemicals is a group called persistent organic pollutants (POPs).

POPs are natural chemical substances with a particular combination of physical and chemical properties, such as toxicity, bioaccumulation, persistence, and long-range atmospheric transport. POPs produced and used in the industrial, urban, and agricultural sector are the primary sources from which these chemicals are transferred to the environment. In response to the global challenge and health risks posed by POPs, the Stockholm Convention, adopted in 2001 and entered into force in 2004, demands state parties to the convention to adopt measures aimed at reducing and eventually eliminating the release of POPs into the environment [1].

*** Corresponding author: Rafael Sarji Ngumbu,** Environmental Research and Radiation Safety Laboratory, Department of Compliance and Enforcement, Environmental Protection Agency of Liberia, P.O. Box 4024 4th Street, Sinkor Tubman Boulevard, 1000 Monrovia, Liberia; Analytical Chemistry Cluster, Department of Chemistry, University of Liberia, Fendall Campus, Monrovia, Liberia, e-mail: rafaelngumbu@yahoo.com, ngumburs@ul.edu.lr, rngumbu@epa.gov.lr
Oliver Vaye: Beijing Key Laboratory of Bio-Inspired Energy Materials and Devices, Department of Environmental Science and Engineering, School of Space and Environment, Beihang University, Beijing, 100191, China; Environmental Research and Radiation Safety Laboratory, Department of Compliance and Enforcement, Environmental Protection Agency of Liberia, P.O. Box 4024 4th Street, Sinkor Tubman Boulevard, 1000 Monrovia, Liberia
Dan Xia: Beijing Key Laboratory of Bio-Inspired Energy Materials and Devices, Department of Environmental Science and Engineering, School of Space and Environment, Beihang University, Beijing, 100191, China

The analysis of complex matrices including POPs-containing-transformer oil is often a daunting challenge especially when the sample contains multiple compounds or when the composition of the analyte of interest is at the ultra-trace level. Conventional techniques, such as gas chromatography, are incapable of adequately separating such compounds and may even result in the overlapping of peaks, rendering analyte identification and quantification rather improbable. Multidimensional techniques, such as two-dimensional (2D) gas chromatography (GC × GC), are better suited for such analysis due to the fact that they have a superior separation space allowing component peaks to spread out across new coordinates, reducing the risk of overlap [2]. Another major advantage of 2D methods over traditional 1D approaches can be observed during sample elucidation. Although conventional GC techniques show data on a fraction of the sample, comprehensive 2D methods allow the passage of the entire sample through the system resulting in adequate identification and quantification of the analyte.

GC × GC was originally introduced by Liu and Phillips in 1991 [3], and by the genesis of the twenty-first century, significant advancements were made on the modulators. Initial applications were skewed toward the analysis of petrochemicals, making GC × GC a revelation in the oil and gas industry. The past two decades have witnessed a tremendous surge in the number of GC × GC publications and the range of applications has increasingly widened. Besides petrochemical analysis [2–7], GC × GC is, nowadays, used in the analysis of foodstuff [8–12], environmental media, biological specimen [13–18], cosmetic products, and essential oils [19]. The rising popularity of the technique may be partly due to the availability of commercial instruments and software but most certainly due to greater awareness of the many advantages offered by this and associated methods.

The superior separation space and wide peak capacity of GC × GC come with a need for a detector capable of promptly attaining the huge packets of data generated during the sample separation phase. Moreover, the narrow second dimension peaks produced during cryogenic modulation require a mass spectrometer capable of quick scanning rates for improved compound elucidation in complex matrices. The incorporation of automatic spectral deconvolution allows the use of spectra data to distinguish and properly identify coeluting compounds. Compounds within complex matrix are identified using coupling fast-scanning mass spectrometry (MS) with GC × GC [2].

MS, another significant part of separation science that aid gas chromatography, be it conventional or multidimensional gas chromatography system, is an analytical technique that is useful for the measurement of the mass-to-charge ratio (*m/z*). MS is considered as one of the most powerful single tools for the identification of chemical components based on different *m/z* ratios of analytes and their fragment ions. The field of MS has experienced tremendous improvements since it was first developed by Thompson who did the first MS studies in 1912 [19]. For instance, from 1958 to the present, gas chromatography used with MS has significantly changed the analysis of volatile organic compounds. In the 1980s, MS technique became available for the study of nonvolatile compounds such as peptides, oligosaccharides, phospholipids, and bile salts. In the field of analytical chemistry, the most recent applications of MS are directed toward biochemical analysis. Comprehensive 2D paired with MS are routinely applied to analyze ultra-trace levels of organic pollutants including POPs.

Over the last decade, significant reviews have been written on comprehensive GC × GC [19–30]. Among the reviews written, some have precisely dived in the field of MS coupled with GC × GC [19,31–33]. The current review focuses on the applications of comprehensive 2D gas chromatography coupled with mass spectrometry (GC × GC-MS)-based techniques for the analysis of ultra-trace levels of organic pollutants. Special mentions were made on the format, regarding the types of MS presented by Tranchida et al. [32]. The authors of this current review restricted the theme around the applications of MS detection techniques that are mostly used with GC × GC analysis of POPs and ultra-trace level organic pollutants from various environmental matrices (air, soil, water, and wastewater) and recent trends over the last 5 years (2014–2019). Studies in the field of separation science have proven that electron capture detector (ECD) has improved selectivity and sensitivity toward halogenated (bromine and chlorine) compounds found in ultra-trace levels of environmental media. Therefore, some techniques of GC × GC-ECD and GC × GC-μECD in the last 5 years (2014–2019) are also discussed.

2 GC × GC-MS-based technique: Applications and analysis of ultra-trace levels of organic pollutants in various environmental media

2.1 Quadruple MS

2.1.1 Single quadrupole mass spectrometry (qMS)

Over the years, the single quadrupole mass spectrometers have become much more sensitive, and the source fragmentation has revolutionized. It acts as a mass filter, allowing one mass channel at a time to reach the detector as the mass range is scanned. Quadrupole mass spectrometers are intrinsically low-resolving-power instruments but are relatively cheap, robust, and user-friendly. They are mostly suitable for qualitative analysis.

Wang et al. [35] reported a cheaper but significant approach when GC × GC and quadrupole mass spectrometers are combined. The authors explicitly focused on peaks matching to identify about 125 volatile organic compound, including alkanes, alkenes, aromatics, oxygenated hydrocarbon, and halocarbons in a mixture of urban air samples in Beijing. The authors used an flame ionization detector detector as a complement to its quadrupole counterpart for a quantitative purpose as the quadrupole mass spectrometer is not robust in a quantitative analysis. For example, the 26.96 data acquisition provided 4 to 6 data points in the second-dimensional column. Decreasing the mass scanning range to less than 300 amu will increase the data acquisition rate, which in turn serves as a better option for more identification of targeted analytes, the authors affirmed.

There have been tremendous advancements, over the past decade, in different techniques aimed at producing safe, clean, and portable water for the growing world population. One of such water treatment techniques is disinfection, an approach used since the nineteenth century to reduce waterborne disease. Three widely used disinfectants are chlorines, chloramines, and ozone. All these disinfectants can react with natural organic matters, inorganic materials, and emerging anthropogenic contaminants in water to produce disinfection by-products (DBPs). The identification and quantification of DBPs in treated drinking water sources has captivated the attention of several researchers. Li et al. [36] presented a robust method for identifying unknown by-products in drinking water during the aforementioned disinfection process using GC × GC-MS. To achieve a higher data acquisition, a rate of 20 spectra per s was applied; the researchers reduced the mass scanning range (45–300 Da). A similarity threshold of 600–700 compounds was used to avoid missing some compounds that had lower matching factors and, at the same time, present in water samples. The study identified more than 500 compounds in each water sample (chlorines, chloramines, and ozone). The authors further studied the changes in composition and amount of dissolved organic matter (DOM) throughout the drinking water treatment plants using the same MS technique. In their study, a nontargeted screening approach was applied to track changes of different chemical classes of compounds in DOM during both conventional and advanced drinking water treatment processes.

2.1.2 Triple quadrupole mass spectrometry (QqQ-MS)

QqQ-MS is a tandem MS technique in which the first and third quadrupoles usually act as mass filters, and the second causes fragmentation of the analyte through interaction with a quadrupole radiofrequency or collision gas. This approach can either be used for quantification of an analyte of interest or for obtaining structural information of the analyte. QqQ-MS technique offers a number of inherent benefits including improved selectivity, better signal-to-noise ratio (S/N), lower limits of quantitation, more comprehensive linear range, and improved accuracy. This system provides an order of magnitude improvement in sensitivity allowing analysts to meet detection-limit requirements using a reduced volume of sample and organic solvent in the sample preparation stage [1].

Hashimoto et al. [37] used a triple quadruple with a neutral loss scan (NLS) to comprehensively and selectively detect organochlorines and organobromines. NLS-35 for 35Cl and NLS-79 for 79Br were used to identify both organochlorines and organobromines in a routine scan range of m/z = 150–550. Figure 1 shows the detection of NLS-35 and conventional scans.

2.2 Time-of-flight (TOF) MS

2.2.1 Low-resolution (LR) TOF MS

Low-resolution time-of-flight mass spectrometry (TOFMS) is the most widely used GC × GC detectors for the analysis of complex pollutants from various environmental matrices due to its high spectral frequencies reaching as high as 100 Hz, and deconvolution abilities, good sensitivity in a full-spectrum mode and its ability to scan ions in full pulses park coming from different sources [32]. The combination of GC × GC with high-speed data acquisition LR TOFMS has proved to be a viable option for the analysis of ultra-trace levels of organic pollutants. As compared to conventional 1D GC, the advantage of using this technique is its ability to prevent interferences between a sample of interest with lower cost and user-friendly characteristics. This technique has been used in most environmental applications because of the features mentioned above. Sulej-suchomska et al. [38] developed, optimized, and validated a headspace solid phase micro extraction using the GC × GC-LR-TOFMS approach to

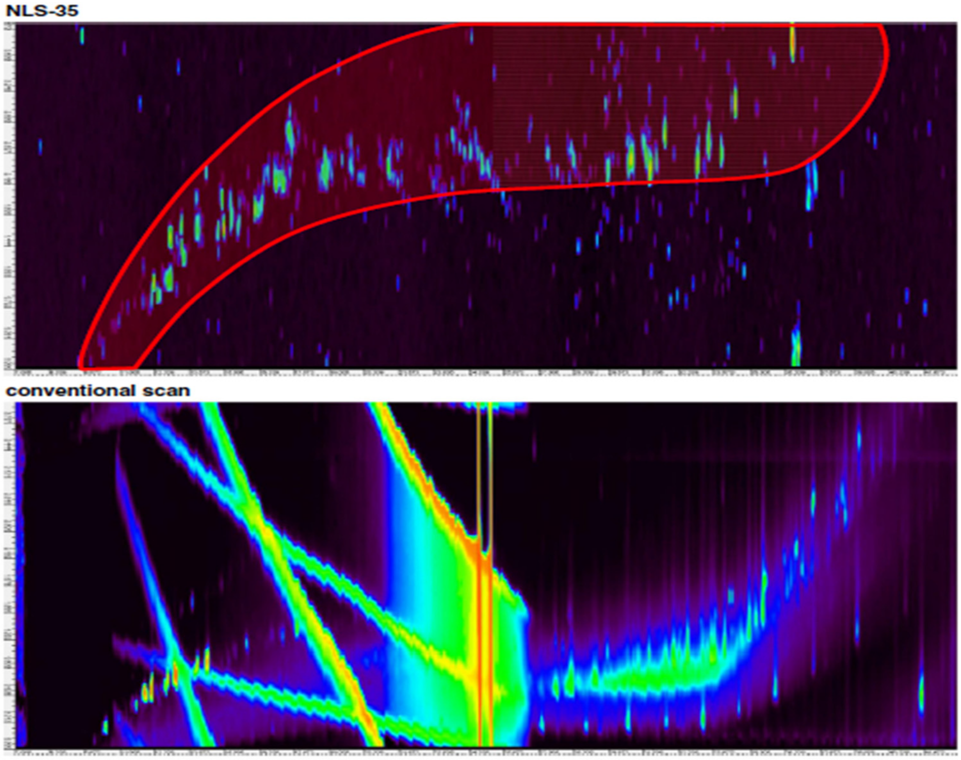

Figure 1: Two-dimensional total ion chromatograms (TICs) of a sediment sample (NIES CRM20), as measured by 35Cl neutral loss scanning (NLS-35, upper), which was expected to detect organochlorines selectively. The lower section shows scan obtained by a more conventional approach using GC × GC-MS/MS. The red translucent shape in the upper chromatogram shows the area where organohalogens were expected to appear [37].

determine 16 polycyclic aromatic hydrocarbons (PAHs) in samples of airport runoff water. Although the authors did not explicitly explain the significance of using the TOFMS with the GC × GC, it was noted that individual peaks were detected automatically based on a 10:1 S/N on analytical results submitted to a data processing module. Their findings indicated an enhanced S/N ratio and higher sensitivity achievements.

Based on a targeted-discovery technique, GC × GC-LR-TOFMS, combined with ChromaTOF, was used in a study done by Prebihalo et al. [39] to identify halogenated benzotriazoles and phenol in wastewater plant and soil samples at Pennsylvania State University. Rxi-5 SilxRtx-200 were used as column set for the first and second dimensions. A mass range of 50–550 amu, an electron ionization (EI) energy of 70 eV, an acquisition rate of 200 Hz with a solvent delay time of 450 s was used as mass spectrometer information. Extracted ions chromatogram (*m/z* 167) showing benzotriazole compounds observed in the collected effluent were presented by the authors [39].

GC × GC coupled with LR time-of-flight (GC × GC-LR-TOF) was first used by Escobar-Arnanz et al. [40] in a nontargeted characterization of volatile and semivolatile compounds in soil impacted by a tire fire and ash collected at the scene of the fire in Sesena, Spain. The authors collected a total of seven soil samples in the vicinity of the tire fire at the beginning and after the burning episode. Total ion monitoring was performed in the *m/z* 75–750 range; the energy of ionizing electrons was 70 eV, and the voltage of the multiplier was 1,770 V. Sample extracts were analyzed at acquisition rates of 50 Hz for general sample inspection and of 100 Hz for improved mass spectra information. The minimum required S/N ratio for each detected peak was 30. Results of the analysis show the fractionation of 118 volatile and semivolatile aromatic compounds. About 88% of the 118 compounds were either identified by comparison with authentic standards or tentatively assigned on the base of their respective mass spectra and group-type distribution.

Another benefit of using the LR-TOFMS as a detection technique is its central features to produce a broad range of mass data information with masses of interest extracted from the chromatogram to further reduce bulk data. GC × GC-TOFMS was used in a study conducted by Organtini et al. [41]. Using a qualitative approach to MS analysis, the authors conducted two different experiments:

the first experiment involved a household fire, consisting of a mattress, a sofa chair, a vinyl, and wood chair, five pillows, a piece of carpet, and one television and the second experiment involved a vibrant electronic fire having two TVs, a microwave, two printers, two computer monitors, one laptop computer, and a variety of different cables and wires. A GC × GC-LR-TOFMS equipped with Agilent 7890 A gas chromatograph and Agilent 7683B autosampler was used. The TOF mass spectrometer was operated with an ion source temperature of 250°C and an electron energy of –70 V. The authors chose a detector voltage of 1,900 V to yield an S/N of approximately 1,000 for hexachlorobenzene injected on the column at 200 pg and quantified at 284 *m/z*. A filament delay technique of 550 s was used to eliminate the solvent peak from detection. A mass range of 75–825 µ was collected at an acquisition rate of 200 spectra per s (200 Hz), and a mass defect of –60 mu/100 µ was used to obtain the most mass accurate mass spectra of halogenated compounds of interest. Although both experiments produced a considerable amount of polybrominated dibenzofurans, only the rich electronic fire experiment produced a mixture of halogenated (Br/Cl) dibenzofurans in a significant amount above the limit of detection of the analytical technique used.

In China, Zou et al. [42] developed a novel technique using GC × GC-NCI-LR TOFMS for the determination of congeners profiles group of short chain chlorinated paraffins (SCCPs) from a mixture of five commercial products (polyvinyl chloride, cable, lubricant, rubber, and styrene foam) and urban air samples using a high-volume air sampler (HV-1000 F, Shibata, Japan) deployed at the rooftop of a municipal building in Beijing. The air samples were collected from August 2013 to April 2014, using air sampler at a flow rate of 700 L·min^{-1} daily. The soft ionization technique (negative chemical ionization (NCI)) had the advantage of enhancing the sensitivity of dominant fragment ions, which gave information on precursor congeners. The most abundant and second most ions were selected in SIM mode with a data acquisition rate of 12.5 Hz. The concentration of air samples ranged from 12.8 to 49.1 ng·m^{-3}, with the highest observed during summer and lowest in winter. For the five commercial products of SCCPs, the authors used two sets of columns with the first set (InertCap 5MS/Sil-BPX-50), producing an excellent separation of 24 SCCPs congeners in four chromatograms indicating C_{10}, C_{11}, C_{12}, and C_{13}.

Ahn et al. [43] performed a comparative study of GC-qMS and GC × GC-LR-TOFMS for the quantitative analysis of 18 target PAHs in aerosol samples. The authenticity of the quantitative results obtained by GC × GC-TOFMS and GC-qMS in the SIM mode was demonstrated by several methods of performance parameters such as linearity, accuracy, and repeatability. GC × GC-LR-TOFMS proved to be advantageous than GC-qMS because of its increased peak capacity, and its results showed improved detectability and structured chromatograms for nontarget analysis. Moreover, TOFMS excellence mass fractionation and its automated peak-finding credential were the features for high resolution of complex mixed mass spectra, a problem caused by overlapping chromatographic peaks and spectral deconvolution of individual mass spectra for unknown analytes.

Blum et al. [44] conducted a nontarget screening of potentially persistent, bioaccumulating and toxic wastewater contaminants and their removal in on-site and large-scale sewage treatment plants. In this study, GC × GC-LR-TOFMS showed excellent efficiency in removing hydrophobic compounds compared to hydrophilic compounds in effluents from sewage plants.

The LECO Corp. (St. Joseph, MI 49085, United States of America) GC × GC-LR-TOFMS had a mass tolerance window of 0.005 and an S/N >10 using the ChromoTOF software (LECO Corp., St. Joseph, MI 49085, United States of America). Twelve of the 26-targeted analytes, including several organophosphates, a rubber additive, UV stabilizers, fragrances, a surfactant impurity, and a food additive were identified in wastewater samples in the range of nanogram to microgram per liter. The National Institute of Standard Technology library search resulted in 47 tentatively identified components with 2,4,7,9-tetramethyl-5-decyn-4,7-diol, α-tocopheryl acetate, galaxolide, and octocrylene found in both targeted and nontargeted analysis.

Planche et al. [45] presented a multiresidue technique based on GC × GC-LR-TOF for the analysis of 206 dioxin-like contaminants, which consisted of 189 PCBs congeners and 17 PCDD/Fs congeners. The TOFMS was operated with ionization energy of 70 eV, a detector voltage of 1,800 V, and a data acquisition rate of 100 Hz. The run time for each sample was 75 min. Two different "column sets" were used, including Rtx-PCB/BPX-50 and Rtx-Dioxin2/BPX-50, with Rtx-Dioxin2/BPX-50 producing a better separation efficiency [46].

2.2.2 High-resolution TOF mass spectrometry (HR-TOFMS)

HR-TOFMS is characterized by its ability to generate full-spectrum data for both high resolution and mass accuracy. It can also be used as both targeted and untargeted analysis through MS database identification with the intrinsic feature of posttargeted analysis where full spectrum of data is later investigated for the availability of previously unsearched compounds. Work for routine environmental analysis done in this field over recent years has seen much more advancement.

Myers et al. [47] presented a nontargeted and targeted MS screening using HR-TOFMS in three freshwater species (*Lumbriculus variegatus*, *Hexagenia* spp., and *Pimephales promela*) exposed to the soil at a recycling plant fire site. The authors used an Agilent HP 6890 gas chromatograph (Agilent Technologies, Mississauga, CAN) paired with a Waters Premier TOF mass spectrometer with EI (Waters, Milford, USA), and the mass range was 150–800 *m*/*z* scanned at an acquisition rate of 10 Hz and a mass resolution of 7,000 FWHM. Thirty-six isomers and congeners of PCN, Cl-PAH, X-PAH, polychlorinated dibenzofurans (PCDF), and PXDD/PXDF, respectively, were identified by GC × GC-HR-TOFMS with a new bioaccumulation potential of X-PAH revealed. Usually, GC × GC-MS analyses are done at an acquisition rate greater than 100 Hz with a unit mass resolution. The authors affirmed that the reduction of the acquisition rate to 10 Hz created errors in the replicate injection and the BSAFs calculations, serving as a limiting factor in their study. Talking about the low acquisition rate, the benefits of utilizing a high acquisition rate of HR-TOFMS combine with GC × GC were seen when Xia et al. [48] presented a new technique for simultaneous profiling and quantifying of 48 chlorinated paraffins (chlorinated (CPs); SCCPs and middle chain chlorinated paraffins (MCCPs)) congeners groups from sediments and fish samples. The GC × GC instrument was connected to HR-TOFMS (Tofwerk, Thun, Switzerland), operated in electro-chemical negative ionization (ECNI) mode with an electron energy of 125 eV. The MS instrument was tuned to give a resolving power of 5000 and a mass accuracy of 5 ppm (calculated using the full width at half maximum), using perfluoroperhydrophenanthrene as the mass calibrator. The HR-TOFMS instrument proved to provide an accurate mass measurement by separating $C_{11}H_{17}C_{l7}$ [M-Cl$^-$], and $C_{13}H_{23}C_{l5}$ [M$^-$] ions separated well with a narrow mass ratio window (*m*/*z* 0.02) that was not separated by LR-TOFMS because of its LR power of 1,000. Additionally, the high resolution offered by GC × GC enabled the separation of other classes of organic pollutants with similar physical and chemical properties from CPs in full scan mode (see Figure 2). The authors concluded that the high separating power of GC × GC and the exact mass resolution of HR-TOFMS were reasons for improved selectivity and obtaining different CPs formula congeners group.

Hashimoto et al. [37] used an Agilent 6890GC (Agilent Technologies, Santa Clara, CA, USA) with a Zoex KT-2006 GC×GC system (Zoex Corporation, Houston, TX, USA) combined with a JEOL JMS-T100GC (JEOL Ltd., Tokyo, Japan), followed by sophisticated software to selectively and simultaneously detect and identify many organohalogen compounds, including hazardous chemicals (PCDFs and others POPs). The authors used a mass resolution range of 8,000–10,000, a mass range of 30–600 *m/z*, and a mass spectrum of 33 Hz. NCI for selective ionization of organohalogens as well as EI using a triple quadrupole mass spectrometer discussed above (see Section 1.2) of this review. Data extraction performance was enhanced effectively by deconvolution of peaks and mass spectra as compounds were coeluted even when GC × GC was used, depending on the sample medium.

Dust sample collected from an electronic waste recycling plant was analyzed using GC × GC-HR-TOFMS, a study presented by Ubukata et al. [49]. The GC × GC Agilent

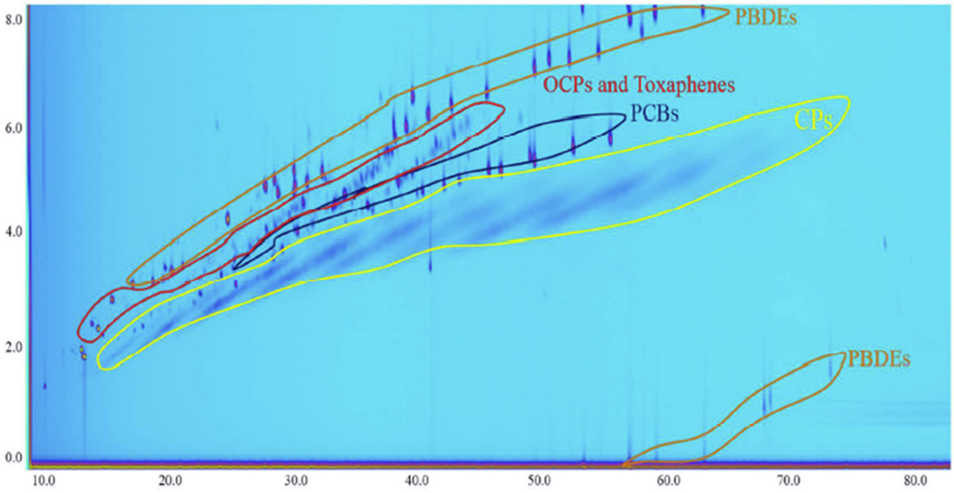

Figure 2: GC × GC-ECNI-HRTOF-MS TIC chromatograms of a mixture of 27 OCP congeners, 39 PBDE congeners, 72 PCB congeners, and technical toxaphenes, technical SCCPs (51.5% Cl), and technical MCCPs (57% Cl). The resolution offered by GC × GC allowed the CPs to be clearly separated from the other classes of compounds in the full scan mode [48].

7890A, combined with HR-TOFMS (JOEL JMS-T100GCV 4G) were used in this study. The researchers compare the results of HR-TOFMS and a conventional Kendrick mass defect. For readers who have an interest in this software can consider reading this article. Our attention was drawn to the significant efforts of GC × GC-HR-TOFMS in their study. The two ionization modes found for HR-TOFMS were electron impact (EI) ionization and ECNI. Both had a broader mass range of (45–800 *m/z*) and (30–800 *m/z*), respectively. Even though EI showed excellent fingerprint identification of several known and unknown emerging contaminants based on formula groups using a qualitative approach, ECNI demonstrated a better technique than EI for its ability to combine both qualitative and quantitative analysis of low-concentration compounds in challenging samples.

2.2.3 Quadrupole-TOF (QTOF) MS

QTOF technology is increasingly being used more specifically for dependable targeted analysis and screening for suspected analytes and unknowns because of its high resolution and accurate mass spectra deconvolution; however, these techniques are still rarely used in environmental analysis due to their high cost, making them unaffordable for most environmental laboratories [50]. Throughout the period mentioned in this review, only one article was published in this field relating to an environmental application, creating an avenue for researchers to explore.

Naphthenic acids, typically found in hydrocarbon deposits (petroleum, oil sands bitumen, and crude oils), are acids that contained a considerable amount of saturated aliphatic and alicyclic carboxylic acids. These acids primarily enter the surface water systems through effluent discharge but also through groundwater mixing and erosion of riverbank oil deposits. They are considered as one of the most complex mixtures of organic compounds found at ultra-trace levels in the environment around the world because their characterization is challenging for the analytical chemist. Some factors that pose a limitation to their research are the availability of international standards and their absence in the mass spectra libraries. Bowman et al. [51] presented, for the first time, a report on the application of two dimensional gas chromatography couple with atmospheric pressure chemical ionization high resolution quadrupole mass spectrometry (GC × GC-APCI-HRQ-TOFMS) for the characterizing of naphthenic acid and fraction compounds (NAFCs) in a fluid fine tailing in pore water extracts. The analysis was executed on an Agilent 7890B gas chromatograph combined to Waters Xevo G2-XS quadrupole TOF mass spectrometer. The detector operated in an acquisition range of 50–1,200 amu with an acquisition rate of 30 Hz and resolution power of >20,000 (full width at half maximum (FWHM)). Selected ion chromatograms with narrow mass windows of ±0.003 *m/z* were significant for simplifying complex nominal mass chromatograms and resolving NAFCs from five different chemical classes.

2.3 ECD and micro-ECD

To the best of the current authors' knowledge and with the search in Scopus, from the beginning of 2014 to the end of August 2019, only six articles were published in this field. This result shows a gradual decrease in the application of the ECD technique. The question that arises is: "Are we witnessing the decline and eventual demise in the applications of ECD techniques for the analysis of halogenated compounds in environmental matrices"? The authors think we are experiencing a break, for there are still many research opportunities in this field because a tremendous amount of chemicals possessing halogenated characteristics are continually produced through different anthropogenic activities in our environment.

The first application within the period aforementioned in this review for ECD was executed on an Agilent (7890) GC system [52]. Column choice had a significant impact as DM-x BPX-50 combination produced an excellent group type separation of SCCPs congeners in complex mixtures. A 300 ms hot pulse was used to produce a sharp peak in the second dimension with a 50 Hz data acquisition applied to avoid unwarranted band broadening. Results showed an excellent sensitivity with good separating power for more than 1,500 compounds, including SCCPs congeners and other organochlorine compounds in fish extracts. Results such as these truly demonstrate the intrinsic features of the ECDs. In November 2014, a new quantitative technique using data processing and a different peak integration algorithms along with a new baseline estimation algorithm (Eilers) [53] was used in a study done by Samanipour et al. [54]. The study was performed on a Leco Corp. instrument equipped with a modified Agilent 7890 A GC system coupled to µECD. A chemometric test was used for finding and handling specific sources of errors that arise during the quantification of analytes by GC × GC-µECD. An 11-targeted chlorinated hydrocarbon in a lake water extract was quantified. In fact, Eilers was recommended by the authors for its ability to eliminate unresolved signal that give rise to visible matrix effects.

The µECD is an excellent detector for the quantitative analysis of halogenated compounds, and its order of magnitude is more sensitive to halogenated analytes

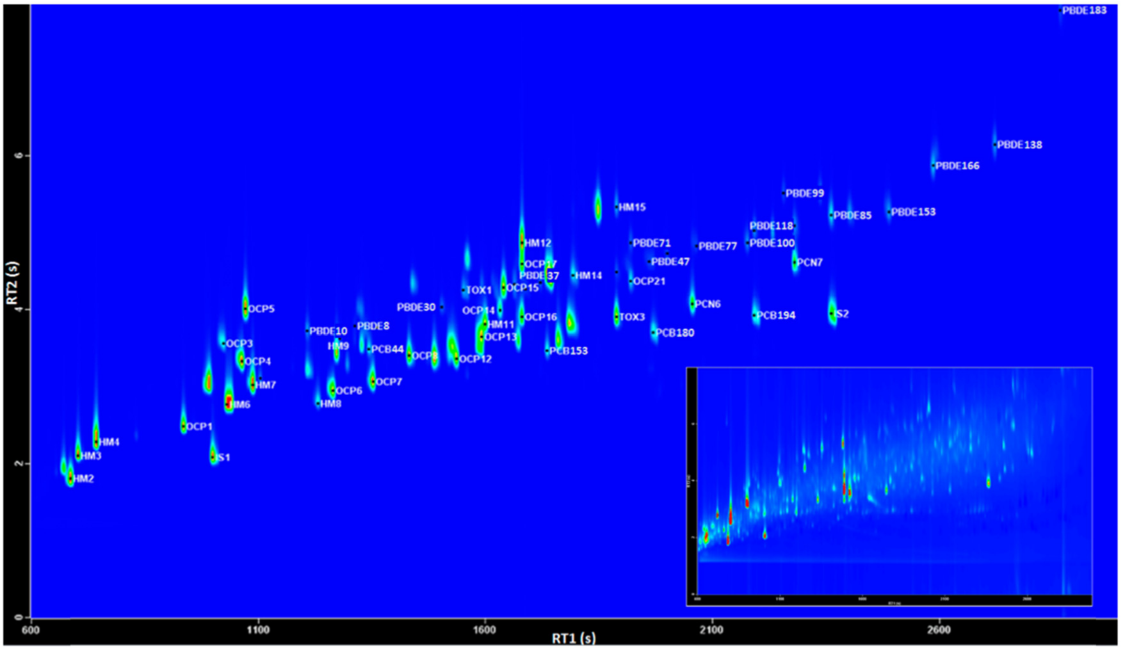

Figure 3: GC × GC-μECD chromatograms of the standard mixtures of well-separated target analytes and the internal standards. GC × GC-μECD chromatograms of the extract of an effluent liquid-phase sample are shown in the inset at the lower right of the above figure [56].

then TOFMS with electron impact ionization. A robust, targeted technique for the quantification of a wide range of halogenated nonpolar micropollutants in wastewater treatment plant (WWTP) influent, effluent, and sludge samples (both liquid and particle phases) was used in a study done by Dimitriou-Christidis [55] using GC × GC-μECD. Results showed that 59 target analytes included toxaphenes, polychlorinated naphthalenes, organochlorine pesticides, polychlorinated biphenyls, polybrominated diphenyl ethers, and emerging persistent and bioaccumulative chemicals. The resulting 59 well-resolved target analytes retained for further analysis are shown in Figure 3. The approximate agreement between the two detectors (μECD and electron chemical negative ionization couple with time-of-flight mass spectrometry) used in this study substantiate the authors' claims that μECD technique is ideal for the identification of targeted analytes in WWTP streams.

Probably what we will refer to as the last application of μECD in environmental analysis was published in 2016 by Muscalu et al. [57]. In that study, GC × GC-μECD proved to be the technique of choice for detecting and quantifying CPs in environmental samples. The GC × GC-μECD Leco Corp. (St. Joseph, MI, USA) GC system was used in the study with a 50 Hz data acquisition rate. ChromaTOF software (LECO Corp.) was used for data acquisition and processing for all analyses performed for this study. Even though 118 compounds were detected and quantified, some drawbacks experienced by the analysts included the following: (1) Other targeted analytes such as PCBs were not differentiated in the area of high concentration of SCCPs. (2) SCCPs, however, were not adequately separated and quantified when different technical mixtures were present, causing overlap of both short and medium chain chlorinated paraffin. (3) Finally, data handling tool was cumbersome because of peak integration leading to more than 250 slices integration for each standard.

3 Conclusion

Protecting our environment has been a paramount objective, not just in recent years, but as early as the 1970s. MS has played an essential role in analyzing pollutants of environmental concerns during these early movements. MS, coupled with comprehensive GC × GC, allowed the precise detection of the ultra-trace level of organic pollutants and enabled a better understanding of their environmental fates. The MS-based approach of comprehensive GC × GC for the analysis of POPs and an ultra-trace level of organic pollutants have been discussed in this current review. The excellent performance of μECD for the analysis of halogenated contaminants is also shown within the mentioned periods.

Just as when researchers start to think that the field of MS combined with GC × GC has matured [34] and all of the analytical techniques have been fully explored, a new technique might be created. For instance, the development of a new data processing algorithm [35,49] for better detection. The tremendous revolutions that have occurred over these years in the field of both GC × GC and MS are an accolade to the tireless efforts of the bright and innovative scientists who continue to develop new techniques and improve analysts' abilities to analyze and quantified emerging pollutants of environmental concerns from different matrices. The recent decrease in the application of ECD is due to the improvements in MS technology. For example, HR-TOFMS instruments are capable of detecting pollutants in environmental samples as low as 0.03 pg·μL^{-1} [58] when compared to the ECD [59]. As for the field of MS, it is the current authors' belief that routine environmental analysis of MS-based technology will experience continued growth with particular intention turning toward new algorithms to aid in data processing for better quantification and improve mass spectra analysis of emerging contaminants.

Acknowledgment: Special gratitude is extended to the Executive Director of the Environmental Protection Agency of Liberia, Prof. Wilson K. Tarpeh and his principal deputy, Hon. Randall M. Dobayou II for affording two of the authors (RSN and OV) time off duty to carry out this research.

Funding information: Authors state no funding involved.

Author contributions: Oliver Vaye developed the review concept, carried out the review, and prepared the manuscript; Rafael Sarji Ngumbu carried out the review, prepared the manuscript, and proofread the manuscript; and Dan Xia developed the review concept and proofread the manuscript.

Conflict of interest: Authors state no conflict of interest

References

[1] Alavanja MCR. Pesticides use and exposure extensive worldwide. Rev Env Health. 2009;24:303–9.
[2] Giddings JC. Concepts and comparisons in multidimensional separation. J High Resol Chromatogr Comm. 1987;10:319–23.
[3] Liu Z, Phillips JB. Comprehensive two-dimensional gas chromatography using an on-column thermal modulator interface. J Chromatogr Sci. Jun. 1991;29(6):227–31. doi: 10.1093/chromsci/29.6.227.
[4] Hu SZ, Li SF, Cao J, Zhang DM, Ma J, He S, et al. A comparison of normal and reversed phase columns in oil analysis by comprehensive two-dimensional gas chromatography with time-of-flight mass spectrometry. Pet Sci Technol. Mar. 2014;32(5):565–74. doi: 10.1080/10916466.2011.598896.
[5] Cheng G, Wang B, Wang P, Wang T. Occurrence-and-geochemical-significance-of-monoterpenoid-hydrocarbons-in-crude-oils. Shiyou Xuebao/Acta Petrolei Sinica; 2015.
[6] Zhang G, Peng Q, Wang L. Analysis of components of rocket kerosene by comprehensive two-dimensional gas chromatography/time-of-flight mass spectrometry. Chem Technol Fuels Oils. Nov. 2016;52(5):559–64. doi: 10.1007/s10553-016-0743-9.
[7] Chang X, Shi B, Han Z, Li T. C5–C13 light hydrocarbons of crude oils from northern Halahatang oilfield (Tarim Basin, NW China) characterized by comprehensive two-dimensional gas chromatography. J Pet Sci Eng. Aug. 2017;157:223–31. doi: 10.1016/j.petrol.2017.07.043.
[8] Djokic MR, MullerNenad H, Ristic ND, Akhras AR, Steffen H.Symoens, Symoens SH, et al. Combined characterization using HT-GC × GC-FID and FT-ICR MS: a pyrolysis fuel oil case study. Fuel Process Technol. Dec. 2018;182:15–25. doi: 10.1016/j.fuproc.2018.10.007.
[9] Zhu G, Chi L, Zhang Z, Li T, Yang H, Chen W, et al. Composition and origin of molecular compounds in the condensate oils of the Dabei gas field, Tarim Basin, NW China. Pet Explor Dev. Jun. 2019;46(3):504–17. doi: 10.1016/S1876-3804(19)60031-5.
[10] Kupska M, Chmiel T, Jędrkiewicz R, Wardencki W, Namieśnik J. Comprehensive two-dimensional gas chromatography for determination of the terpenes profile of blue honeysuckle berries. Food Chem. Jun. 2014;152:88–93. doi: 10.1016/j.foodchem.2013.11.129.
[11] Chin ST, Marriott PJ. Multidimensional gas chromatography beyond simple volatiles separation. Chem Commun. 2014;50:8819–33. doi: 10.1039/c4cc02018a.
[12] Kupska M, Wasilewski T, Jędrkiewicz R, Gromadzka J, Namieśnik J. Determination of terpene profiles in potential superfruits. Int J Food Prop. Dec. 2016;19(12):2726–38. doi: 10.1080/10942912.2016.1144066.
[13] Schütt J, Schieberle P. Quantitation of nine lactones in dairy cream by stable isotope dilution assays based on novel syntheses of carbon-13-labeled γ-lactones and deuterium-labeled δ-lactones in combination with comprehensive two-dimensional gas chromatography with time-of-flight mass spectrometry. J Agric Food Chem. Dec. 2017;65(48):10534–41. doi: 10.1021/acs.jafc.7b04407.
[14] Cordero C, Guglielmetti A, Bicchi C, Liberto E, Baroux L, Merle P, et al. Comprehensive two-dimensional gas chromatography coupled with time of flight mass spectrometry featuring tandem ionization: challenges and opportunities for accurate fingerprinting studies. J Chromatogr A. Jul. 2019;1597:132–41. doi: 10.1016/j.chroma.2019.03.025.
[15] Marney LC, Hoggard JC, Skogerboe KJ, Synovec RE. Methods of discovery-based and targeted metabolite analysis by comprehensive two-dimensional gas chromatography with time-of-flight mass spectrometry detection. 2014;1198:83–97.
[16] Peng ZX, Wang Y, Gu X, Xue Y, Wu Q, Zhou JY, et al. Metabolic transformation of breast cancer in a MCF-7 xenograft mouse model and inhibitory effect of volatile oil from Saussurea lappa Decne treatment. Metabolomics. Jun. 2015;11(3):636–56. doi: 10.1007/s11306-014-0725-z.

[17] Oliveira AS, Santos M, Rudnitskaya A, Todo-Bom A, Bousquet J, Rocha SM. Urinary metabolomic profiling of asthmatics can be related to clinical characteristics. Allergy. Sep. 2016;71(9):1362–5. doi: 10.1111/all.12935.

[18] Wong YF, Perlmutter P, Marriott PJ. Untargeted metabolic profiling of Eucalyptus spp. leaf oils using comprehensive two-dimensional gas chromatography with high resolution mass spectrometry: expanding the metabolic coverage. Metabolomics. May 2017;13(5):46. doi: 10.1007/s11306-017-1173-3.

[19] De Hoffmann E, Stroobant V. Mass spectrometry: principles and applications. 3rd edn. West Sussex, England: John Wiley & Sons Ltd.

[20] Mondello L, Tranchida PQ, Dugo P, Dugo G, Farmaco-chimico D. Comprehensive two-dimensional gas chromatography-mass spectrometry: a review. Mass spectrometry Rev. 2008;27:101–24. doi: 10.1002/mas.

[21] Cortes HJ, Winniford B, Luong J, Pursch M. Comprehensive two dimensional gas chromatography review. J Sep Sci. Mar. 2009;32(5–6):883–904. doi: 10.1002/jssc.200800654.

[22] Mostafa A, Edwards M, Górecki T. Optimization aspects of comprehensive two-dimensional gas chromatography. J Chromatogr A. Sep. 2012;1255:38–55. doi: 10.1016/j.chroma.2012.02.064.

[23] Tranchida PQ, Sciarrone D, Dugo P, Mondello L. Heart-cutting multidimensional gas chromatography: a review of recent evolution, applications, and future prospects. Anal Chim Acta. Feb. 2012;716:66–75. doi: 10.1016/j.aca.2011.12.015.

[24] Murray JA. Qualitative and quantitative approaches in comprehensive two-dimensional gas chromatography. J Chromatogr A. Oct. 2012;1261:58–68. doi: 10.1016/j.chroma.2012.05.012.

[25] Shi X, Wang S, Yang Q, Lu X, Xu G. Comprehensive two-dimensional chromatography for analyzing complex samples: recent new advances. Anal Methods. 2014;6(18):7112–23. doi: 10.1039/C4AY01055H.

[26] Sampat A, Lopatka M, Sjerps M, Vivo-truyols G. Forensic potential of comprehensive two-dimensional gas chromatography. Trends Anal Chem. 2016;80:345–63. doi: 10.1016/j.trac.2015.10.011.

[27] Van Stee LLP, Brinkman UAT. Peak detection methods for GC × GC: an overview. Trends Anal Chem. 2016;83:1–13. doi: 10.1016/j.trac.2016.07.009.

[28] Gruber B, Weggler BA, Jaramillo R, Murrell KA, Piotrowski PK, Dorman FL. Comprehensive two-dimensional gas chromatography in forensic science: a critical review of recent trends. TrAC Trends Anal Chem. Aug. 2018;105:292–301. doi: 10.1016/j.trac.2018.05.017.

[29] Pollo BJ, Alexandrino GL, Augusto F, Hantao LW. The impact of comprehensive two-dimensional gas chromatography on oil & gas analysis: recent advances and applications in petroleum industry. TrAC Trends Anal Chem. Aug. 2018;105:202–17. doi: 10.1016/j.trac.2018.05.007.

[30] Muscalu AM, Górecki T. Comprehensive two-dimensional gas chromatography in environmental analysis. TrAC – Trends Anal Chem. 2018;106:225–45. doi: 10.1016/j.trac.2018.07.001.

[31] Machado ME. Comprehensive two-dimensional gas chromatography for the analysis of nitrogen-containing compounds in fossil fuels: a review. Talanta. Jun. 2019;198:263–76. doi: 10.1016/j.talanta.2019.02.031.

[32] Tranchida PQ, Franchina FA, Dugo P, Mondello L. Comprehensive two-dimensional gas chromatography-mass spectrometry: recent evolution and current trends. Mass Spectrometry Rev. 2014;2008:1–11. doi: 10.1002/mas.

[33] Tranchida PQ, Purcaro G, Maimone M, Mondello L. Impact of comprehensive two-dimensional gas chromatography with mass spectrometry on food analysis. J Sep Sci. Jan. 2016;39(1):149–61. doi: 10.1002/jssc.201500379.

[34] Tranchida PQ, Aloisi I, Giocastro B, Mondello L. Current state of comprehensive two-dimensional gas chromatography-mass spectrometry with focus on processes of ionization. TrAC – Trends Anal Chem. 2018;105:360–6. doi: 10.1016/j.trac.2018.05.016.

[35] Wang Y, Xu X, Yin L, Cheng H, Mao T, Zhang K, et al. Coupling of comprehensive two-dimensional gas chromatography with quadrupole mass spectrometry: application to the identification of atmospheric volatile organic compounds. J Chromatogr A. 2014;1361:229–39. doi: 10.1016/j.chroma.2014.08.006.

[36] Li C, Wang D, Li N, Luo Q, Xu X, Wang Z. Identifying unknown by-products in drinking water using comprehensive two-dimensional gas chromatography–quadrupole mass spectrometry and in silico toxicity assessment. Chemosphere. 2016;163:535–43. doi: 10.1016/j.chemosphere.2016.08.053.

[37] Hashimoto S, Zushi Y, Takazawa Y, Ieda T, Fushimi A, Tanabe K, et al. Selective and comprehensive analysis of organohalogen compounds by GC × GC–HRTofMS and MS/MS. Env Sci Pollut Res. 2015;25(8):7135–46. doi: 10.1007/s11356-015-5059-5.

[38] Sulej-suchomska AM. Analytical methods dimensional gas chromatography – time-of-flight mass spectrometry: a new tool for determining PAHs in airport runoff water samples. Anal Methods. 2016;4509–20. doi: 10.1039/c6ay00401f.

[39] Prebihalo S, Brockman A, Cochran J, Dorman FL. Determination of emerging contaminants in wastewater utilizing comprehensive two-dimensional gas-chromatography coupled with time-of-flight mass spectrometry. J Chromatogr A. 2015;1419:109–15. doi: 10.1016/j.chroma.2015.09.080.

[40] Escobar-arnanz J, Mekni S, Blanco G, Eljarrat E, Barceló D, Ramos L. Characterization of organic aromatic compounds in soils affected by an uncontrolled tire landfill fire through the use of comprehensive two-dimensional gas chromatography – time-of-flight mass spectrometry. J Chromatogr A. 2018;1536:163–75. doi: 10.1016/j.chroma.2017.10.044.

[41] Organtini KL, Myers AL, Jobst KJ, Cochran J, Ross B, McCarry B, et al. Comprehensive characterization of the halogenated dibenzo-p-dioxin and dibenzofuran contents of residential fire debris using comprehensive two-dimensional gas chromatography coupled to time of flight mass spectrometry. J Chromatogr A. 2014;1369:138–46. doi: 10.1016/j.chroma.2014.09.088.

[42] Zou Y, Niu S, Dong L, Hamada N, Hashi Y, Yang W. Determination of short-chain chlorinated paraffins using comprehensive two-dimensional gas chromatography coupled with low resolution mass spectrometry ☆. J Chromatogr A. 2018;1581–1582:135–43. doi: 10.1016/j.chroma.2018.11.004.

[43] Ahn YG, Jeon SH, Lim HB, Choi NR, Hwang GS, Kim YP, et al. Analysis of polycyclic aromatic hydrocarbons in ambient aerosols by using one-dimensional and comprehensive two-dimensional gas chromatography combined with mass spectrometric method: a comparative study. J Anal Methods Chem. 2018;2018:8341630. doi: 10.1155/2018/8341630.

[44] Blum KM, Andersson PL, Renman G, Ahrens L, Gros M, Wiberg K, et al. Non-target screening and prioritization of potentially persistent, bioaccumulating and toxic domestic wastewater contaminants and their removal in on-site and large-scale sewage treatment plants. Sci Total Env. 2017;575:265–75. doi: 10.1016/j.scitotenv.2016.09.135.

[45] Planche C, Ratel J, Mercier F, Blinet P, Debrauwer L, Engel E. Assessment of comprehensive two-dimensional gas chromatography-time-of-flight mass spectrometry based methods for investigating 206 dioxin-like micropollutants in animal-derived food matrices. J Chromatogr A. 2015;1392:74–81. doi: 10.1016/j.chroma.2015.02.054.

[46] Planche C, Ratel J, Mercier F, Blinet P, Debrauwer L, Engel E. Assessment of comprehensive two-dimensional gas chromatography-time-of-flight mass spectrometry based methods for investigating 206 dioxin-like micropollutants in animal-derived food matrices. J Chromatogr A. May 2015;1392:74–81. doi: 10.1016/j.chroma.2015.02.054.

[47] Myers AL, Watson-Leung T, Jobst KJ, Shen L, Besevic S, Organtini K, et al. complementary nontargeted and targeted mass spectrometry techniques to determine bioaccumulation of halogenated contaminants in freshwater species. 2014;48:13844–54. doi: 10.1021/es503090s.

[48] Xia D, Gao L, Zheng M, Tian Q, Huang H, Qiao L. A novel method for profiling and quantifying short- and medium-chain chlorinated paraffins in environmental samples using comprehensive two-dimensional gas chromatography-electron capture negative ionization high-resolution time-of-flight mass spectrometr. Env Sci Technol. 2016;50(14):7601–9. doi: 10.1021/acs.est.6b01404.

[49] Hoh E, Dodder NG, Lehotay SJ, Pangallo KC, Reddy CM, Maruya KA. Non-targeted analysis of electronics waste by comprehensive two-dimensional gas chromatography combined with high-resolution mass spectrometry: using accurate mass information and mass defect analysis to explore the data. J Chromatogr A. 2015;1395:152–9. doi: 10.1016/j.chroma.2015.03.050.

[50] Ballesteros-g A. Recent advances in environmental analysis. 2011;83:4579–613. doi: 10.1021/ac200921j.

[51] Bowman DT, Jobst KJ, Ortiz X, Reiner EJ, Warren LA, McCarry BE, et al. Improved coverage of naphthenic acid fraction compounds by comprehensive two-dimensional gas chromatography coupled with high resolution mass spectrometry. J Chromatogr A. Feb. 2018;1536:88–95. doi: 10.1016/j.chroma.2017.07.017.

[52] Xia D, Gao L, Zhu S, Zheng M. Separation and screening of short-chain chlorinated paraffins in environmental samples using comprehensive two-dimensional gas chromatography with micro electron capture detection. Anal Bioanal Chem. Nov. 2014;406(29):7561–70. doi: 10.1007/s00216-014-8209-6.

[53] Eilers PHC. Parametric time warping. 2004;76(2):404–11. doi: 10.1021/ac034800e.

[54] Samanipour S, Dimitriou-Christidis P, Gros J, Grange A, Samuel Arey J. Analyte quantification with comprehensive two-dimensional gas chromatography: assessment of methods for baseline correction, peak delineation, and matrix effect elimination for real samples. J Chromatogr A. Jan. 2014;1375:123–39. doi: 10.1016/j.chroma.2014.11.049.

[55] Dimitriou-Christidis P, Bonvin A, Samanipour S, Hollender J, Rutler R, Westphale J, et al. GC × GC quantification of priority and emerging nonpolar halogenated micropollutants in all types of wastewater matrices: analysis methodology, chemical occurrence, and partitioning. Env Sci Technol. Jul. 2015;49(13):7914–25. doi: 10.1021/es5049122.

[56] Dimitriou-Christidis P, Bonvin A, Samanipour S, Hollender J, Rutler R, Westphale J, et al. GC × GC quantification of priority and emerging nonpolar halogenated micropollutants in all types of wastewater matrices: analysis methodology, chemical occurrence, and partitioning. Env Sci Technol. 2015;49(13):7914–25. doi: 10.1021/es5049122.

[57] Muscalu AM, Morse D, Reiner EJ, Górecki T. The quantification of short-chain chlorinated paraffins in sediment samples using comprehensive two-dimensional gas chromatography with MECD detection. Anal Bioanal Chem. 2016;409(8):2065–74. doi: 10.1007/s00216-016-0153-1.

[58] Xia D, Gao L, Zheng M, Wang S, Liu G. Simultaneous analysis of polychlorinated biphenyls and polychlorinated naphthalenes by isotope dilution comprehensive two-dimensional gas chromatography high-resolution time-of-flight mass spectrometry. Anal Chim Acta. 2016;937:160–7. doi: 10.1016/j.aca.2016.07.018.

[59] Muscalu AM, Morse D, Reiner EJ, Górecki T. The quantification of short-chain chlorinated paraffins in sediment samples using comprehensive two-dimensional gas chromatography with μECD detection. Anal Bioanal Chem. Mar. 2017;409(8):2065–74. doi: 10.1007/s00216-016-0153-1.