


REVIEW

Open Access



Comparative examination of analytical instruments for detecting pentachlorophenol in wood and environmental samples

K. Koushika¹, Quan (Sophia) He³, H. Niati³ and C. U. Emenike^{1,2*} 

Abstract

Pentachlorophenol (PCP) is a manmade chemical that is widely present in the environment and is mostly used as a wood preservative. Therefore, to conduct remediation studies, it is imperative to determine the most effective PCP analytical technique. PCP can be analyzed using a variety of analytical tools, including non-destructible methods like X-ray fluorescence spectrometry (XRF) and electrochemical sensors (EC), destructible tools like gas chromatography (GC), thin layer chromatography (TLC), colorimetry, ultraviolet–visible and infrared spectroscopy (UV–vis/IR), and high-performance liquid chromatography (HPLC). The colorimetric approach is less recommended because of its low sensitivity and precision, whereas TLC offers superior recovery rates and precision but is expensive, takes longer, and is unable to resolve complicated combinations. Higher recovery rates, sensitivity, precision, and superior separation are all offered by HPLC; however, its effectiveness is impacted by time, money, and solvent compatibility. The most favored destructible approach is GC because it is efficient in terms of both cost and time and offers superior precision and separation. Although XRF is frequently used in the wood industry to test PCP in treated wood and treating solutions, scientific research has avoided using it because of its high cost and ability to identify chemicals based only on their elemental composition—in the case of PCP, it is chloride. Among all methods, EC is shown to be more dependable than the other methods listed because it is extremely specialized, less expensive, and offers a faster response. It is possible to make more changes to the current analytical techniques, such as enhancing extraction techniques, creating a universal HPLC column, developing more affordable and high-precision EC electrodes, and evaluating a larger variety of samples from different matrices. This review has shed light on the many analytical tools available for determining PCP and the knowledge gaps in the field of study.

Keywords Pentachlorophenol, Wood preservative, GC, HPLC, TLC, Colorimetry, XRF destructive and non-destructive methods

The article titled “Comparative analysis of analytical instruments for the detection of pentachlorophenol in wood and environmental samples” elucidates mainly on available analytical instruments for the determination of organic pollutant pentachlorophenol (PCP). PCP was predominantly used as a wood preservative that is persistent in the environment. This review paper provides research gaps and possible new research ideas to improve the analysis of the samples with PCP. The article submitted also provides the best option among the available method or instrument for the detection of PCP.

*Correspondence:

C. U. Emenike

Chijioko.emenike@dal.ca

Full list of author information is available at the end of the article



© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

Introduction

Pentachlorophenol (PCP) is an organochlorine compound that is a phenol substituted with five chlorine atoms. It is primarily used as a wood preservative, but it also functions as a biocide, fungicide, herbicide, algacide, disinfectant, defoliant, anti-sap stain and antimicrobial agent. Its applications include agriculture, industrial cooling systems, food packaging materials, dental products, antimicrobial soaps, and dermatological and medical products (Crosby 1981; Jones 1985). PCP and its sodium salt are particularly poisonous to wood-decaying fungi, which were developed in the 1930s and have been widely used in the industry since then (Carswell and Hatfield 1939). It is, nonetheless, highly persistent in the environment because of the stability of its structure (i.e. presence of phenol) and a high level of chlorination, which makes it highly toxic to the environment (Xu et al. 2017).

It is found in wood preservation facilities, sewage effluents, soil, water bodies, sediments, and other areas adjacent to these sources. It is widely distributed throughout the environment. It was added to the list of persistent organic pollutants in the Stockholm Convention because of its potential for toxicity and endocrine disruption (Darbre 2021). Although it was once outlawed in many nations, including Austria, India, Indonesia, New Zealand, Sweden, and Switzerland, it was still in use in North America because utility poles and railroad ties were seen as essential infrastructure (Tullo 2020; UNEP-FAO 1996). However, in Canada, it was banned from use as a wood preservative in 1990 and taken off the market in 2023 (PMRA 2022).

Despite being phased out of the industry, PCP remains heavily accumulated in the environment across a variety of matrices, including soil, water, the atmosphere, and human tissues and fluids, because of its persistent nature. Consequently, it is crucial to conduct research on the removal of PCP from contaminated areas, which calls for precise quantification methods for effective PCP detection. PCP can be measured and examined using a variety of destructive and non-destructive techniques. In contrast to the non-destructive method, which analyzes the sample without causing any damage to the original sample, the destructive technique involves making permanent changes to the specimen to distort or destroy the material to identify the point of failure. For example, gas chromatography/mass spectrometry (GC/MS), thin-layer chromatography (TLC), colorimetry, ultraviolet-visible and infrared spectroscopy, high-performance liquid chromatography (HPLC), electrochemical sensor (EC), and X-ray fluorescence spectrometry (XRF) are some of the

destructive and non-destructive quantification techniques available for the detection of PCP from various matrices of samples. These analytical tools are used to quantify PCP in wood and assess environmental sample data.

When used in conjunction with mass spectrometry (MS), gas chromatography is a method for separating tiny volatile and semi-volatile organic compounds. It can be used to separate complex mixtures, measure analytes, identify unknown peaks, and detect traces of contamination (Thermo Fisher Scientific 2006). The high-performance liquid chromatography (HPLC) instrument was developed in 1900 for studying leaf pigments, particularly chlorophyll. It is a highly effective method for molecularly separating a target molecule from a mixture of compounds. The efficiency, versatility, and speed of the HPLC instruments used today have greatly increased (Raja and Barron 2022). X-ray fluorescence spectrometry (XRF) is a nondestructive analytical technique used to determine the elemental composition of materials using the fluorescence emitted by X-rays (Thermo Fisher Scientific 2020). Electrochemical sensors are inexpensive, easy to use, sensitive, and fast in the reaction. They measure the electrical energy produced by the chemical reaction in the cell (Fethi and Hicham 2022). TLC is a popular chromatographic method that uses a thin stationary phase supported by an inert backing for separation. Its simplicity, affordability, high sensitivity, and speed of separation make it a popular choice (Chemistry LibreTexts 2022). A colorimeter is a light-sensitive instrument used to quantify and contrast the amount of light transmitted through a pure solvent with the amount of light absorbed in the solution (Choudhury 2014). UV-vis and IR spectroscopy use the UV and visible regions of the electromagnetic spectrum, whereas IR employs the low-energy infrared portion of the electromagnetic spectrum to measure how a matter interacts with or emits electromagnetic radiation. (Madhu 2022). However, GC/MS is a widely used technique for detecting organic contaminants like PCP, because it works well at separating and quantifying organic molecules and gases—PCP being a volatile chemical (Zhang 2006).

However, many destructive methods require laborious extractions, and certain techniques lack the sensitivity and selectivity required to find PCP with any degree of accuracy. To validate the most effective method for reliably detecting PCP, it will be crucial for future research to comprehend the advantages and disadvantages of destructive and non-destructive tools. As a result, the reliability of several analytical tools used to measure PCP will be reviewed in this study.

Pentachlorophenol physicochemical properties

PCP is a synthesized chemical and is a chlorophenol; its phenol group has been altered with five chlorine atoms, and it lacks isomers (Fig. 1).

Pure PCP is a white crystalline solid (PubChem 2023). The technical grade wood preservative known as impure PCP, which is 86% pure, typically uses petroleum oil as a carrier (Ammeri et al. 2020; USEPA 2008). Technical grade PCP is 10 times more effective than pure PCP because of contaminants such as trichlorophenol, hexachlorobenzene, polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and chlorinated phenoxyphenols (CCME 1999; USEPA 2008). Each compound's degree of chlorination determines its level of toxicity and other characteristics (USEPA 2008). These pollutants are more or equally harmful to the environment and are persistent. As a result, it becomes crucial to examine these contaminants in addition to PCP. PCP dissolves effectively in organic solvents and is only marginally soluble in water (Table 1). PCP is volatile due to its high vapor pressure of 1.1×10^{-4} mm Hg at 25 °C (Government of Canada 2013). Volatilization of PCP in water is pH-dependent, and the unionized form of PCP is more volatile. The other properties of PCP are given in Table 2.

Measuring PCP using analytical instruments and their principles

Before selecting the ideal instrument, it is crucial to comprehend the fundamental workings of each instrument. The methods used to examine PCP, which include GC/MS, HPLC, TLC, colorimetry, UV-vis & IR, EC, and XRF, will be discussed. In GC/MS, using a capillary column with a stationary phase that uses nitrogen, hydrogen, and helium as inert carrier gases, the sample is efficiently vaporized into the gas phase and divided into

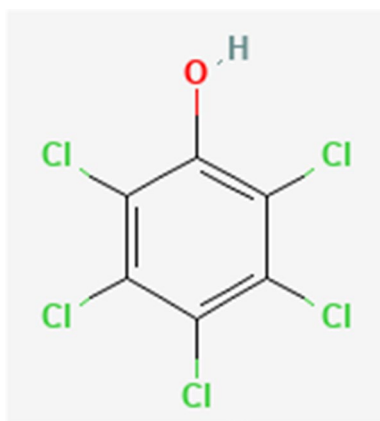


Fig. 1 Structure of pentachlorophenol

Table 1 Solubility of PCP in different solvents

Solvents	Solubility
Water	14 mg/L at 20 °C
Methanol	1.7 g/g
Benzene	0.014 g/g
Diethyl ether	53–60 ppm
Ethanol,	47–52 ppm
Acetone	21–33 ppm
Carbon tetrachloride	2–3 ppm

Sources (Bevenue et al. 1968; PubChem 2023; USEPA 2008)

different components to evaluate volatile or semi-volatile substances, such as PCP. After leaving the GC column, these chemicals are separated and ionized by mass spectrometry (MS) using electron or chemical ionization sources. The separated components are then examined using an ion trap or quadrupole mass spectrometer (Thermo Fisher Scientific, 2006). The substances in the sample are chromatographically separated by HPLC as it passes through the stationary phase, which is a stagnant bulk liquid in the form of a column filled with tiny porous particles, and the mobile phase, which is a moving liquid pumped into the column (Raja and Barron 2022). The detector finds molecules that have eluted from the column after the stationary phase of the column divides the constituents of interest according to their characteristics. The UV and photodiode array detector (PDA) is the most commonly used detector for HPLC analysis. Although TLC is a chromatographic instrument similar to HPLC, its name suggests that it uses a thinner stationary phase supported by an inert backing to separate the mixture's

Table 2 Other physicochemical properties of PCP

Property	Value
Pure PCP color	Colorless white crystalline solid
Impure PCP color	Dark gray to brown and exists as dust, beads, or flakes
Molecular weight	266.35 g/mol
Density	1.978 g/ml
Dissociation constant (K _a) at pH 4.99	1.6×10^{-14}
Sublimes	54 ± 2 °C
Melting point	190–191 °C
Boiling point	309 °C
Log octanol/water partition coefficient (log K _{ow}) at 25 °C	5.05
Odor threshold in water	0.86 mg/L at 30 °C
pK _a	4.74 at 25 °C
Henry's law constant	5×10^{-7} atm·m ³ /mol

Sources: (USEPA 2008; Government of Canada 2013; PubChem 2023)

constituent components at a pressure that is lower than HPLC's (Chemistry LibreTexts 2022).

A colorimeter is a type of photometer used to measure the amount of light a colored solution can transmit to calculate the concentration of light-absorbing materials in the solution (Choudhury 2014; Giri 2022). It is typically used in all procedures that include the production of colored products that can be estimated quantitatively. With regard to UV–vis spectroscopy, the radiation incidence results in light absorption in the PCP, which shifts the electronic energy levels. It also determines the wavelength at which this radiation absorbance occurs, which varies for every component (Madhu 2022). Every component in a sample has a distinct set of properties, and each element has a particular X-ray fluorescence, which results in electron transfer between shell levels to produce peaks (Thermal Fisher Scientific 2020). Peak height/intensity reflects the concentration, whereas peak energy aids in element identification. The fundamental principle of an electrochemical cell is the production of electrical current by the transfer of electrons from the redox reaction. This device is used in the electrochemical method to convert chemical energy into electrical energy and vice versa. One can identify and quantify a molecule based on the electrical energy created or the charge transfer in the electrochemical cell (Fethi and Hicham 2022).

Instrument performances

Colorimetry

Several investigations have been conducted to determine PCP levels in various samples using colorimetric methods. Various studies have utilized different chemicals in the pretreatment technique to obtain the chromophores. For the study of biological and water samples, PCP was oxidized to a mixture of ortho and para tetrachloroquinones in the presence of fuming nitric acid, yielding a reddish yellow product that was extracted into chloroform and quantified using a concentration-dependent spectrophotometer. The investigation established a linear calibration curve from 50 to 1 mg (Deichman and Schafer 1942). In fabric samples, PCP was condensed with 4-amino antipyrine in the presence of potassium ferricyanide and dilute sodium carbonate, forming a green dye and receiving the concentration-dependent curve at 640 nm for this dye and calibration curve between 300 and 1 mg (Gottlieb and Marsh 1946). The sawdust spiked with the known quantity of PCP, necessitates liquid–liquid partitioning of PCP against toluene at acidic and alkaline pH, after which PCP is linked with 4-amino antipyrine in the presence of sodium persulfate to generate a dye that is detected at 580 nm. The limit of detection (LOD) for 1 g of wood was 1 ppm (Gremaud and Turesky 1997). The main concern with these approaches is that

pollutants interfere with the pretreatment procedures used to extract chromophores and determine PCP.

Furthermore, these procedures have a lower level of accuracy and are insufficiently sensitive to detect PCP concentrations smaller than a milligram. A new extractive colorimetric approach for analyzing water, plant material, and biological materials produced good findings for identifying PCP (Sao et al. 2006). In this approach, the contaminated material is heated with strong nitric acid to generate chloranil, which liberates iodine with potassium iodide and forms a yellow–brown complex with cetyltrimethylammonium bromide with an absorbance maximum of 300 nm. The LOD and LOQ were 0.0018 and 0.0063 ppm, respectively. As a result, the continued development of new colorimetric methods can improve LOD for various samples. The US Environmental Protection Agency (USEPA) developed a method for detecting PCP in soil using UV-induced colorimetry, which can detect up to 1.5 mg of PCP/kg of soil (Fig. 2) (USEPA 2008). In this study, the colorimetric approach was used to determine chloride content in PCP-contaminated wastewater to test the effect of *Pseudomonas* sp. on PCP bioaugmentation, where the chloride content is directly proportional to the removal of PCP increase in wastewater due to the release of CO₂, HCl, and H₂O from the PCP biodegradation process. To obtain a crimson and permanent color precipitate, the wastewater was mixed with 2–3 drops of nitric acid, 0.2 g of calcium carbonate, and 3 drops of 10% potassium chromate. The chloride content was calculated using the formula (Volume of the titrating solution poured by a volume V ml of sample-volume of the titrating solution poured by a volume V mL of distilled water)/V × Number of mg of chlorides equivalent to 1 mL of titrant solution (10 mg Cl⁻) × 1000 × dilution factor, and the organisms increased the chloride content from 0.64 to 3.12 g/L in 7 days (Werheni et al. 2022). From the review, the colorimetric equipment and method of detection are not expensive; nonetheless, the instrument is not widely used for PCP detection and has poor precision and sensitivity compared with other detection techniques.

Briefly in Fig. 2, PCP was added to methanol; shaken well, and then added to acidified HPLC grade water and loaded into a solid phase extraction (SPE) column, which produced a sample with the hexane elute. The hexane elute is added with basic water and shaken well, where the hexane is decanted off at the end. The remaining PCP in the aqueous solution is added to acidic water, octane, and cobalt chloride, which is then shaken well for separation. PCP in octane is added to sodium sulfate solution, where the aliquot of octane is then added to a commercially available quick test reagent for PCP detection in soil in isopropyl alcohol. The mixture is then tested in an

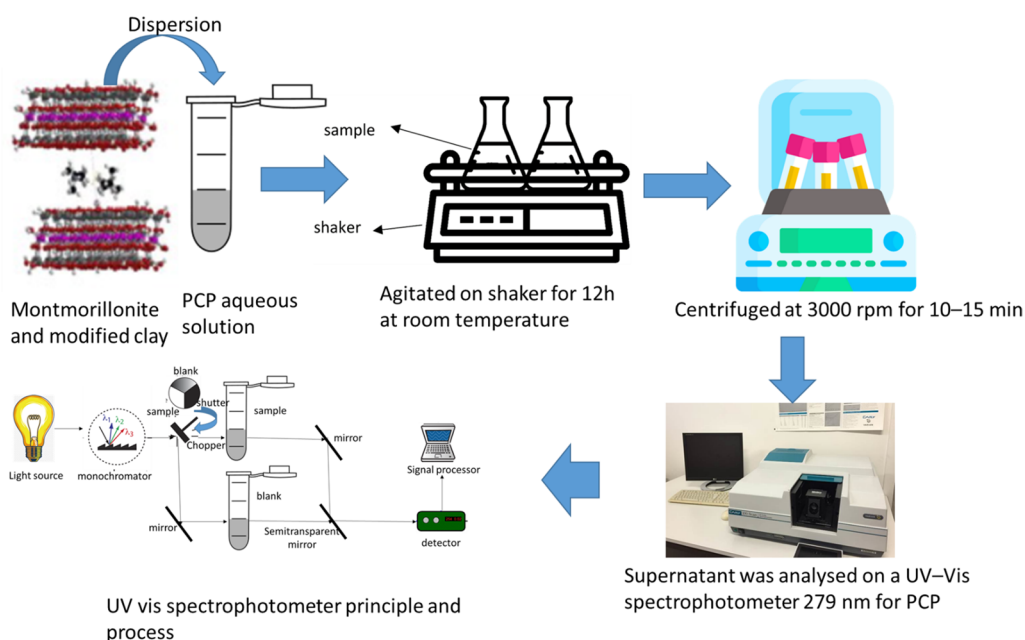


Fig. 3 Detection of PCP concentration in aqueous solution to test the effect of montmorillonite and modified clay in the removal of PCP from water

Thin-layer chromatography

Performance Paper chromatography and TLC are related methods for separating PCP from other similar chemicals and identifying them. On the other hand, TLC is faster, produces more compact spots, and achieves better separation while minimizing tailing difficulties. The detection of PCP in aqueous solution using TLC yielded an LOD of 8–35 ng and LOQ of 25–98 ng, with a recovery rate ranging from 89.21 to 101.74% (Faraji et al. 2011). Figure 4 shows the methods used for detecting PCP in an aqueous solution (Faraji et al. 2011). Sawdust spiked with PCP was evaluated by TLC after nitric acid-mediated oxidation of PCP to tetrachloro-1,4-benzoquinone, with an LOD of 1 ppm when 100 mg of wood was used (Gremaud and Turesky 1997). Several studies have used two-directional TLC, which separates and detects PCP using distinct solvent systems in water, wood, and even latex materials. In latex samples, excellent separation was accomplished with the chloroform–acetic acid solvent system (100:1), with PCP developing bright brown spots on a light blue background with the copper sulfate pyridine reagent with a retention factor (R_f) value of 0.5 (Davies and Thuraisingham 1968). PCP in treated wood samples was analyzed using TLC, with TLC plates containing PCP in a solvent system that included cyclohexane–acetone–liquid paraffin (15:3:2) in one direction and ethyl acetate–glacial acetic acid in the other, yielding an R_f value of 0.25 for PCP (Henshaw et al. 1975). In raw and treated river water, benzene in the first direction helps in removing interfering

organic contaminants, and 6 mL of 1 N sodium hydroxide in 94 mL of acetone helps in separating PCP from other phenols. The reagents silver nitrate and 4-amino antipyrine of sensitivity 0.1 and 0.5 μg respectively was used to find PCP, and PCP was found with an R_f value of 0.09 (Zigler and Philips 1967).

Advantages and disadvantages Thin-layer chromatography is an excellent analytical method because it saves time by allowing samples to be evaluated simultaneously and uses less solvent per sample, which lowers costs. Furthermore, it outperforms the colorimetric approach in terms of accuracy and precision, and sensitivity in the nanogram and pictogram ranges. However, TLC can only assess nonvolatile substances, has low-resolution capabilities (peak capacities of 10–50), and lacks completely automated systems (Deepak 2015). It cannot resolve complicated combinations of chemicals, but GC can. In TLC, the carrier liquid progresses on the plate because of gravitational force or capillary action; however, in HPLC, the mobile phase flows through the column, making it faster because it is pushed through by a pump (Deepak 2015). It does not have the same range of detectors as GC and HPLC; hence, it cannot provide large and sensitive detection alternatives. However, combining TLC with other analytical procedures such as HPLC, MS, and Fourier transform infrared spectroscopy (FTIR) will yield better sample analysis results (Chemistry LibreTexts 2022). It incurs significant expenses because new TLC plates must

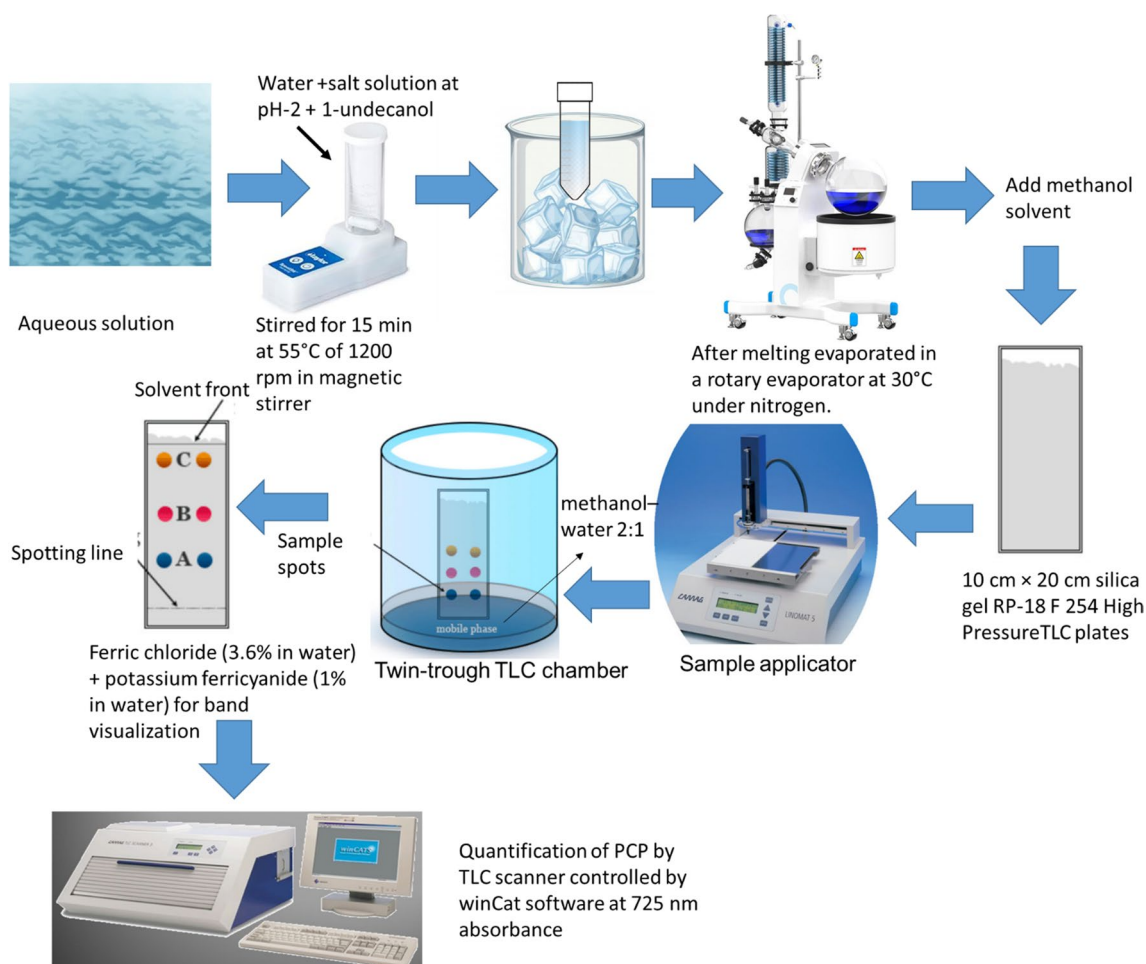


Fig. 4 Pentachlorophenol detection in thin-layer liquid chromatography (TLC) instrument

be inserted at each analysis and cannot be reused, unlike other procedures.

The extraction process employed in Fig. 4 is described as follows: 10 mL of water sample saturated with salt at pH-2 is mixed with 9 mL immiscible extracting solvent (1-undecanol) stirred in a magnetic stirrer for 15 min at 55 °C at a stirring rate of 1200 rpm. After stirring the vial was placed in an ice bath for 5 min; then solidified organic extractant transferred to conical vial for melting which is then evaporated to dryness in rotary evaporators at 30 °C under nitrogen; residue from evaporator dissolved in 200 mL of methanol and final solution used for analysis in TLC. TLC parameters: 10 cm x 20 cm silica gel RP-18 F254 HPTLC plates were used for analysis and samples were applied on the plates using Linomat V Sample applicator; mobile phase is methanol-water 2:1 (v/v) mixture taken in twin-trough chamber to 80 mm distance by the ascending technique; winCat software was used to control TLC scanner III system; absorbance—725 nm; slit dimensions—4 mm x 0.1 mm;

scanning speed—60 mm s⁻¹; spray solution for visualization—3.6% ferric chloride solution in water and 1% potassium ferricyanide in water (1:1). The steps to be followed for PCP detection were obtained from (Faraji et al. 2011). Pictures of instruments were taken from (Sonika 2023; Bernard-Savary and Poole 2015; Lab wrench 2024).

Gas chromatography (GC)

Gas chromatography (GC) is commonly used to study chlorinated byproducts in the production of chlorinated phenols. It was initially used by Barry et al. who effectively separated PCP from its homologs using a silicone high vacuum grease column at 200 °C and infrared spectroscopy to validate the compounds (Barry et al. 1962). However, early GC has low sample resolution and tailing of chlorophenols. To circumvent these issues, carbowax 20 M and 2% phosphoric acid at 200 °C were employed to resolve the combination of chlorophenols containing PCP on one column without tailing (Kolloff et al. 1963). It has a range of detectors such as a flame ionization

detector, thermal conductivity detector, electron capture detector, nitrogen phosphorous detector, mass selective detector, and flame photometric detector that offers lower detection limits than those of the other methods.

GC electron capture detection Pentachlorophenol concentrations in fish, crabs, frogs, turtles, and shrimp samples from China's fish market ranged from less than the method's limit of detection ($0.5 \mu\text{g}/\text{kg ww}$) to $61 \mu\text{g}/\text{kg ww}$. The samples were extracted into an organic solvent and quantified using GC and electron capture detection (EC) (Ge et al. 2007). A covalently prepared monolithic mixed matrix membrane of functionalized multi-walled carbon nanotubes polyethersulfone was used as a solid-phase microextraction fiber for the extraction of PCP followed by GC-EC analysis, with a lower LOD of $0.3\text{--}30 \text{ ng}/\text{L}$ from human urine and serum samples and a high recovery rate of $91.6\text{--}102.5\%$ (Matin et al. 2020). PCP in water samples recovered by dispersive liquid-liquid microextraction with deep eutectic solvent has a LOD of $0.015\text{--}1.0 \mu\text{g}/\text{L}$ and $0.05\text{--}3.0 \mu\text{g}/\text{L}$, with recoveries between 32 and 91% and repeatability values of $2.0 \mu\text{g}/\text{L}$ (Fattahi et al. 2022). The residues of PCP in fruits were determined by GC-EC after forming methyl ether of PCP and chromatographic the sample on an acid-washed Chromosorb W column with silicone oil at 180°C . The LOD was 0.01 ppm, and the material recovered between 76 and 90 (Cheng et al. 1993). PCP was extracted from soil and fish samples with 0.1 M potassium hydroxide and toluene, and the concentration was evaluated using EC-GC and a mass spectrometer,

which could detect a minimum of 0.5 ppb with 80–100% recovery of PCP (Stark 1969). As a result, GC-EC was chosen as the preferred method for analyzing PCP and other related phenols because it can detect smaller amounts (milligram to picogram) of PCP with less manipulation, better separation, and a greater recovery rate. GC-EC was widely used because of its strong sensitivity to PCP and its derivatives. However, significant pretreatment, extraction, preconcentration, and derivatization are required because EC does not respond as well to free PCP as it does to PCP ether.

GC-MS Several studies have used GC with various detector combinations to detect low levels of PCP in a variety of human, environmental, and food samples, including human urine (Thompson and Treble 1994), tissue (Wagner et al. 1991), textile materials (Mou et al. 1999), different food samples (Campillo et al. 2007), food packaging materials (Peng et al. 2021), and meat-tissue (Zhao 2014). PCP in seawater was extracted using liquid-liquid microextraction with toluene, and the reduced extract was mixed with a solvent mix containing methanol and trimethylsilyl derivatives of methanol (MeOTMS), allowing for good chromatographic resolution of underivatized PCP acting as a lubricant along the glass liner during the injection phase in GC-triple quadrupole MS. The study obtained 106% PCP recovery from seawater, with a low LOQ of $0.050 \mu\text{g L}^{-1}$ (Amendola et al. 2017). Figure 5 demonstrates the procedure for extracting PCP from seawater and analyzing it using GC/MS.

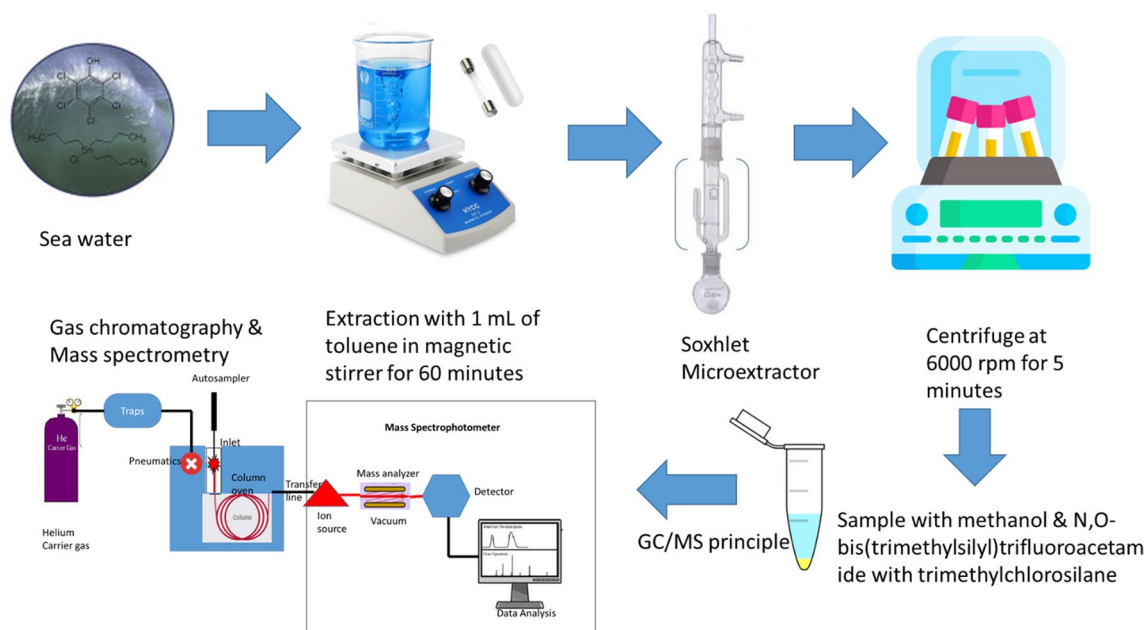


Fig. 5 Detection of PCP in seawater by GC/MS

(Amendola et al. 2017). In GC–MS, a GC fitted with a dual-flame ionization detector provided precise results in the ppb to ppm range for phenols by absorbing phenols on macroporous anion-exchange resin, eluting the sample with acetone, and injecting it straight onto the GC column. PCP was determined in sawdust spiked with a known quantity of PCP by derivatizing the extract with acetic anhydride in a biphasic solvent comprising toluene and 0.1% Na₂CO₃ (pH 11.4) pentachlorophenyl acetate (Gremaud and Turesky 1997). The LOD was 50 ppb when 100 mg of wood was tested. GC/MS has quickly become the preferred method for more precise detection of PCP. Both GC-EC and GC/MS were used to assess PCP levels in meat and fish. The analyte was extracted with methanol and trichloroacetic acid using accelerated solvent extraction and derivatized with acetic anhydride-pyridine. The LOD for this approach was in the range of 0.25–0.41 and 0.49–1.01 mg/kg in the muscle and liver of swine and bovine, as well as in the muscle of carp and finless eel, with 71.1% spiking recovery and consistent results from both the GC-EC and GC/MS (Zhao 2014). In GC, considerable extraction and derivitization are used to improve the volatility of PCP, which contributes to mistakes and exposes the analyst to solvents and organic reagents. It is inexpensive to use GC rather than HPLC because the costs associated with GC can be decreased in the long term with gas generators, which ensures that the carrier gas is available when needed without the need for costly storage and delivery.

In Fig. 5, the seawater spiked with PCP was extracted using 1 mL in the magnetic stirrer for 60 min, which was extracted further using a customized soxhlet micro-extractor. Upon emulsion, the extract was further centrifuged at 6000 rpm for 5 min. The extracted samples were added to methanol and *N,O*-bis(trimethylsilyl)trifluoroacetamide with trimethylchlorosilane to make a solvent mixture. Instrumentation: VF-XMS capillary column with 60 m–0.25 mm i.d.–0.25 µm film thickness; carrier gas–helium with a flow rate of 1.5 mL/min. The extracted sample was injected into the GC inlet, vaporized, and carried along with the helium to the chromatographic column. Injector parameters in solvent vent mode: heater temperature, 90 °C; pressure, 27.999 psi; total flow, 104.5 mL/min; septum purge flow, 3 mL/min; purge flow to split vent, 100 mL/min at 2 min; vent flow, 150 mL/min; vent pressure, 0 psi until 0.5 min. GC oven temperature for a total of 36 min: (1) 90 °C–4.8 min; (2) 40 °C/min up to 155 °C held for a min; 9 °C/min up to 240 °C held for 10.5 min; 20 °C/min up to 265 °C held for 2 min; 20 °C/min up to 340 °C held for 2 min. The MS-collision gas was nitrogen 5.5 at a collision cell flow rate of 1.5 mL/min. Transfer line and ion source temperatures of 310 and 300 °C, respectively (Amendola et al. 2017).

As the sample flows via the column, the compound of interest is separated by the relative interaction between the coating of the column (stationary phase) and helium (mobile phase). Furthermore, the column passes into the heated transfer line, which ends in an ion source where compounds eluting from the column are converted into ions, and these ions are analyzed in the mass spectrophotometer, where electrical impulses are recorded as visual displays (Wu et al. 2012).

High-pressure liquid chromatography (HPLC)

Performance HPLC is a quick approach for the detection and analysis of PCP that does not require derivatization. HPLC detectors include UV, refractive index, electrochemical, fluorescence, conductivity, and mass selectivity detectors, as well as photodiode array detection systems that allow for simultaneous detection. Pentachlorophenol was found in wastewater using HPLC to investigate the effect of *Pseudomonas mosseli* and *P. putida* on PCP removal, with HPLC confirming 800 mg/L of PCP in the wastewater (Werheni et al. 2022). HPLC–UV detection of 11 phenolic analytes, including PCP in water, yielded a LOD range of 0.51–13.79 µg/ml and a mean recovery of 67.9 ± 7.28 to 99.6 ± 4.26% (Opeolu et al. 2010). Wood spiked with PCP was tested by HPLC using a photodiode array detector, and the recovery of the spiked PCP standard in the leachate solution exceeded 85% with a LOD of 10 g/L. In the same study, HPLC analysis yielded results that were consistent with the non-destructible analytical approach of XRF (Zha 1992). Figure 6 shows the extraction of PCP from soil using ultrasonication, followed by HPLC analysis for PCP detection (Zha 1992). When methanol with 2 g/L of ammonium acetate (20:80) was used as the solvent in fish tissue samples at the 305 nm detection wavelength, PCP recovery was 76% with a limit of detection of 14 g/L (Liao et al. 2004). The retention time for PCP detection in wastewater was 12.9 min using acetonitrile and phosphoric acid as solvents (Alsingery 2013). Derivatization with dansyl chloride in HPLC-tandem MS resulted in 91–101% recovery with a range of LOD of 0.01–1.0 µg/L for the direct detection of PCP in well water, demonstrating great sensitivity and specificity (Noestheden et al. 2012). Ion-pair HPLC has been widely used to detect PCP concentration in samples such as water, lumber, fish, shrimps, and oysters, although it only detects PCP at high concentrations ranging from 5 to 15 mg/kg. All samples, including animal tissue and fluids, egg yolks, and egg whites, had a high mean recovery rate of 73–108%; however, determining PCP concentration in whole eggs was difficult because the recovery rate was only 50–84% using HPLC on porous silica with methanol as the eluent (Mundy and Machin 1981).

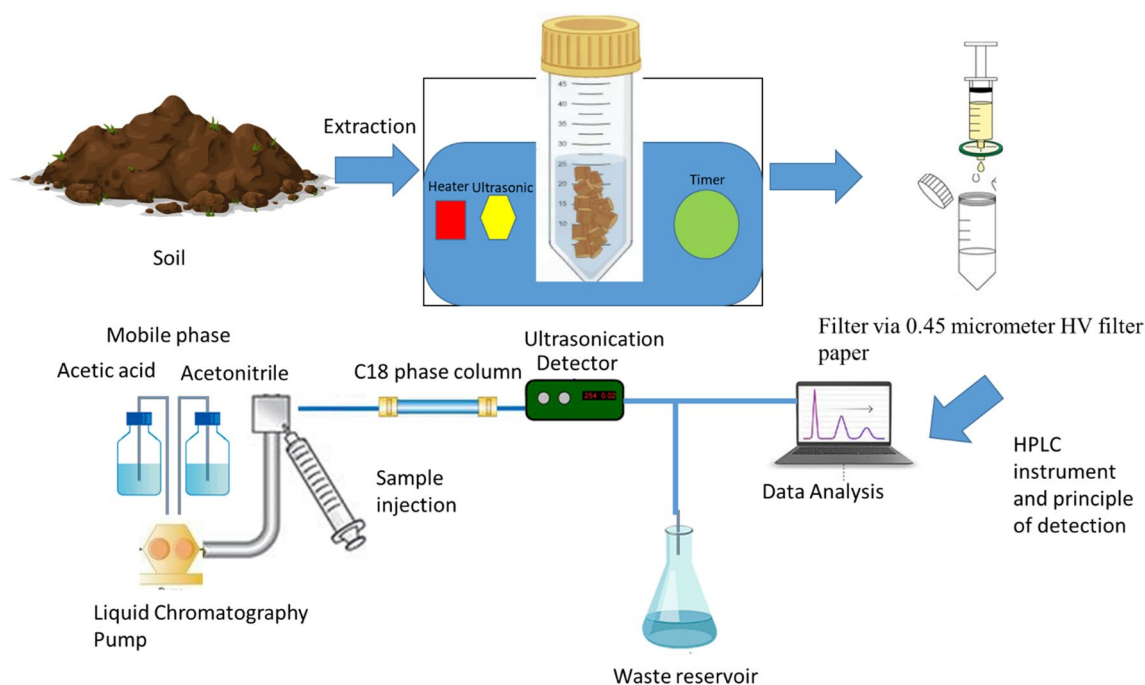


Fig. 6 Detection of PCP in soil using HPLC

Advantages and disadvantages It has a lower sensitivity to detect PCP when a UV detector is employed, although this can be avoided if an alternative and more appropriate technique of concentration is available. Furthermore, the cost of HPLC equipment and its maintenance is significantly higher than that of GC. This is mostly because the solvents used in HPLC are more expensive than purchasing gas canisters. HPLC also requires a pressure pump to drive the mobile phase through the column. HPLC is a liquid-based chromatographic approach, whereas GC is a gas chromatographic method that involves gasifying the chemical before examination.

As a result, in HPLC, the polarity of the mobile and stationary phases affects separation, which is why the solvents employed must be compatible with the chemical being examined. There is no universal solvent in HPLC, whereas such complications do not exist in GC. Furthermore, the column used in GC is extremely universal and may be used to analyze a variety of samples for different analytes. However, HPLC does not have such universal columns and requires distinct columns for different analytes depending on their characteristics and the mobile phase. The division in high-execution fluid chromatography is less effective than that in GC.

In Fig. 6, PCP is extracted from the soil using ultrasonication, where 1 g of soil is added to 50 mL of acetonitrile. After sonication for 1 h, the extracted liquid will be filtered using a 0.45 μm HV syringe filter. The

filtered samples were injected into the HPLC instrument for detection. The HPLC instrument operational conditions include column: C18 reversed-phase column (15 cm*3.9 mm), packed with 5 μm silica particles. The instrument parameters include; mobile phase—1% Acetic acid: Acetonitrile; operation temperature: ambient; mobile phase running on a gradient program: (1) Time=0.0 min. 1% HAC: CH₃CN=40:60 (2) Time=4.0 min. 1% HAC: CH₃CN=40:60 (3) Time=14.0 min. 1% HAC: CH₃CN=10:90 (4) Time=17.0 min. 1% HAC: CH₃CN=40:60 (5) Time=25.0 min. 1% HAC: CH₃CN=40:60; Flow rate: 1 ml/min; UV detection: 305 nm; detector sensitivity: 0.2 absorbance units full scale; and the injection amount is 50, or 25 μL (Zha 1992).

X-ray fluorescence

Performances X-ray fluorescence is a fast and accurate method for identifying the elemental composition of a material. The main benefits of this instrument in the wood industry are that it requires little sample concentration, and the element of interest and its concentration can be determined non-destructively in minutes. The XRF screening portable equipment is not limited to identifying the elemental composition of inorganic compounds; it can also perform a quantitative assessment of observed chlorine, which can be used as a marker element for the presence of organochlorines such as PCP. In textile sam-

ples, the limit of detection for chlorine atoms in organic compounds ranges from 5 to 160 ppm. (Krug and Hahn 2014). Historically, industrial preservatives for treated wood have been tested using XRF. A study examined the detection of PCP in treated wood using GC/MS and XRF, and the results were equivalent. To detect PCP in treated woods, the LOD for chlorine atoms was 10 µg/g of material (Murray 2007). It is a simple and effective method for detecting PCP because XRF uses the interaction of Cl ions with radiation to determine the concentration, with only sample homogenization required to ensure that each particle of wood is penetrated and thermalized in the same manner (KanggieBer 2003). Figure 7 demonstrates the identification of PCP from treated wood using XRF (Murray 2007).

XRF in the wood industry Portable XRF has been used in the wood industry’s quality control process for decades to quantify the concentration of organic wood compounds in treated wood and treating solutions because it is time-saving, simple, dependable, and comfortable. Previously, in XRFs used in 1954, crystals were used to reflect radiation measured by a Geiger counter, which had various disadvantages such as high detection limits, high expense, and restrictions in matching the crystal materials to the element of interest (Sturdivant et al. 2020). XRFs now include a source that excites electrons near the nucleus of atoms, resulting in K-band X-rays. XRF instrument designs from the 1950s to the 2000s featured a paired source, filter, and detector that were opti-

mized for a specific element or group of elements used in a single application of interest, in which radiations were directly detected using proportional counters and compared to known samples(Sturdivant et al. 2020). Although these designs are sturdy and produce consistent findings, the configured instruments were inflexible to industry changes. The current market XRF technology can analyze various wood-treating processes without requiring costly setup adjustments.

XRF future work Due to the high cost of equipment operation, XRF spectroscopy is rarely used to examine treated wood and treatment solutions. The main problem with XRF is that it cannot distinguish individual organochlorine chemicals. We must employ other procedures to validate the presence of these substances and determine their nature. Furthermore, it is difficult to identify volatile and semi-volatile organic biocides such as PCP using a non-destructive approach like XRF. In addition, XRF detects and quantifies certain elements inside a substance but not the complex itself. As a result, chlorine detection can provide information about the distribution and quantitative data of PCP. Although XRF is the best non-destructible method for obtaining a reliable result in minutes, it has only been used for the analysis of PCP in wood and treating solutions, and it is not widely used for other sample matrices because of its high equipment cost and lack of specificity in identifying and quantifying organic compounds.

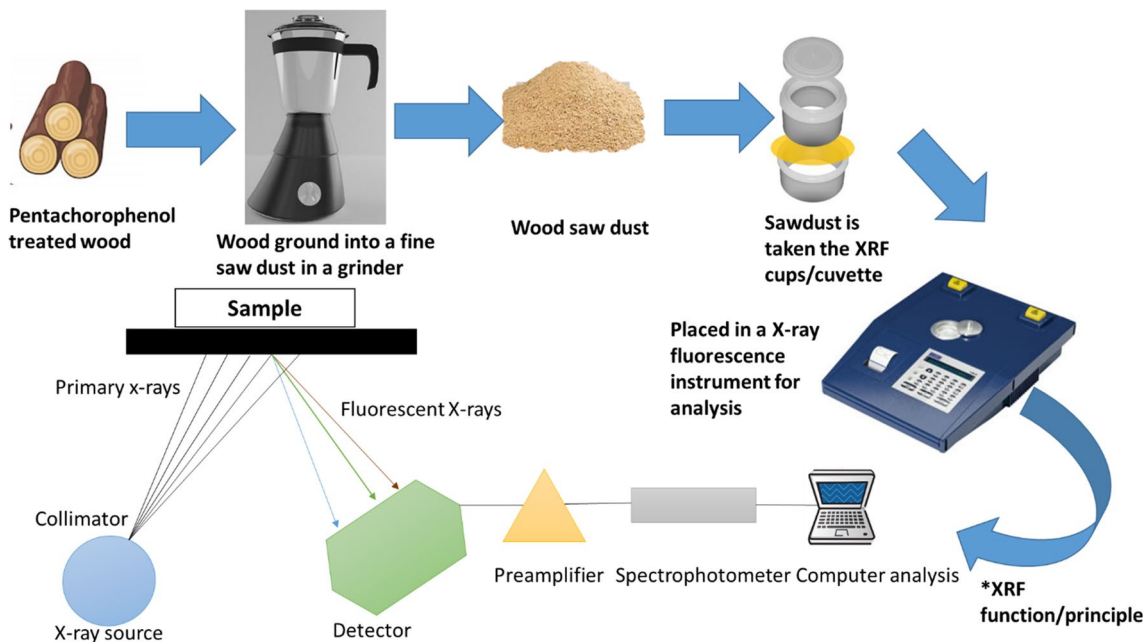


Fig. 7 Steps to detect PCP in out-of-service utility poles using XRF

The steps to detect PCP in out-of-service utility poles using XRF is shown in Fig. 7. Briefly, the wood is ground to a fine saw dust and then filled into the XRF cuvettes and placed into XRF instrument for detection. The methodology was obtained from Murray 2007. The key components of the XRF instrument include an X-ray source to produce X-rays, X-ray beam optics (collimators) to control spot size, a sample stage to place the sample, a solid state semiconductor detector, a preamplifier, a digital processor to process fluorescent X-ray signals, and a computer to analyze the results. The X-rays diffracted from the samples enter via a thin beryllium window that produces electron–hole pairs in the semiconductor region of the detector. These electron–hole pairs formed are based on the amount of X-ray energy that enters the detector, which is collectively recorded as a negative pulse. The negative pulses are then counted by a multi-channel analyzer that sorts them based on their sizes (Horiba Scientific 2024).

Electrochemical sensor

Electrochemical techniques and sensors have been extensively used to develop instruments that are sensitive and selective for detecting phenolic and other chemical compounds because of their high specific recognition, adsorption capacity for analytes, and chemical stability (Fethi and Hicham 2022). Since nanotechnology and material sciences have advanced, electrochemical-based sensors based on advanced materials and new composites have sparked widespread interest in the scientific community (Deshmukh et al. 2018; Fethi and Hicham 2022). Advanced materials include metal and metal oxide (Boyacıoğlu et al. 2022), carbon nanotubes (Hicham et al. 2022), metal–organic frameworks (MOF) (Tajuddin et al. 2021), graphene (Karaman et al. 2021a, b), and graphene oxide (Karaman et al. 2022).

Metal–organic frameworks (MOFs) are composed of organic ligands and inorganic crystalline metal nodes with a large specific area, numerous reactive sites, and remarkable catalytic activity (Banerjee et al. 2012; Chen et al. 2018; Tajuddin et al. 2021). However, the isolating qualities of organic ligands and the d-orbital engagement of coordination ions between metal ions and organic ligands prevent the electron from properly delocalizing over the entire framework (Meskher, et al. 2022a). As a result, integrating MOFs with carbon-based materials such as graphene-reduced oxide (rGO) can serve as a supportive background because of their excellent conductivity, environmental stability, and biocompatibility (Karaman, et al. 2021a, b; Liu et al. 2021; Noor et al. 2019). Graphene-reduced oxide is chemically inert and atomically smooth, preventing active substance adherence to the electrode surface and minimizing electrode

fouling (Meskher et al. 2022a, b). The nanocomposite rGO/MOF demonstrated strong electrical conductivity and catalytic activity, with a linear range of 50 μM to 200 μM , a LOD of 75.63 nM, and an LOQ of 254.54 nM (Meskher, et al. 2022a). A study demonstrated good PCP recovery using a sensitive electrochemical sensor made by altering a glassy carbon electrode with silver-reduced graphene oxide (AgNPs-rGO) nanocomposites from vegetable samples, and the results were cross-checked with HPLC data (Wang et al. 2020). It has demonstrated remarkable electrochemical activity for PCP oxidation because of its enhanced surface area, porous structure, good electron transport capabilities, and better enrichment effect of AgNPs-rGO. The sensor has a linear range of 0.008 to 10.0 μM and a LOD of 0.001 μM , significantly lower than the USEPA's recommended PCP limit of 0.0037 μM for drinking water. Compared with graphene, rGO has advantages in electron transfer rate, π -electron distribution, biocompatibility, density at active sites, and adsorption capacity (Meskher et al. 2022a, b) (Fig. 8). A nickel–aluminum layered double hydroxide modified glassy carbon electrode (Ni–Al–LDH@GCE) was used to detect PCP in real water samples and showed satisfactory recovery values with detection and quantification limits of 0.004 μM and 0.0132 μM , respectively (Khan et al. 2024).

A nickel–cobalt layered double hydroxide (NiCo-LDH) supported on green organic–inorganic nanohybrid (rGO-CuO) was drop cast on a gold electrode (AuE). Electrochemical measurements showed good conductivity and large active surface area favoring the electrochemical redox reaction of PCP with a linear range of 1–50 μM and LOD was estimated to be 12.64 nM (Meskher et al. 2023). (Zhu et al. 2020) created a sensor with an interface made of a hollow zeolitic imidazolate framework (ZIF)-derived mesoporous carbon material (HZC/SPCE) that detects PCP without the use of enzymes, pre-concentration, or metals. The sensor was created by chemically etching ZIF-8 material with tannic acid and then pyrolyzing it, which gave HZC a mesoporous hollow structure that allowed for conductivity and PCP transport via the solid/liquid interface.

This approach has a concentration range of 0.001 to 26.8 mg L^{-1} with a limit of detection (LOD) of 2.05 nM and recoveries ranging from 92.0% to 107.0% in spiked food packaging samples. A natural N and S co-doped carbon dots (NSCD) that is a “off–on” fluorescence sensor for the detection of PCP generated by hydrothermal synthesis using food-derived crawfish shells as green precursors (Chen et al. 2023). The synthesized NSCDs provided a large quantum yield of 18.57% with an LOD of 2.30 μM for PCP (Chen et al. 2023). Carbon dots (CD) are highly water soluble and stable, have strong biocompatibility

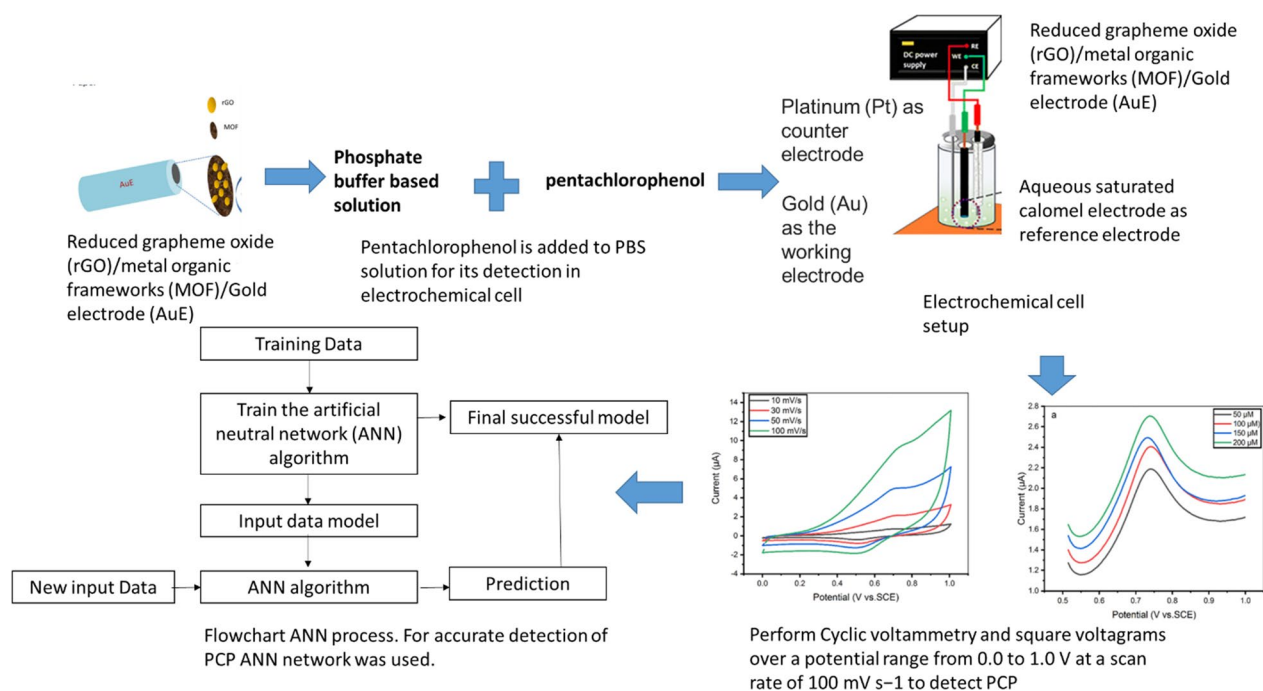


Fig. 8 PCP detection using a highly sensitive reduced graphene oxide (rGO)/metal-organic frameworks (MOF)/gold electrode (AuE) electrochemical sensor and artificial neural network (ANN) application

with low toxicity, easy functionalization, and enhanced photobleaching resistance compared with conventional semiconductor quantum dots (Wan et al. 2019; Zhu et al. 2021). Carbon supplies from natural sources, such as NSCDs, are less expensive, more environmentally friendly, and may be manufactured in higher quantities than chemical CDs, such as ethylenediamine, norepinephrine, and 5-amino-1,10-phenanthroline (Chen et al. 2023).

In the method shown in Fig. 8, PCP was added to the phosphate buffer-based solution (PBS) where PCP was detected by an electrochemical cell followed by cyclic voltammetry and square voltammograms for quantification (Meskher et al. 2022a, b). For accurate quantification and to estimate the very low concentration of PCP, a novel method called ANN application was used (Begum et al. 2019).

Performance of different extraction methods

The biggest challenge in detecting a trace level of PCP using the chromatographic approach is isolating and pre-concentrating the target component from the extraneous matrix (Zha 1992). In general, chlorophenols, including PCP, were measured in water using liquid-liquid extraction (LLE) and solid-phase extraction (SPE). Conventional liquid-liquid partitioning processes have been widely used to isolate PCP residues from plants, animals, and human materials (AWPA 2022; Castline 1985; Heinz

1976; NiMi and Chow 1983). However, the SPE of trace organic molecules from water outperforms standard LLE in terms of reproducibility and efficiency (Marvin and Brindle 1990). The solid-phase extraction approach effectively isolates and concentrates PCP in samples, particularly those with low PCP concentrations. However, the SPE approach followed by HPLC for detecting PCP and other phenols in water has demonstrated 12% less repeatability, with recovery ranging from 67.9 ± 7.28 to $99.6 \pm 4.26\%$ (Opeolu et al. 2010). It is difficult to extract PCP from intricate matrix-like tissue samples in an LLE because it is a small molecular compound. PCP is difficult to extract from complicated matrix-like tissue samples in an LLE because it is a tiny molecular molecule. Few studies have found that both LLE and SPE procedures have increased uncertainty in the measurement of the analyte, frequently demand high organic solvent, substantial training to operate, and are time-consuming (Bernal et al. 1996; Brossa et al. 2002; Supleco 1998).

In both TLC and GC-MS methods, extraction of PCP added to sawdust at 1.0 ppm with methanol and an acid/base solvent partition against toluene resulted in 80–85% recovery, and at alkaline conditions, recovery can be increased to more than 65% by extracting the toluene phase with 3 mL of 5 mM sodium carbonate (Gremaud and Turesky 1997). Similarly, sulfuric acid was employed to extract PCP from its salt, and the entire PCP was collected in toluene (Buhr et al. 2000). However, the main

disadvantages of using these traditional procedures are that they are extremely time consuming and require potentially dangerous extraction and derivatization steps. Sonication and Soxhlet extraction procedures are most commonly used for PCP analysis (Buhr et al. 2000). PCP was extracted ultrasonically from wood samples using acetonitrile solvent in HPLC, with an extraction efficiency of 90% (Zha 1992). Extraction of PCP from the given sample ultrasonically is the most common method used for analysis using HPLC (AWPA 2022; Zha 1992).

Solid-phase microextraction (SPME) has several advantages in sample preparation, including speed, sensitivity, and versatility, as sampling can be performed immediately without a solvent and is easily automated (Pawliszyn 1997). The global uncertainty in PCP detection in wastewater was less than 20% for LOD ranges between 5 and 40 µg/L, but increased to 64% at the LOD value of 0.75 µg/L based on the results of different studies on the detection of PCP extracted by SPME followed by GC–MS (Brás et al. 2011). Accelerated solvent extraction can boost the analyte dissolution ability while also analytically accelerating analytes from the complex matrix.

When PCP was extracted from animal and fish tissue using an accelerated solvent extraction procedure followed by GC/MS and GC-ECD, the recovery rate increased by more than 71.1% (Zhao 2014). Recently, various studies have been conducted to optimize PCP extraction, particularly to determine the optimum fiber to employ in SPME. A study was conducted to test the effectiveness of different fiber materials in the SPME method followed by GC-ECD to extract PCP from paper and board. 100 µm polydimethylsiloxane (PDMS), apolar, and 85 µm polyacrylate (PA), quite polar, were evaluated for their extraction performances compared to the conventional extraction method LLE. Among the fibers used, PDMS outperformed the PA fiber. However, PCP recovered from SPME was 70–84% of that produced by the traditional LLE technique. In recent research, a monolithic mixed matrix membrane of functionalized multi-walled carbon nanotubes polyethersulfone was prepared

using a covalent approach and used as a solid-phase microextraction fiber for the extraction of PCP from human serum and urine samples with a recovery rate of 91.6–102.5% (Matin et al. 2020).

Comparison of performance of instruments in the detection of PCP

Each instrument has its advantages and disadvantages. Based on the data acquired, the performance of each piece of equipment in detecting PCP was compared and graded in Table 3. Electrochemical sensors, a non-destructible approach, have piqued scientists' interest in detecting PCP because of their high sensitivity, fast reaction, and low cost (Alizadeh et al. 2021; Mehmandoust et al. 2021; Salmanpour et al. 2017). It is sensitive, cost-effective, easy to use, and selective in the real matrix, making it a viable choice for PCP detection (Baig and Kawde 2015; Jin and Maduraiveeran 2017; Mustafa 2024). However, there are still issues that need to be addressed in existing electrochemical methods, such as low sensitivity or narrow linear range (Xu et al. 2014; Zou et al. 2013), relatively complex construction and time-consuming processes (Yuan et al. 2013; Zhu et al. 2016) and the high cost of platinum, which is the most commonly used metal for electrochemical cells (Nesakumar et al. 2017). Research has been and continues to be conducted to develop novel electrochemical sensors that are simple and quick to fabricate.

Among the destructible strategies, GC is an excellent choice for PCP detection. GC was given a better ranking because it is more cost-effective and can deliver a rapid analysis with high sensitivity than the other destructible procedures. However, they are less reliable than electrochemical sensors because of their low selectivity and high cost. Among non-destructible techniques, although XRF is not as cost-effective as electrochemical sensors, it ranks second due to its speed and ease of use, particularly in the wood preservation business. XRF has been used in the wood business for several years and has proven to be a flawless non-destructible approach; nevertheless, it is

Table 3 Ratings of instruments based on different characteristics

Instrument name	Recovery rate	Limit of detection	Time	Cost-effectiveness	Rating (1–10) ^a
Colorimetry	100%	g–mg	N/A	Low cost	4
UV–vis/IR	100%	N/A	Faster	Low cost–recent technology	7
TLC	N/A	ng–pg	Slower than GC and HPLC	Higher than GC	6
GC	70–100%	ng–pg	Faster than HPLC	Low cost	8
HPLC	50–108%	ng–pg	Slower than GC	Higher than GC	7
XRF	Results are more reliable	N/A	In minutes	High cost	9
Electrochemical sensor	92–107%	ng	Quick and high selectivity	High cost-effective	9.5

^a Ratings 1 to 4—poor; 5 to 8—good; 9 and 10: excellent

less dependable and specific in the research sector since it identifies compounds based on elemental composition, such as chlorine in the case of PCP. HPLC comes next, despite its great sensitivity and recovery rate, because it is time-consuming and expensive. Thin layer chromatography, like HPLC, received a lower ranking because of its low sensitivity, high time consumption, and high cost. The colorimetric method received a poor rating because of its low sensitivity and specificity, and it is not as widely used as other methods. Finally, UV–vis/IR spectrometry has a modest ranking because it is a low-cost instrument used for qualitative analysis that supports the PCP obtained from GC and HPLC analyses.

Conclusion

PCP is a man-made substance that is widely distributed in the environment. Although it has been prohibited in some countries and phased out of industry in Canada, due to its persistence in the environment, it is critical to test PCP in diverse samples to determine a suitable remediation approach for removing PCP from the environment. Several analytical tools and procedures have been used to examine PCP. In terms of PCP, GC is a popular analytical instrument for a variety of samples because of its ability to obtain PCP fast, at a low cost, and with maximum precision. Other instruments were not favored because they were difficult to handle, had poorer sensitivity and precision, and were expensive.

Although HPLC is a good instrument, it has not been used to assess PCP for various samples because it is not suitable for them, possibly because of analyte and solvent incompatibility with the column. Developing a universal column for HPLC, similar to GC, could improve HPLC efficiency and lower analysis costs. Furthermore, because of the high cost of XRF, there is limited literature on the analysis of PCP in various sample matrices.

Further investigation into the usefulness of non-destructible technologies such as XRF, not only in wood and wood solutions but also in various sample matrices, could assist in improving the effectiveness of PCP analysis. In addition to XRF, various other non-destructible technologies have been evaluated for efficacy. For example, among all the approaches presented, EC, a non-destructible method, is more reliable because of its faster response time, lower cost, and high specificity. Furthermore, research into modifying existing analytical procedures to improve efficacy can be conducted. To improve precision and specificity in the EC approach, more studies are needed to find electrodes that are inexpensive and highly compatible with PCP detection. In addition to these analytical approaches, electrochemical chemiluminescence, ultra-high-performance supercritical fluid chromatography-mass spectrometry, and solid-phase

microextraction have been developed for effective PCP analysis. As a result, this study has paved the way for some new studies to improve PCP analysis.

Acknowledgements

Not applicable.

Author contributions

Koushika Kumaresan: Writing-Original draft preparations, methodology, software. Hamed Niati: Reviewing, proofreading, editing. Sophia He: Conceptualization, writing-reviewing. Emenike Chijioke Uche: Conceptualization, writing-reviewing and editing, validation, methodology, Software.

Funding

Not available.

Availability of data and materials

Not applicable.

Declarations

Competing interests

The authors have no conflict of interest to declare.

Author details

¹Department of Plant, Food, and Environmental Sciences, Dalhousie University, Halifax, Canada. ²Department of Microbiology, Hezekiah University, Nkwerre, Nigeria. ³Department of Engineering, Faculty of Agriculture, Dalhousie University, Truro, Canada.

Received: 27 December 2023 Accepted: 8 May 2024

Published online: 13 June 2024

References

- Alizadeh M, Mehmandoust M, Nodrat O, Salmanpour S, Erk N. A glassy carbon electrode modified based on molybdenum disulfide for determination of folic acid in the real samples. *J Food Meas Charact*. 2021;15(6):5622–9. <https://doi.org/10.1007/s11694-021-01128-w>.
- Alsingery RMD. Determination of trace pentachlorophenol (PCP) in wastewater using solid phase extraction. *Adv Appl Sci Res*. 2013;4(3):344–434.
- Amendola L, Cortese M, Vinatoru D, Sposato S, Insoigna S. Innovative analytical method for the determination of underivatized tributyltin and pentachlorophenol in seawater by gas chromatography-triple quadrupole mass spectrometry. *Anal Chim Acta*. 2017;975:70–7. <https://doi.org/10.1016/j.jaca.2017.04.004>.
- Ammeri RW, Abdenaceur H, Hidri Y. Effect of PCP pesticide contamination on soil quality. In: Larramendy ML, Soloneski S, editors. *Soil contamination—threats and sustainable solutions*. London: IntechOpen; 2020a. <https://doi.org/10.5772/intechopen.93714>.
- AWPA. American wood protection association—AWPA standard A9–90. Birmingham: Moore Tech Solutions Inc.; 2022.
- Baig N, Kawde A-N. A novel, fast and cost effective graphene-modified graphite pencil electrode for trace quantification of l-tyrosine. *Anal Methods*. 2015;7(22):9535–41. <https://doi.org/10.1039/C5AY01753J>.
- Banerjee A, Gokhale R, Bhatnagar S, Jog J, Bhardwaj M, Lefez B, Hannover B, Ogale S. MOF derived porous carbon–Fe₃O₄ nanocomposite as a high performance, recyclable environmental superadsorbent. *J Mater Chem*. 2012;22(37):19694–9. <https://doi.org/10.1039/C2JM33798C>.
- Barry JA, Vasisht RC, Shelton FJ. Analysis of chlorophenols by gas-liquid chromatography. *Anal Chem*. 1962;34(1):67–9. <https://doi.org/10.1021/ac60181a017>.
- Begum A, Fatima F, Sabahath A. International conference on communication and signal processing (ICCSPP), Chennai, India. 2019;0172–0175
- Bernal JL, del Nozal MJ, Rivera JM, Jiménez JJ, Atienza J. Determination of the fungicide vinclozolin in honey and bee larvae by solid-phase extraction with gas chromatography and electron capture and mass spectrometric detection. *J Chromatogr A*. 1996;754:507–13.

- Bernard-Savary P, Poole CF. Instrument platforms for thin-layer chromatography. *J Chromatogr A*. 2015;1421:184–202. <https://doi.org/10.1016/j.chroma.2015.08.002>.
- Bevenue A, Emerson ML, Casarett LJ, Yaeger WL. A sensitive gas chromatographic method for the determination of pentachlorophenol in human blood. *J Chromatogr*. 1968;38(4):467–72. [https://doi.org/10.1016/0021-9673\(68\)85075-7](https://doi.org/10.1016/0021-9673(68)85075-7).
- Boyacıoğlu H, Yola BB, Karaman C, Karaman O, Atar N, Yola ML. A novel electrochemical kidney injury molecule-1 (KIM-1) immunosensor based covalent organic frameworks-gold nanoparticles composite and porous NiCo₂S₄@CeO₂ microspheres: the monitoring of acute kidney injury. *Appl Surf Sci*. 2022;578:152093. <https://doi.org/10.1016/j.apsusc.2021.152093>.
- Brás I, Ratola N, Alves A. Uncertainty in the quantification of pentachlorophenol in wood processing wastewaters by SPME-GC-MS. *J Anal Chem*. 2011;66(8):756–62. <https://doi.org/10.1134/S1061934811080053>.
- Brossa L, Marce RM, Borrull F, Pocurull E. Application of on-line solid-phase extraction-gas chromatography-mass spectrometry to the determination of endocrine disruptors in water samples. *J Chromatogr A*. 2002;963:287–94.
- Buhr A, Genning C, Salthammer T. Trace analysis of pentachlorophenol (PCP) in wood and wood-based products -comparison of sample preparation procedures. *Fresenius J Anal Chem*. 2000;367(1):73–8. <https://doi.org/10.1007/s002160051601>.
- Campillo N, Peñalver R, Hernández-Córdoba M. A sensitive solid-phase microextraction/gas chromatography-based procedure for determining pentachlorophenol in food. *Food Addit Contam*. 2007;24(7):777–83. <https://doi.org/10.1080/02652030701216735>.
- Carswell TS, Hatfield I. Pentachlorophenol for wood preservation. *Ind Eng Chem*. 1939;31:1431–5.
- Castline JL. Uptake, translocation, and transformation of pentachlorophenol in soybean and spinach plants. *Environ Res*. 1985;378:101–18.
- CCME. Canadian environmental quality guidelines for the protection of environment and human health- Pentachlorophenol. Canadian Council of Ministers of Environment; 1999.
- Chemistry LibreTexts. Thin Layer Chromatography. *Chromatographic Technique*; 2022. https://chem.libretexts.org/Ancillary_Materials/Demos_Techniques_and_Experiments/General_Lab_Techniques/Thin_Layer_Chromatography
- Chen X, Chen X, Yu E, Cai S, Jia H, Chen J, Liang P. In situ pyrolysis of Ce-MOF to prepare CeO₂ catalyst with obviously improved catalytic performance for toluene combustion. *Chem Eng J*. 2018;344:469–79. <https://doi.org/10.1016/j.cej.2018.03.091>.
- Chen J, Xia X, Li P, Yu H, Xie Y, Guo Y, Yao W, Qian H, Cheng Y. A facile “off-on” fluorescence sensor for pentachlorophenol detection based on natural N and S co-doped carbon dots from crawfish shells. *Food Chem*. 2023;405:134802. <https://doi.org/10.1016/j.foodchem.2022.134802>.
- Cheng WN, Coenraads PJ, Hao ZH, Liu GF. A health survey of workers in the pentachlorophenol section of a chemical manufacturing plant. *Am J Ind Med*. 1993;24(1):81–92. <https://doi.org/10.1002/ajim.4700240108>.
- Choudhury AKR. 6—Colour measurement instruments. In: Choudhury AKR, editor. *Principles of colour and appearance measurement*. Cambridge: Woodhead Publishing; 2014. p. 221–69. <https://doi.org/10.1533/9780857099242.221>.
- Crosby DG. Environmental chemistry of pentachlorophenol. *Pure Appl Chem*. 1981;53(5):1051–80. <https://doi.org/10.1351/pac198153051051>.
- Darbire PD. Endocrine disruption and human health. 2nd ed. Cambridge: Academic press; 2021.
- Davies JR, Thuraisingham ST. Quantitative determination of free elemental sulphur in rubber vulcanizates by thin-layer chromatography. *J Chromatogr A*. 1968;35:513–8. [https://doi.org/10.1016/S0021-9673\(01\)82417-1](https://doi.org/10.1016/S0021-9673(01)82417-1).
- Deepak. Advantages of HPLC and GC over thin-layer chromatography. *Lab-Training.Com*. Auriga Research; 2015. <https://lab-training.com/advantages-of-hplc-over-thin-layer-chromatography-tlc/>
- Deichman W, Schafer LJ. Spectrophotometric estimation of pentachlorophenol in tissues and water. *Ind Eng Chem Anal Ed*. 1942;14:310–2.
- Deshmukh MA, Shirsat MD, Ramanaviciene A, Ramanavicius A. Composites based on conducting polymers and carbon nanomaterials for heavy metal ion sensing (review). *Crit Rev Anal Chem*. 2018;48(4):293–304. <https://doi.org/10.1080/10408347.2017.1422966>.
- Faraji H, Saber-Tehrani M, Mirzaie A, Waqif-Husain S. Application of liquid-liquid microextraction-high-performance thin-layer chromatography for pre-concentration and determination of phenolic compounds in aqueous samples. *J Planar Chromatogr Mod TLC*. 2011;24(3):214–7. <https://doi.org/10.1556/JPC.24.2011.3.7>.
- Fattahi N, Pirsahab M, Moradi M, Mohebbi A, Karimi P, Hashemi B. Dispersive liquid-liquid microextraction-assisted by deep eutectic solvent for the extraction of different chlorophenols from water samples followed by analysis using gas chromatography-electron capture detection. *Microchem J*. 2022;180:107608. <https://doi.org/10.1016/j.microc.2022.107608>.
- Fethi A, Hicham M. Carbon electrodes as emerging platforms for miniaturization of electrochemical biosensors. In: Chandra P, Mahato K, editors. *Miniaturized biosensing devices: fabrication and applications*. Cham: Springer; 2022. p. 39–55. https://doi.org/10.1007/978-981-16-9897-2_2.
- Ge J, Pan J, Fei Z, Wu G, Giesy JP. Concentrations of pentachlorophenol (PCP) in fish and shrimp in Jiangsu Province, China. *Chemosphere*. 2007;69(1):164–9. <https://doi.org/10.1016/j.chemosphere.2007.04.025>.
- Giri D. Colorimeter: principle, instrumentation, and uses. *Parkes Scientific Canada. Biochemistry*; 2022. <https://laboratorytests.org/colorimeter/>
- Gottlieb S, Marsh PB. Quantitative determination of phenolic fungicides. *Ind Eng Chem Anal Ed*. 1946;18(1):16–9. <https://doi.org/10.1021/i560149a004>.
- Governemnt of Canada. Factsheet: pentachlorophenol. Public services and procurement of Canada; 2013. <https://gost.tpsgc-pwgsc.gc.ca/Contfs.aspx?ID=63&lang=eng>
- Gremaud E, Turesky RJ. Rapid analytical methods to measure pentachlorophenol in wood. *J Agric Food Chem*. 1997;45(4):1229–33. <https://doi.org/10.1021/jf9605963>.
- Haas K. UV/Vis instrumentation. LibreTexts Chemistry. 2021 https://chem.libretexts.org/Courses/Duke_University/CHEM_401L%3A_Analytical_Chemistry_Lab_Manual/03%3A_Caffeine_serial_dilution_and_analysis_using_%28UV-vis%29_spectroscopy/3.03%3A_UV_Vis_Instrumentation
- Heinz JH. A study of the inhalation of pentachlorophenol by rats. *Bull Environ Contam Toxicol*. 1976;15:18–85.
- Henshaw BG, Morgan JWW, Williams N. The detection of organic solvent preservatives in wood by thin-layer chromatography. *J Chromatogr*. 1975;110:37–41.
- Hicham M, Fethi A, Ha S, Khaldoun B. Antifouling double layers of functionalized-multi-walled carbon nanotubes coated ZnO for sensitive and selective electrochemical detection of catechol. *Fullerenes Nanotubes Carbon Nanostruct*. 2022;30(3):334–47. <https://doi.org/10.1080/153683X.2021.1940150>.
- Horiba SCIENTIFIC. XRF key components. *Energy Dispersive X-Ray Fluorescence (ED-XRF)*; 2024. <https://www.horiba.com/int/scientific/technologies/energy-dispersive-x-ray-fluorescence-ed-xrf/key-components/#component4>
- Jin W, Maduraiveeran G. Electrochemical detection of chemical pollutants based on gold nanomaterials. *Trends Environ Anal Chem*. 2017;14:28–36. <https://doi.org/10.1016/j.teac.2017.05.001>.
- Jones MJ. Conservation systems and crop production. In: *Conference on Agricultural Development in Drought-Prone Africa*. London: Royal Commonwealth Society; 1985.
- KanggieBer B. Quantification procedures in micro X-ray fluorescence analysis. *Spectrochim Acta B*. 2003;58:609–14.
- Karaman C, Karaman O, Atar N, Yola ML. Sustainable electrode material for high-energy supercapacitor: biomass-derived graphene-like porous carbon with three-dimensional hierarchically ordered ion highways. *Phys Chem Chem Phys*. 2021a;23(22):12807–21. <https://doi.org/10.1039/D1CP01726H>.
- Karaman C, Karaman O, Yola BB, Ülker İ, Atar N, Yola ML. A novel electrochemical aflatoxin B1 immunosensor based on gold nanoparticle-decorated porous graphene nanoribbon and Ag nanocube-incorporated MoS₂ nanosheets. *New J Chem*. 2021b;45(25):11222–33. <https://doi.org/10.1039/D1NJ02293H>.
- Karaman O, Özcan N, Karaman C, Yola BB, Atar N, Yola ML. Electrochemical cardiac troponin I immunosensor based on nitrogen and boron-doped graphene quantum dots electrode platform and Ce-doped SnO₂/SnS₂ signal amplification. *Mater Today Chem*. 2022;23:100666. <https://doi.org/10.1016/j.mtchem.2021.100666>.
- Khan MM, Shaikh H, Al Souwaileh A, Khan MY, Batool M, Memon SQ, Solangi AR. A highly selective nickel-aluminum layered double hydroxide

- nanostructures based electrochemical sensor for detection of pentachlorophenol. *Arab J Chem.* 2024;17(3):105604. <https://doi.org/10.1016/j.arabjc.2024.105604>.
- Kolloff RH, Breuklander LJ, Barkley LB. Gas chromatographic analysis of chlorophenol mixtures. *Anal Chem.* 1963;35(11):1651–4. <https://doi.org/10.1021/ac60204a032>.
- Krug S, Hahn O. Portable X-ray fluorescence analysis of pesticides in the textile collection at the German Historical Museum. *Berlin Stud Conserv.* 2014;59(6):355–66.
- Lab wrench. Camag—Scanner 3 Community, Manuals and Specifications. LabWrench; 2024. <https://www.labwrench.com/equipment/9650/camag-scanner-3>
- Liao L, Yan Y, Lin L, Yang L. Detection of pentachlorophenol in biomaterial using HPLC. *Sichuan Da Xue Xue Bao Yi Xue Ban J Sichuan Univ Med Sci Ed.* 2004;35(3):427–8.
- Liu Y, Zhou H, Zhou W, Meng S, Qi C, Liu Z, Kong T. Biocompatible, high-performance, wet-adhesive, stretchable all-hydrogel supercapacitor implant based on PANI@rGO/Mxenes electrode and hydrogel electrolyte. *Adv Energy Mater.* 2021;11(30):2101329. <https://doi.org/10.1002/aenm.202101329>.
- Madhu. What is the difference between UV-Vis and IR spectroscopy. *Difference between.Com. Analytical Chemistry*; 2022. <https://www.differencebetween.com/what-is-the-difference-between-ir-and-uv-and-visible-spectroscopy/>
- Marvin CH, Brindle ID. Automated high performance liquid chromatography for the determination of pesticides in water using solid phase extraction. *Anal Chem.* 1990;62:1495–8.
- Matin AA, Biparva P, Gheshlaghi M, Khosrowshahi EM, Farhadi K. Monolithic mixed matrix membrane based on polyethersulfone/functionalized MWCNTs nanocomposite as an SPME fiber: application to extract chlorophenols from human urine and serum samples followed by GC-ECD. *J Chromatogr B Anal Technol Biomed Life Sci.* 2020. <https://doi.org/10.1016/j.jchromb.2020.122190>.
- Mehmandoust M, Erk N, Alizadeh M, Salmanpour S. Voltammetric carbon nanotubes based sensor for determination of tryptophan in the milk sample. *J Food Meas Charact.* 2021;15(6):5288–95. <https://doi.org/10.1007/s11694-021-01100-8>.
- Meskher H, Achi F, Ha S, Berregui B, Babanini F, Belkhalifa H. Sensitive rGO/MOF based electrochemical sensor for penta-chlorophenol detection: a novel artificial neural network (ANN) application. *Sens Diagnos.* 2022a;1(5):1032–43. <https://doi.org/10.1039/D2SD00100D>.
- Meskher H, Achi F, Zouaoui A, Ha S, Peacock M, Belkhalifa H. Simultaneous and selective electrochemical determination of catechol and hydroquinone on a nickel oxide (NiO) reduced graphene oxide (rGO) doped multiwalled carbon nanotube (fMWCNT) modified platinum electrode. *Anal Lett.* 2022b;55(9):1466–81. <https://doi.org/10.1080/00032719.2021.2008951>.
- Meskher H, Achi F, Moussa FB, Henni A, Belkhalifa H. A novel pentachlorophenol electrochemical sensor based on nickel-cobalt layered double hydroxide doped with reduced graphene oxide composite. *ECS Adv.* 2023;2(1):016503. <https://doi.org/10.1149/2754-2734/acc117>.
- Mou J, Chen M, Zou M. Determination of pentachlorophenol residues in textiles and leather and leather products by gas chromatography/mass spectrometry. *Se Pu Chin J Chromatogr.* 1999;17(4):386–8.
- Mundy DE, Machin AF. Determination of pentachlorophenol and related compounds in animal materials by high-performance liquid chromatography and gas chromatography. *J Chromatogr.* 1981;216:229–38. [https://doi.org/10.1016/s0021-9673\(00\)82351-1](https://doi.org/10.1016/s0021-9673(00)82351-1).
- Murray G. The development and evaluation of a recycling methodology for out-of-service pentachlorophenol treated utility poles. *Dalhousie University*; 2007. <https://dalspace.library.dal.ca/bitstream/handle/10222/54927/NR27648.PDF?sequence=1>
- Mustafa YF. Coumarins from carcinogenic phenol: synthesis, characterization, in silico, biosafety, anticancer, antioxidant, and anti-inflammatory assessments. *Chem Pap.* 2024;78(1):493–504. <https://doi.org/10.1007/s11696-023-03105-7>.
- Nesakumar N, Gumpu MB, Nagarajan S, Ramanujam S, Rayappan JBB. Simultaneous voltammetric determination of captan, carbosulfan, 2,3,7,8-tetrachlorodibenzodioxin and pentachlorophenol in groundwater by ceria nanospheres decorated platinum electrode and chemometrics. *Measurement.* 2017;109:130–6. <https://doi.org/10.1016/j.measurement.2017.05.047>.
- NiMi AJ, Chow CY. Laboratory and field analysis of PCP accumulation by salmonids. *Water Res.* 1983;17:1791–5.
- Noestheden M, Noot D, Hindle R. Fast, extraction-free analysis of chlorinated phenols in well water by high-performance liquid chromatography–tandem mass spectrometry. *J Chromatogr A.* 2012;1263:68–73. <https://doi.org/10.1016/j.chroma.2012.09.021>.
- Noor T, Zaman N, Nasir H, Iqbal N, Hussain Z. Electro catalytic study of NiO-MOF/rGO composites for methanol oxidation reaction. *Electrochim Acta.* 2019;307:1–12. <https://doi.org/10.1016/j.electacta.2019.03.116>.
- Opeolu B, Fatoki O, Odendaal J. Development of a solid-phase extraction method followed by HPLC-UV detection for the determination of phenols in water. *Int J Phys Sci.* 2010;5:576–81.
- Park Y, Ayoko GA, Kurdi R, Horváth E, Kristóf J, Frost RL. Adsorption of phenolic compounds by organoclays: implications for the removal of organic pollutants from aqueous media. *J Colloid Interface Sci.* 2013;406:196–208. <https://doi.org/10.1016/j.jcis.2013.05.027>.
- Pawliszyn J. *Solid Phase Microextraction: Theory and Practice.* Wiley.Com; 1997. <https://www.wiley.com/en-us/Solid+Phase+Microextraction%3A+Theory+and+Practice-p-9780471190349>
- Peng Y, YinPing L, Yang L, FuZun C, LiYing W. Determination of pentachlorophenol by gas chromatography mass spectrometry in paper packaging materials for foodstuffs. *J Food Saf Qual.* 2021;12(5):1699–704.
- PMRA Re-evaluation note REV2022-02, Update on the special review of Pentachlorophenol. *Pest Management Regulatory Agency*; 2022. anada.ca/en/health-canada/services/consumer-product-safety/reports-publications/pesticides-pest-management/decisions-updates/reevaluation-note/2022/update-special-review-pentachlorophenol.html
- PubChem. Pentachlorophenol. 2023 <https://pubchem.ncbi.nlm.nih.gov/compound/992>
- Raja PMV, Barron AR. High Performance Liquid chromatography. *Chemistry LibreTexts.* Rice University via OpenStax CNX; 2022. [https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Physical_Methods_in_Chemistry_and_Nano_Science_\(Barron\)/03%3A_Principles_of_Gas_Chromatography/3.02%3A_High_Performance_Liquid_chromatography](https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Physical_Methods_in_Chemistry_and_Nano_Science_(Barron)/03%3A_Principles_of_Gas_Chromatography/3.02%3A_High_Performance_Liquid_chromatography)
- Salmanpour S, Abbasghorbani M, Karimi F, Bavandpour R, Wen Y. Electro-catalytic determination of cysteamine uses a nanostructure based electrochemical sensor in pharmaceutical samples. *Curr Anal Chem.* 2017;13(1):40–5.
- Sao A, Pillai A, Gupta VK. An extractive colorimetric method for determination of pentachlorophenol (PCP). *Indian J Chem Technol.* 2006;13:294–7.
- Sonika. Thin layer chromatography. *Career Power*; 2023. <https://www.careerpower.in/school/chemistry/thin-layer-chromatography>
- Stark A. Determination of pentachlorophenol contamination in the fish and the soil sediments. *J Agric Food Chem.* 1969;17:871.
- Stuckey NG, Larsen K. Field determinations of pentachlorophenol in water using UV/Vis spectroscopy. *Aust J Chem.* 2012;66(1):105–12. <https://doi.org/10.1071/CH12286>.
- Sturdivant RL, Luckie V, Bartek RP. X-ray fluorescence for the analysis of DCOI in the industrial market. *American Wood Protection Association (AWPA)*; 2020.
- Supleco. Solid phase microextraction: theory and optimization of conditions. *Bulletin923.* Sigma-Aldrich Co; 1998. <https://gcms.labrulez.com/labrulez-bucket-strap-h3hsga3/39b099fcca3f4a75920edaa148681827/4547.pdf>
- Tajuddin MHA, Jaafar J, Hasbullah H, Awang N, Ismail AF, Othman MHD, Rahman MA, Yusof N, Aziz F, Salleh WNW. Metal organic framework in membrane separation for wastewater treatment: potential and way forward. *Arab J Sci Eng.* 2021;46(7):6109–30. <https://doi.org/10.1007/s13369-021-05509-7>.
- Thermal fisher scientific. What is XRF (X-ray Fluorescence) and how does it work? *Industrial Applied Sciences*; 2020. [https://www.thermofisher.com/blog/ask-a-scientist/what-is-xrf-x-ray-fluorescence-and-how-does-it-work/#:~:text=composition%20of%20materials-,XRF%20\(X%20Ray%20Fluorescence\)%20is%20a%20non%2Ddestructive,a%20primary%20X%20Ray%20source.](https://www.thermofisher.com/blog/ask-a-scientist/what-is-xrf-x-ray-fluorescence-and-how-does-it-work/#:~:text=composition%20of%20materials-,XRF%20(X%20Ray%20Fluorescence)%20is%20a%20non%2Ddestructive,a%20primary%20X%20Ray%20source.)
- Thermo Fisher Scientific. Gas chromatography-mass spectrometry (GC-MS) information. *Industrial and Applied Sciences*; 2006. <https://www.thermofisher.com/ca/en/home/industrial/mass-spectrometry/mass-spectrometry>

- rometry-learning-center/gas-chromatography-mass-spectrometry-gcms-information.html
- Thompson TS, Treble RG. Preliminary results of a survey of pentachlorophenol levels in human urine. *Bull Environ Contam Toxicol*. 1994;53(2):274–9. <https://doi.org/10.1007/BF00192044>.
- Tullo AH. Making pillars of the community safer: the days of preserving utility poles with pentachlorophenol appear to be numbered, and the industry is looking for substitutes. *Chem Eng News*. 2020;98(14):22–3.
- UNEP-FAO. Decision guidance documents—Pentachlorophenol and its salts and esters. United Nations Environment Programme-Food and Agriculture Organization of United Nations; 1996. http://www.pic.int/Portals/5/DGDs/DGD_Pentachlorophenol_EN.pdf
- USEPA. United States of Environmental Protection Agency; prevention, pesticides, and oxid substances. EPA 739-R-08-008, Registration Eligibility decision for Pentachlorophenol; 2008
- USEPA. Method 8540: Pentachlorophenol in soil by UV-induced colorimeter. U.S. Environmental Protection Agency; 2007. <https://www.epa.gov/sites/default/files/2015-12/documents/8540.pdf>
- Wade AL, Hawkrige FM, Williams HP. Direct determination of pentachlorophenol by differential pulse polarography. *Anal Chim Acta*. 1979;105:91–7. [https://doi.org/10.1016/S0003-2670\(01\)83740-5](https://doi.org/10.1016/S0003-2670(01)83740-5).
- Wagner SL, Durand LR, Inman RD, Kiigemagi U, Deinzer ML. Residues of pentachlorophenol and other chlorinated contaminants in human tissues: analysis by electron capture gas chromatography and electron capture negative ion mass spectrometry. *Arch Environ Contam Toxicol*. 1991;21(4):596–606. <https://doi.org/10.1007/BF01183883>.
- Wan Y, Wang M, Zhang K, Fu Q, Gao M, Wang L, Xia Z, Gao D. Facile and green synthesis of fluorescent carbon dots from the flowers of *Abelmoschus manihot* (Linn.) Medicus for sensitive detection of 2,4,6-trinitrophenol and cellular imaging. *Microchem J*. 2019;148:385–96. <https://doi.org/10.1016/j.microc.2019.05.026>.
- Wang L, Li X, Yang R, Li J-J, Qu L-B. A highly sensitive and selective electrochemical sensor for pentachlorophenol based on reduced graphite oxide-silver nanocomposites. *Food Anal Methods*. 2020;13(11):2050–8. <https://doi.org/10.1007/s12161-020-01823-2>.
- Werheni R, Ben-Ghorbal S, Mehri I, Hassen W, Hassen A. Bioaugmentation of pentachlorophenol by *Pseudomonas mosseli* HM627603 and *P. putida* HM627611 in secondary treated wastewater—UVC254 inactivation. *New J Sci*. 2022. <https://doi.org/10.55416/sunbjns01.2201.08704>.
- Wu S, Lou R. Applications of chromatography hyphenated techniques in the field of lignin pyrolysis. *Appl Gas Chromatogr*. 2012. <https://doi.org/10.5772/32446>.
- Xu J, Wang Y, Qiu H, Zhang Y. The electrochemical oxidation of pentachlorophenol and its sensitive determination at chitosan modified carbon paste electrode. *Russ J Electrochem*. 2014;50(6):531–6. <https://doi.org/10.1134/S1023193514060093>.
- Xu Y, He Y, Tang X, Brookes PC, Xu J. Reconstruction of microbial community structures as evidences for soil redox coupled reductive dechlorination of PCP in a mangrove soil. *Sci Total Environ*. 2017;596–597:147–57. <https://doi.org/10.1016/j.scitotenv.2017.04.073>.
- Yuan S, Peng D, Hu X, Gong J. Bifunctional sensor of pentachlorophenol and copper ions based on nanostructured hybrid films of humic acid and exfoliated layered double hydroxide via a facile layer-by-layer assembly. *Anal Chim Acta*. 2013;785:34–42. <https://doi.org/10.1016/j.aca.2013.04.050>.
- Zha Y. Determination of pentachlorophenol in wood and leachate from discarded treated wooden poles. A Thesis Submitted to the Faculty of New Jersey Institute of Technology; 1992.
- Zhang J. Analysis of pentachlorophenol and other chlorinated phenols in biological samples by gas chromatography or liquid chromatography-mass spectrometry. *Pest Protoc*. 2006. <https://doi.org/10.1385/1-59259-929-X:111>.
- Zhao D. Determination of pentachlorophenol residue in meat and fish by gas chromatography-electron capture detection and gas chromatography-mass spectrometry with accelerated solvent extraction. *J Chromatogr Sci*. 2014;52(5):429–35. <https://doi.org/10.1093/chromsci/bmt054>.
- Zhu X, Zhang K, Lu N, Yuan X. Simultaneous determination of 2,4,6-trichlorophenol and pentachlorophenol based on poly(Rhodamine B)/graphene oxide/multiwalled carbon nanotubes composite film modified electrode. *Appl Surf Sci*. 2016;361:72–9. <https://doi.org/10.1016/j.apsusc.2015.11.154>.
- Zhu X, Zhao H, Shen J, Chen H, Cai X, Xu J, Wang X, Wang L, Lan M. A metal-free and preconcentration-free method for non-enzymatic amperometric determination of pentachlorophenol using a ZIF-derived hollow carbon material. *Microchim Acta*. 2020;187(4):224. <https://doi.org/10.1007/s00604-020-4180-4>.
- Zhu W, Zhou Y, Liu S, Luo M, Du J, Fan J, Xiong H, Peng H. A novel magnetic fluorescent molecularly imprinted sensor for highly selective and sensitive detection of 4-nitrophenol in food samples through a dual-recognition mechanism. *Food Chem*. 2021;348:129126. <https://doi.org/10.1016/j.foodchem.2021.129126>.
- Zigler MG, Philips WF. Thin-layer chromatographic method for estimation of chlorophenols. *Environ Sci Technol*. 1967;1:65–7.
- Zou J, Ma J, Zhang Y, Li L, Jiang J, Chen J. Electrochemical determination of pentachlorophenol using a glassy carbon electrode modified with a film of CuS nanocomposite-chitosan. *Anal Lett*. 2013;46(7):1108–16. <https://doi.org/10.1080/00032719.2012.749483>.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.