

Environmental Forensics of Emerging Contaminants through Analytical Techniques

Uditya Narayan Keshari¹, Shruti Srivastava^{1*}

¹Department of Pharmaceutical Chemistry, Amity Institute of Pharmacy, Lucknow, Amity University Uttar Pradesh, Sector 125, Noida, 201313, India

Corresponding author Email: ssrivastava16@lko.amity.edu

Abstract

Environmental forensics focuses on identifying the sources, distribution, and impacts of contaminants in the environment. Emerging contaminants, such as pharmaceuticals, personal care products, and microplastics, have become a growing concern due to their potential risks to ecosystems and human health. These contaminants, often present in trace amounts, are not easily detected through traditional methods. Advanced analytical techniques, such as gas chromatography-mass spectrometry (GC-MS), liquid chromatography-tandem mass spectrometry (LC-MS/MS), and high-resolution mass spectrometry (HRMS), are crucial in identifying and quantifying these substances in various environmental matrices, including water, soil, and air. Solid phase based microextraction techniques include thin film microextraction, needle trap devices, microextraction by packed sorbent, stir bar sorptive extraction and magnetic solid phase extraction whereas liquid phase based microextraction involves analytical techniques like single drop microextraction, directly suspended droplet microextraction, dispersive liquid-liquid microextraction, along with membrane assisted liquid phase microextraction. These techniques have been discussed further in this review that are utilized for the analysis of different forms of emerging contaminants. Through these sophisticated techniques, researchers can trace contaminants to their sources, determine their fate and transport in the environment, and assess their ecological and toxicological effects. Environmental forensics also aids legal and regulatory frameworks by providing evidence of contamination and assigning responsibility. The continual improvement of analytical methods, along with the development of more sensitive and selective detection techniques, enhances the ability to monitor emerging contaminants, offering critical insights into their environmental behavior and proposing mitigation strategies to reduce their impact.

Keywords: Microextraction, Emerging contaminants, Chromatography, Trace elements.

1. Introduction

Regulated contaminants are rigorously assessed and controlled on a global level through the deployment of validated analytical methodologies. These methodologies allow for the evaluation of the presence of a contaminant at levels that are regarded as toxicologically acceptable within the analyzed samples. Consequently, ensuring that contaminant concentrations remain below the maximum permissible limits established by esteemed organizations such as the Safe Drinking Water Act and US Environmental Protection Agency is essential for the implementation of public health safeguarding measures. The term 'contaminants of emerging concern (CEC)' is commonly employed to refer to those chemical agents that, although currently unregulated, may necessitate evaluation in forthcoming regulatory frameworks due to their potential risks to human health and environmental integrity. Alongside the regulated contaminants, there exists a notable multitude of unregulated chemical substances identified as CEC and are capturing greater interest in current research. These contaminants can be associated with a variety of sources, including but not limited to oil spills, industrial effluents, and urban development, which collectively impact air, water, and soil ecosystems. The adeptly ascertain, characterize, and eliminate a range of these diverse substances includes hydrocarbons, polycyclic aromatic hydrocarbons, heavy metals such as mercury, and volatile organic compounds (VOCs) is vital to implement specialized analytical strategies due to the complex nature of these substances and their compositions. In order to elucidate the origins, fate, and impact of contaminants, the discipline of environmental forensics is of paramount importance. It is vital to ascertain their existence and assess influents and effluents due to the continuous synthesis and release of novel compounds, particularly from wastewater treatment plants [1].

The need for environmental forensics department from the fact that the emerging contaminants (ECs) are intrinsically hazardous to human health and that their improper disposal harms the ecosystem. The field of EC gathered attention at the onset of the 21st century owing to progressions in analytical methodologies that facilitated their identification at minute concentrations in diverse environmental matrices. The fact that EC is frequently found in drinking water, groundwater, wastewater, and surface and groundwater is one reason leading to the growing awareness. Urbanization, industrial activities, and the extensive use of pharmaceuticals and personal care items are often the main causes of these EC levels. A rising amount of study is being done to understand the sources, behaviors, and environmental effects of EC as well as to develop management and removal measures. This is due to the identification of possible problems connected with EC. Throughout the 19th and early 20th centuries, asbestos was extensively utilized in a wide range of goods and building construction without being thought to pose a risk to human health or the environment. Certain types of pollutants, classified as either classic or emergent classes, were present in the environment.

This review provides an overview of CECs whose tracking are especially important, such as technologically advanced rare earth elements, organic and synthetic nanomaterials, illicit drugs, medicinal products, PCPs, endocrine disruption agents, recently designated pesticides, surfactants, and DBPs. More details on the origins of CECs, how they are transported and degraded, problems relating to the environment and human health, and EC remediation techniques. Personal care products (PPCPs), flame retardants, medicines, endocrine disruptors (EDCs), and nanoparticles are just a few examples of the many newly identified manufactured or naturally occurring substances that are classified as ECs. As these substances are ubiquitous, they endanger both the environment and human beings. Prolonged exposure to some EDCs, for instance, may have an impact on the reproductive system, whereas PPCPs combined with retardant fires may cause neurotoxicity and endocrine system malfunction. The first questions in EF investigations address impacted areas, contamination sources, site background, and pollutant transport. Customized forensic processes provide a more thorough analysis, while basic EPA techniques help identify the type and extent of chemicals. Fingerprinting is essential to understanding regulatory contexts and identifying sources in PFAS research. Among other items, paints, pesticides, and firefighting foams include perfluoroalkyl substances (PFAS). The laws controlling them at the state and federal levels are always changing [2].

Modern methods are enhancing detection and analysis to pinpoint specific PFAS chemicals and their origins. While complex forensic procedures provide deeper research and can detect non-target entities,

standard forensic techniques usually produce faster results and have shorter run times. The emergence of new contaminants, such as pesticides, personal care items, illegal substances, medications (both human and veterinary), and perfluorinated compounds identified in the water cycle, has been one of the most fascinating environmental stories of the last several years. After being used by humans and/or animals, these chemicals are removed or released as free and/or conjugate metabolites in their original forms. Thin-layer chromatography, radiation-labeled compounds, and gas chromatography (GC) using non-specific detectors have all been employed in the past to identify TPs. As a result, MS plays an essential role in the field of analytical chemistry. Acknowledging the polar characteristics of target pollutants (TPs), high-performance liquid chromatography (HPLC), or, more inclusively, liquid chromatography (LC), is the principal method utilized for separation. Target pollutants can be identified based on their nominal mass; however, quadrupoles display limited sensitivity in full scan mode, which is crucial for the detection of unknown compounds, and a significant portion of this research endeavor has been carried out employing standards or aqueous solutions at markedly higher concentrations. Established LC-MS interfaces utilize soft ionization approaches that generate minimal fragmentation while continuing to yield molecular details. The crucial fragmentation for complete structural elucidation is generally performed through collision-induced dissociation, which can transpire within a specific collision cell or the intermediate-pressure section of the mass spectrometer, frequently referred to as in-source collision-induced dissociation. The fragmentation pattern of the molecule, along with lengthy and complex processes and various additional confirmatory analyses, aids in determining the structure of unknown TPs [3].

Pharmaceuticals are a class of artificial chemicals that consist of a wide range of substance, such as lipid-lowering medications painkillers, alpha-blockers antimicrobial agents, antiepileptics, and anti-cancer drugs. These substances contribute significantly to environmental pollution. Another crucial group of CECs includes personal care products, which consist of chemicals used in everyday items like cosmetics and hygiene products. These include additives, plasticizers in synthetic musks, odors, and Ultraviolet filters, each of which have been found repeatedly uncovered in drinking water supplies throughout the globe. Illicit drugs are defined as CECs as well as presenting serious threats to natural systems, our surroundings, and people's health. Pesticides, before being sold, must undergo a registration process to assess their potential health and environmental impacts. This category includes both new pesticide compounds and new applications for existing chemicals. Surfactants, known for their ability to dissolve in both polar and nonpolar liquids, are essential in forming micelles and adsorbing at phase boundaries. These chemicals are widely produced and used, particularly as key ingredients in (bio) detergents, cleaners, and various industrial processes. Rare Earth Elements (REEs) are critical in the transition to low-carbon technologies, given their unique properties that are essential in developing advanced technological devices. Nanoparticles (NPs), materials with dimensions between 1 and 100 nanometers, can occur naturally in the environment. The formation of these entities is significantly governed by environmental considerations, including natural organic matter, pH levels, temperature variations, and light intensity, which can facilitate the unintended synthesis of metal nanoparticles alongside their oxides or sulfides through biogeochemical mechanisms. The technique of water disinfection, which seeks to eradicate detrimental microorganisms to prevent waterborne pathogens and elevate water quality, may inadvertently cause the emergence of potentially perilous disinfection by-products (DBPs) through interactions with the disinfectants employed. The trend toward the miniaturization of analytical methodologies is attracting considerable scholarly attention. The rationale behind miniaturization is fundamentally influenced by the need to minimize the size of traditional analytical instruments and the amount of reagents and solvents employed in every analytical task, which consequently leads to a notable reduction in waste output. The challenges encountered in standard sample preparation practices have instigated the rise of multiple downsized techniques, frequently designated as microextraction methods [4].

The most successful analytical technology for solid samples utilized in analytical labs worldwide is solid-phase microextraction (SPME). The concept of SPME is to separate the desired analytes from the specimen and coating an extremely small fiber. As sampling, analyte separation, and enrichment are all done in a single procedure, it is efficient and environmentally conscious. It also offers the expected

special benefits. To enhance extraction speed and increase sample throughput, vacuum-assisted headspace SPME (HS-SPME) was developed, allowing the SPME fiber to be inserted into an evacuated vial and exposed to the sample's headspace. This approach has been used to determine pollutants in soil samples with improved sensitivity, precision, and accuracy, without requiring prior sample preparation. As a miniaturized sample preparation technique, thin film microextraction (TFME) demonstrates considerable benefits when contrasted with standard solid-phase microextraction (SPME), including a greater extraction phase volume and an augmented surface area-to-volume ratio. These innovations render TFME especially competent for ultra-trace and prompt analytical techniques. Since its founding in 2003, extensive initiatives have been undertaken to improve the fiber geometry and to automate the extraction and desorption methodologies. The two different forms of alternative adsorptive microextraction (AmE) techniques are bar adsorptive microextraction (BAME) and the other one namely adsorptive microextraction in multiple spheres (MSAmE). Although in the MSAmE configuration, adsorbents are coated on polystyrene spherical substrates and then fixed by thermal treatment, in the BAME configuration, adsorbents are fixed to polypropylene hollow cylindrical substrates using adhesive films. The technique of magnetic solid-phase extraction utilizes magnetic adsorbents found in the solution or suspension under investigation to effectively extract target analogues. This approach capitalizes on the magnetic properties possessed by the adsorbents alongside the diamagnetic nature of most target molecules and impurities. Another form of microextraction is predicated upon liquid phases. Single drop microextraction (SDME), a condensed version of conventional liquid-liquid extraction (LLE), relies on a microdrop of the extractant phase for the extraction and preconcentration of targeted analytes. Nonetheless, SDME encounters certain limitations, including the challenges associated with retrieving the enriched microdrop post-extraction and the requirement to exclusively utilize hydrophobic solvents having lesser density to that of water, which may influence the extractability of specific analytes. In order to enhance stability and reliability in liquid-phase microextraction (LPME), the implementation of microporous hollow fiber membranes has been proposed. These membranes impart substantial shield to the acceptor phase and facilitate the process of microfiltration through the hollow fiber pores, thereby leading to heightened enrichment factors and more pristine extracts.

Dispersive liquid-liquid microextraction (DLLME) is a notable advancement in microextraction methods. Using a blend of an immiscible organic solvent with a density greater than water and a dispersion solvent such as acetonitrile or acetone a turbid solution is quickly generated in the sample during DLLME. The amplification of the interfacial area markedly enhances the rates of liquid-liquid mass transfer. Following the disruption of the emulsion, typically achieved through centrifugation or solvent-based de-emulsification, the enriched extractant phase is subsequently collected for further analytical evaluation. There are several miniaturized analytical flow based approaches for the determination of CEC such as millifluidic platforms, microfluidic platforms, paper based analytical devices. Furthermore, smaller-scale flow-based methods, including lab-on-a-chip (LOC) and lab-on-valve (LOV) devices, have the ability to combine several analytical process steps, indicating a strong possibility for identifying CECs. The bead injection methodology is founded on the deployment of automatically renewable solid phases that are distinguished by the presence of functional groups or ligands exhibiting biochemical characteristics. A significant advantage of this framework is the ability to utilize a fresh portion of sorbent for each sample through automated microfluidic manipulation. A range of platforms has been advocated for the application of bead injection; however, the most proficient thus far is the LOV format. A salient feature of LOV systems resides in their adaptability concerning the integration of sample preparation and the bead injection methodology relies on the application of automatically replenishable solid phases characterized by the presence of functional groups or ligands demonstrating biological and chemical properties. A variety of detection mechanisms may be embedded within the LOV structure, including optical detection that utilizes compact CCD spectrometers within micro. Total Analysis Systems (mTAS) frameworks. Additionally, redirecting the waste generated from microextraction operations via one of the lateral ports connected to the injection valve or the auto-sampler in multiple instrumental configurations enhances the possibility of forming continuous online or at-line connections to separation methods such as liquid and gas chromatography. A domain of science known as microfluidics has enabled the precise control and modification of fluidic volumes at a micro scale. The core functioning components which encompass setup, processing,

responses, and identification in various quantitative procedures and are unified onto a microchip. Based on their unique liquid means of transport, microfluidic devices can be categorized as capillary, pressure-driven, rotating, electro kinetic, or ultrasonic systems. The monitoring of ECs has been demonstrated to have considerable potential with microfluidic paper-based analytical devices (mPADs). A prime instance of such a method is a multiplexed chemical analysis that was explained as early as 2007 and using mPAD technology. Using the assistance of carefully arranged hydrophobic areas, the micro platelet array circuit regulates a small volume of substance as it flows along the network of capillaries. Moreover, paper-based platforms are capable of fulfilling the ASSURED criteria that stands for being affordable, specific, sensitive, user-friendly, robust, equipment-free, deliverable and rendering them more suitable for field-testing of CECs in comparison to conventional instrumental methodologies, and they exhibit extensive applicability in resource-limited environments that lack sophisticated apparatus and proficient personnel.

The need to minimize the waste produced by the complexity of traditional analytical systems and the quantity of reagents and solvents required for each analysis is one of the benefits motivating the trend towards downsizing. Due to the drawbacks of conventional sample preparation approaches, several types of smaller-scale technologies known as microextraction techniques have been established. Moreover, there is an excellent chance that CEC can be discovered by smaller-scale flow-based techniques, including many analytical tools assisted with devices like lab-on-a-chip (LOC) and lab-on-valve (LOV). There are numerous challenges that must be overcome in the advancement of techniques for trace and ultratrace CEC identification in matrices that are becoming more complex day by day. Ensuring the reliability of these methods through rigorous validation is crucial. Unfortunately, for many EC, the lack of allowed materials for reference and comparison techniques is an everyday barrier to completing this task. Furthermore, tackling environmental and health risks connected to untamed substances could benefit from the invention of more sensitive and selective methods, especially those that take advantage of smaller sample processing processes. These techniques could promote research into the creation and breakdown of these substances as well as keeping track of their distribution in environmental niches. The miniaturization of analytical methodologies is particularly relevant in this context. The motivation behind miniaturization extends beyond simply reducing the size of conventional systems. A number of other benefits are also provided, including a considerable reduction in the amount of sample and chemical used for each analysis, which results in less waste being produced, process step integration, simplification, improved portability, increased efficiency, and excellent performance. During the analytical process, various levels of downsizing can be attained, from cutting back on some phases to developing completely integrated, miniaturized analytical systems. Moreover, the pursuit of more sustainable methods is critical to prevent the unintended consequence of analytical methods designed to detect CECs from exacerbating environmental issues. This review article focuses on the use of modern analytical tools in environmental forensics to address challenges associated with CEC [5].

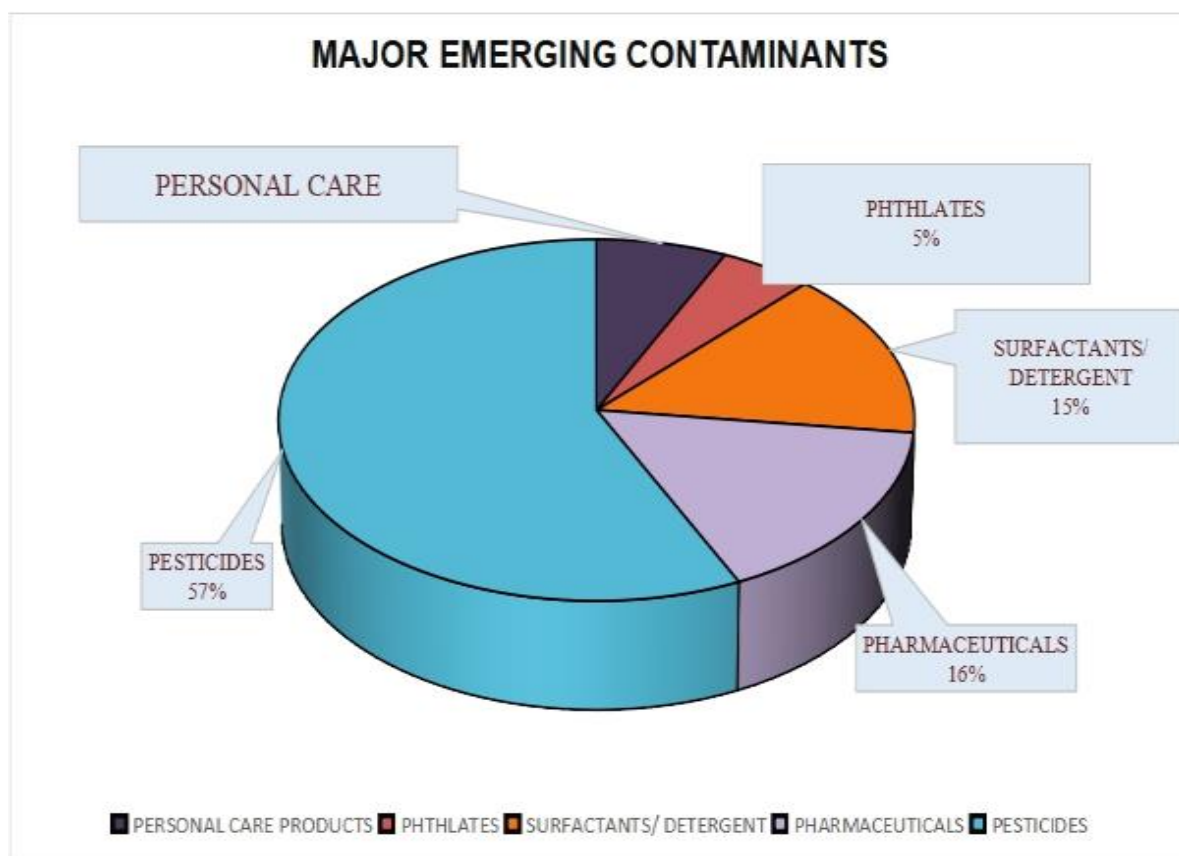


Figure 1: Depiction of various forms of emerging contaminants for environmental forensic.

2. History and Occurrence of Emerging contaminants

Early in the twenty-first century, the idea of Emerging Contaminants (EC) attracted a lot of attention because of improvements in analytical techniques that made it possible to detect them at trace levels in a variety of environmental matrices. The fact that EC is frequently found in drinking water, groundwater, wastewater, and surface and groundwater often as a result of industrialization, urbanization, and the widespread use of medications and personal care products contributes to this increased awareness. The identification of possible hazards linked to extracellular clays (ECs) has incentivized a surge in research endeavors aimed at comprehending their origins, characteristics, and impacts on the ecosystem, in addition to formulating approaches for their mitigation and elimination. Asbestos was extensively utilized in a variety of goods and building construction during the 19th and early 20th centuries without being thought to pose a health or environmental risk. But in the early 20th century, reports of asbestos's detrimental effects—which included lung problems and fatalities began to surface. The UK released the first asbestos industry restrictions in the 1930s, and the US followed suit with laws in the 1980s. Problems with the infrastructure for water treatment emerged in several US states in the 1970s, most notably Southern California, which received water from the Sacramento–San Joaquin River Delta. Although chlorine treatment is a good way to disinfect water, it can also react with organic matter and runoff pollutants to create trihalomethanes (THMs), which have been shown to be toxic and carcinogenic.

The first THM standard was released by the EPA in 1979, and more strict regulations were released in 1998 and 2006. The treatment and control of EC is particularly difficult because to the rapid changes in the sector. For instance, the previously regulated PFAS perfluorooctanoic acid (PFOA) was replaced by GenX, a substitute that had a more negative environmental impact and was subsequently banned. This emphasizes the necessity of treating and managing EC in line with worldwide trends. The possible

effects of EC management on the environment and public health have drawn more attention in recent years. Numerous national and international organizations have started working to combat EC through legislation, public education, and research [56]. Regarding EC in surface waters, the White House Office of Science and Technology Policy announced in January 2024 a coordinated government research project. The goal of this project is to improve knowledge of the causes, manifestations, and consequences of EC while creating practical plans for managing and removing them. Furthermore, the Organization for Economic Co-operation and Development (OECD) has taken a proactive approach to EC, highlighting the significance of global cooperation. Experts from many nations gathered at the OECD Workshop on Managing Contaminants of Emerging Concern in Surface Waters to talk about problems and potential solutions, emphasizing the necessity for coordinated action to address this worldwide issue. This section offers a quick summary of CECs whose monitoring is especially important, including drugs, PCPs, endocrine disruptors (EDs), illicit drugs, newly registered pesticides, pharmaceuticals, high-tech rare earth elements (REEs), natural and engineered nanomaterials (ENMs), and DBPs. Extra details about the origins of CECs, how they are transported and degraded, environmental and human health problems, and CEC remediation techniques [6].

2.1. Pharmaceuticals

Pharmaceuticals, which include β -blockers, antibiotics, antiepileptics, antidepressants, lipid-lowering medications, and antihistamines, are man-made substances that make up one of the largest environmental inputs. From a few ng L^{-1} to high mgL^{-1} , medicines are present in substantial amounts in all water sources. The concentration levels of these components are determined by the prescription profile in the analyzed site and the study area. In addition to aquatic resources and aquatic animals, drugs have also been detected in other environmental compartments, such as soils, albeit in less concentrations. Although pharmaceuticals are frequently present in the environment in very minute concentrations, their continuous release into the environment is a significant cause for concern. Furthermore, a pharmacological molecule acting alone may not present the same acute risk as a molecule present in the same environment as other pollutants, which could result in a synergistic effect [7].

2.2. Personal Care Products (PCPs)

PCPs constitute a noteworthy subset of CECs and include a range of compounds that are frequently present in cosmetics and everyday care products, including perfumes, plasticizers, synthetic musks, UV filters, and preservatives. Worldwide, these compounds are regularly found in environmental waterways. Since they may be harmful to aquatic life, nitro musks are being phased out while polycyclic musks are manufactured and utilized widely. Both kinds of musk chemicals have estrogenic activity and are widely found in the environment. UV filters are specially designed to disperse, reflect, and absorb UV rays, protecting human skin in the process. However, because of their great chemical stability and persistence which are demonstrated by their identification in a variety of environmental compartments UV filters, as CECs, pose serious environmental issues. Because of their lipophilicity and resilience to biodegradation, UV filters are often found in sediments, sludge, watery particles, and the food chain. Studies have revealed that some organic UV filters can degrade through photolysis and interactions with chlorine in marine environments, despite the fact that they are intended to remain stable under UV exposure. While UV filters photolyze slowly in natural waters, photosensitizers can speed up this process, which can lead to additional environmental stress from the breakdown chemicals that arise [8].

2.3. Endocrine Disruptors (EDs)

Endocrine disruptors are a class of substances that, even at extremely low concentrations, have the ability to disturb the endocrine systems of both humans and wildlife by interfering with the manufacture of hormones. These substances are widely used in household, commercial, and agricultural settings and are prone to environmental contamination during production, use, and disposal [64]. Semi-volatile chemicals have a higher tendency to adhere to airborne particles, which is why EDs are frequently detected in the gaseous phase. Furthermore, hydrophobic partitioning allows lipophilic EDs to attach to sediments, increasing their abundance in these compartments. Moreover, EDs can be irrigated directly into the soil by using reclaimed water, biosolids and manure, or wastewater treatment plant (WWTP) effluents. Some EDs can infiltrate the food chain and possibly endanger human health if they are absorbed by plants after they are in the soil [9].

2.4. Illicit Drugs

The environment, ecology, and human health are all negatively impacted by illicit narcotics, which are categorized as CECs. International drug control rules forbid the manufacturing, distribution, and use of illicit drugs, which are psychotropic chemicals not prescribed by doctors. This is according to the United Nations Office on Drugs and Crime (UNODC). Globally, the use of illegal drugs has surged since the 1990s, surpassing the expansion in population. Cocaine, 6-acetylmorphine, morphine, codeine, methadone, amphetamine, methamphetamine, methylenedioxyamphetamine, and 3, 4-methylenedioxymethamphetamine are examples of common illicit substances and their metabolites. There is a significant risk of unintentional harm to aquatic life when these medications and their metabolites are disposed of directly or after being metabolized by humans and discharged into the environment. Drugs that are illegal have been found in large quantities in sewage sludge, air, and environmental waters, suggesting that they are widely distributed. This problem is made worse by the low removal effectiveness of WWTPs, which results in limited waterways in quickly urbanizing areas because current treatment plans do not totally eradicate these CECs. Therefore, it is important to strengthen laws and policies governing the use of illegal drugs and to work toward increasing the effectiveness of these substances' removal from sewage systems [10].

2.5. Pesticides

Pesticides have to go through registration and an evaluation of their possible effects on human health and the environment before they can be sold. Both new pesticide compounds and new uses for already-existing pesticides are included in new registrations. Furthermore, in order to guarantee their continuous safety, licensed pesticides undergo periodic reevaluations. Notably, with their EU approval in 2005, neonicotinoids (NNIs) are a relatively new type of insecticides. Imidacloprid is currently the insecticide that is sold the most globally, and since then, NNIs have grown to be among the most often used pesticides worldwide. As such, it is not surprising that a multitude of studies have reported extensive NNI contamination in a variety of environmental compartments. The main cause of NNIs in soil is their use in agriculture. Remains in the soil can migrate to surface waters or seep into groundwater due to their high solubility in water. NNIs have been found often in tap water, wastewater treatment plant effluents, and other bodies of water. Moreover, treated seeds used in planting, tillage, or wind erosion events might release NNIs into the atmosphere [11].

2.6. Other Emerging Contaminants

A class of substances known as surfactants is soluble in both polar and nonpolar liquids. Because they possess both hydrophilic and hydrophobic qualities, they can form micelles and adsorb at phase borders because they are amphiphilic. Large amounts of these compounds are produced and utilized, particularly in cleaners, (bio) detergents, and other industrial applications. In aquatic habitats, tracking their distribution, behavior, and eventual fate is essential. Surfactants can be used by microbes as sources of nutrition and energy during biodegradation, or they can be metabolized by microbial metabolic processes.

Seventeen elements are classified as rare earth elements (REEs): yttrium (Y), scandium (Sc), and the fifteen lanthanoids (praseodymium, lanthanum, promethium, cerium, europium, and lutetium). Because of their special qualities, which are necessary for a variety of technological gadgets and other uses, REEs are critical for the development of low-carbon technologies. Regarding the effects on the environment and human health, the demand for rare earth elements (REEs) is predicted to increase at a pace of 13.7% each year between 2017 and 2021. Human hair, nails, and biofluids have all been found to contain REEs, which can bioaccumulate through the food chain. Male infertility, fibrotic tissue damage, neurological diseases, kidney damage, and pneumoconiosis are among the negative impacts of human exposure to rare earth elements (REEs) [11].

Table 1: Analytical methodologies used for the detection of diverse EC [12].

Extraction process	Compounds analysed	Analytical methodology
SPE	Pharmaceuticals	HPLC-ESI-MS
SPE	Pharmaceuticals, plasticizers and halogen carrying substances	HPLC-ESI-MS/MS
SBSE	Insecticides, and PAH	GC x GC-MS
SBSE	Priority contaminants of polar and non-polar characteristics	HPLC-ESI-MS/MS
LLE	Pesticides and pollutants	HPLC-FD
SPE	Pharmaceuticals, PCPs, illicit drugs and pesticides	UHPLC-ESI-MS/MS
SPE	Pesticides, drugs, synthetic sweeteners, and perfluronyl compounds	UHPLC-ESI-MS
SPE	Pharmaceutical excipients and antioxidants comprise of phenols and hydrocarbons	GC-EI-MS/MS
SPE	Plasticizers, pesticides and Medicinal products	GC x GC-MS
SPME	Chemical fragrances, triclosan, herbicides, and related chlorophenols	GC-EI-MS

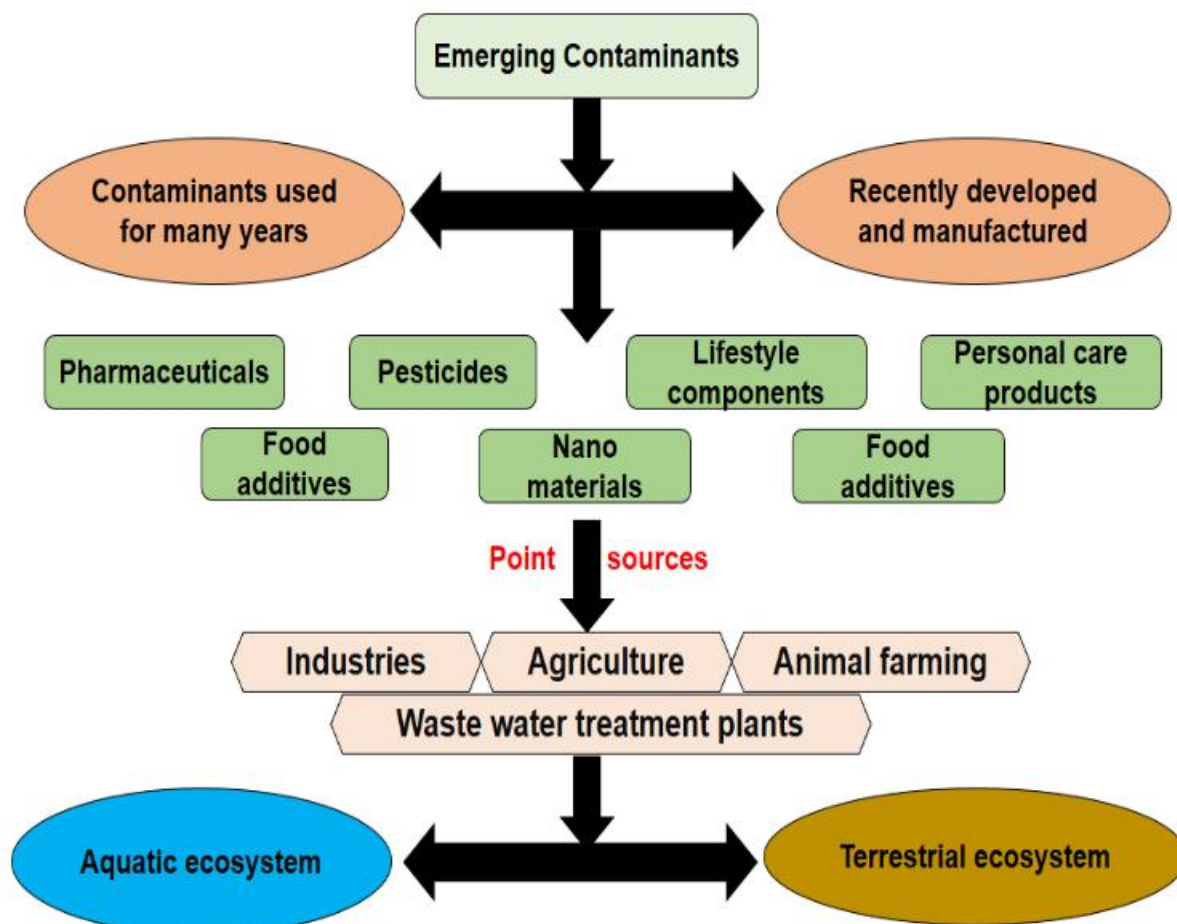


Figure 2: Various emerging contaminants found in aquatic and terrestrial ecosystem.

3. Approaches for determination of contaminants of emerging concerns

An overview of methods for preparing shrunken samples is given in this section. Specifically, pertinent applications utilizing microextraction techniques for target EC determination in environmental sample composition are examined, along with solid-phase and liquid-phase based microextraction methodologies.

3.1. Solid phase based microextraction techniques

3.1.1. Solid-phase micro extraction

Solid-phase microextraction (SPME), initially introduced by Pawliszyn and Arthur in 1990, is widely used in laboratory settings worldwide as a sample analysis technique. Target analytes are divided out of the sample and placed onto a tiny fiber coating in order for SPME to work. This method has built-in benefits, like being efficient and ecologically friendly as well as integrating sampling, analyte isolation, and enrichment into one work. The spectrum of sample types and analytes that can be evaluated has expanded because to multiple improvements made to SPME since its founding. Applications of SPME for in vivo sampling and the detection of CECs in a variety of environmental matrices, including liquids, gases, and solids, have been shown in numerous investigations [13].

ECCs can be retrieved over an established amount of time as well as subsequently thermally eliminated from the fiber at the GC injector port, or they may be eluted with a compatible solvent for further investigation. Typically, LC in conjunction with UV, diode array detection (DAD), or MS detection, or GC, often in conjunction with MS, are employed to perform further separation and characterization. In SPME, fibers based on molecularly imprinted polymers (MIPs) provide improved selectivity for CEC detection. For the purpose of collecting CECs, fibers based on molecularly imprinted polymers (MIPs) provide enhanced selectivity in SPME. These specially designed MIP fibers are often manufactured simply by polymerizing the material in molds like capillaries or glass tubes. Studies have demonstrated that MIP fibers have a high selectivity and excellent adsorption capacity, making them suitable for reuse up to 100 times without compromising their effectiveness. These fibers are used in the analysis of imidazolinones in soil and food samples as well as the detection of antiviral medications in effluents. While MS detection is frequently used, even in complicated matrices like sewage, detection by LC combined with UV or DAD is possible because to the use of selected fibers. With its tiny size, low invasiveness, and improved sensitivity and precision, SPME is also a viable method for in vivo analysis. It also provides a non-lethal sampling method, which yields more precise data regarding ongoing processes in intricate biological systems. Alternative designs have been created to solve issues such as the brittleness of coatings used in SPME. For instance, in-tube SPME (IT-SPME) is a technology developed from capillaries coated with different materials on their inner surfaces. Capillary coatings have been made from a wide range of materials, including as graphene, ionic liquids (ILs), metal-organic frameworks (MOFs), nanomaterials, and MIPs. Direct online coupling to LC systems is made possible by IT-SPME, which shortens analysis times while increasing accuracy and precision. The extraction and preconcentration of phthalate esters and the products of their breakdown, UV filters, and gold nanoparticles containing carboxylic acid from environmental fluids are among the noteworthy uses of IT-SPME [13].

Table 2: Microextraction of solid phase through analytical techniques [13].

Analyte detected	Employed analytical method	Environmental sample analyzed	Sensitivity
Imidazolinones	SPME	Soil and food samples	Moderate
Anti-viral medication	MS-SPME	Effluents	High
Fibers	UV/DAD-SPME	Moderate	Moderate
Phthalate esters	IT-SPME	UV-filters	High
Gold nanoparticles containing arboxylic acid	IT-SPME	Environmental Fluids	High

3.1.2. Thin film microextraction

Thin film microextraction (TFME), one of the reduced sample preparation techniques, has a number of benefits over traditional SPME, including a greater extraction phase volume and a higher surface area-to-volume ratio. Because to these characteristics, TFME is especially well-suited for ultra-trace and quick analysis, as it increases extraction efficiency. There have been continuous efforts to enhance the extraction fiber's geometry and automate the extraction and desorption operations since the creation of the first TFME setup in 2003. Analogously to SPME, the type of extraction phase determines the extraction efficiency of TFME. Polydimethylsiloxane (PDMS) was the original sorbent utilized, but other substitutes have subsequently been studied. A simple, low-cost method that worked well for extracting pyrethroids from Chrysanthemum tea was to cut a polyurethane thin film into 2 cm pieces. In addition, high-throughput analysis is made possible by the simultaneous extraction and desorption of up to 96 samples when TFME is used in conjunction with a 96-well plate system. Even with tiny sample volumes (1.5 mL) of ambient water, this method minimizes analysis time and permits automation, allowing for the investigation of approximately 200 samples in a single working day [14].

3.1.3. Needle trap device

One further needle-based substitute for SPME that overcomes a number of issues with the SPME approach is the needle trap device (NTD). For the purpose of sampling and preconcentrating volatile chemicals, NTD is a solvent-free sample preparation method. In contrast to SPME fibers, NTD's sorbent is contained inside a steel needle, providing increased durability. By increasing the amount of sorbent or sampling quantities (active sampling), the efficiency of NTD extraction can be further improved. High sensitivity, ease of use, speed, and lack of solvent requirement are the distinguishing features of NTD. Furthermore, NTD combines analysis, desorption, and extraction into a single procedure. It successfully gets over the drawbacks of SPME, including fiber brittleness, capacity restrictions, and the incapacity to carry out active sampling. In addition to being an invaluable instrument for workplace air quality monitoring, NTD is also capable of removing aerosols and particulates from the air, feat that SPME finds difficult to accomplish. NTD has been successfully used in the collection and analysis of a variety of environmental pollutants and is easily adaptable for use with pen-sized samplers because to its compact size and simple sampling technique [15].

3.1.4. Microextraction by packed sorbent

MEPS is a scaled-down variant of SPME, with a few important distinctions. Laboratory robotics can be used more easily with MEPS because the sorbent is integrated into the syringe itself, as opposed to being in a separate column. MEPS uses a very little amount of sorbent 1-2 mg—that can be reused more than 100 times. MEPS is useful in forensic toxicology because it can handle sample amounts as tiny as 10-1000 μ L, which makes it especially suitable for scenarios where sample volume is restricted. MEPS is a simple, quick sample preparation method has shown promise in the identification of CECs` in environmental samples. In comparison to conventional extraction techniques, it is also more ecologically friendly because it uses a lot less solvent to elute the analytes that are retained. MEPS can be directly connected to capillary electrochromatography, liquid chromatography, or gas chromatography (GC, LC) and can be entirely automated. Furthermore, MEPS is more economical than SPE. The MEPS syringe is engineered to facilitate bidirectional flow of the sample, as opposed to SPE, which solely permits downward flow of the solution. Careful washing and elution phase optimization is needed for this function. The sorbents used in MEPS are generally the same as those used in SPE, including polymeric sorbents and silica-based sorbents (C2, C8, C18). MIPs that are customized to target molecules can be used to overcome the usual problem of these sorbents being non-selective [16].

3.1.5. Stir bar sorptive extraction

A magnetic stir bar covered with a sorbent substance is used in SBSE, an efficient sample preparation technique first presented by Baltussen et al. in 1999. The three primary parts of the stir bars utilized in SBSE are a thin glass jacket that covers the magnetic stirring rod, a sorbent layer (often polydimethylsiloxane, or ethylene glycol-modified silicone). According to the analytes' octanol-water partitioning coefficient, the sorptive extraction method used in SBSE allows the analytes to be absorbed into the PDMS coating. Due to the enormous extraction phase volume employed in SBSE, materials with varied degrees of complexity have been successfully analyzed with incredibly low limits of detection (LODs). Methods like freeze concentration, which involves freezing clean water while solutes concentrate in the liquid portion of the sample, are recent advances in SBSE. Soluble-swollen PDMS stir bars are used in another type of SBSE known as solvent-assisted SBSE, in which the solvent in the PDMS phase serves as an extra extraction medium in addition to a modifier. The benefits of dispersive micro-solid phase extraction (D-mSPE) and stir bar sorptive-dispersive microextraction (SBSDmE) are combined in this unique technique that uses magnetically modified graphene to enable facile sorbent collection and effective mixing in large sample volumes [17].

3.1.6. Magnetic solid-phase extraction

Safarikova and Safarik originally presented MSPE in 1999. With this method, target analytes are extracted from the sample solution by means of magnetic adsorbents suspended in it. The majority of target molecules and contaminants are diamagnetic, which makes MSPE an effective method for extracting analytes even from complicated samples. These characteristics also apply to the adsorbents' magnetic properties. A magnetic separator facilitates the quick and easy separation of the magnetic adsorbents, allowing the analytes to be eluted for analysis. Simplicity, high extraction efficiency, and reusable adsorbents are the main reasons MSPE has become more and more common. The magnetic adsorbents employed in MSPE are mostly nano- or micro-sized composites, which are frequently based on different ferrites or ferrimagnetic iron oxides such as magnetite or maghemite. Affinity ligands on magnetic nanoparticles or microparticles can be immobilized to produce particular adsorbents. Target analytes or cells can be captured through antigen-antibody interactions in immunomagnetic separation, which entails immobilizing particular antibodies on the adsorbents. Furthermore, magnetization can be applied to conventional SPE adsorbents by means of post-magnetization techniques as microwave-assisted magnetization or magnetic fluid treatment. Magnetic cell labeling and decorating, as well as the detection of xenobiotics and cells in water, are further applications of immunomagnetic methods [18].

Table 3: Solid phase extraction using different analytical methods [18].

Analyte detected	Employed analytical method	Environmental sample analyzed	Sensitivity
Pyrethroids	TFME	Chrysanthemum tea	Moderate
Aerosols and particulates	NTD	Air quality monitoring	High
Pharmaceuticals	MEPS	Environmental sample	High
Freezing clean water	SBSE	Water samples	Moderate
Ferrimagnetic iron oxides	MSPE	Earth metals	Moderate

3.2. Liquid phase based microextraction techniques

3.2.1. Single Drop Microextraction (SDME)

Preconcentrating and extracting target analytes using a microdrop of extractant phase is the goal of Single Drop Microextraction (SDME), a scaled-down variation of conventional Liquid-Liquid microextraction (LLME). There have been other SDME modes developed since Dasgupta and Jeannot & Cantwell's groundbreaking work. During extraction, the extractant phase is kept atop a syringe needle tip in these procedures, resulting in a virtually spherical form. The use of miscible solvents is made possible by the physical separation of the solvent and sample in Headspace SDME (HS-SDME), which offers a wider range of extractant phases than Direct Immersion SDME (DI-SDME). Nevertheless, choosing the right extractant phases might be difficult due to organic solvents' difficult evaporation. In order to address this, ionic liquids (ILs), deep eutectic solvents, solvents with low vapor pressures, or aqueous drops are frequently utilized as extractants in HS-SDME. HS-SDME has been used in several investigations to enrich volatile chemicals. For example, HS-SDME and GC-MS have been used to evaluate the amount of residual 2-phenoxyethanol in fish tissues [19].

3.2.2. Directly Suspended Droplet Microextraction

Directly Suspended Droplet Microextraction (DSDME) can be applied in a manner similar to each LLME. A microvolume of a water-impermeable solvent, such as 1-octanol, is employed in two-phase DSDME to extract analytes, which is then back-extracted into an aqueous phase. However, the size or surface coating of the NPs in this method has been applied to recover silver nanoparticles (NPs) from ambient water samples and achieve femtomolar detection levels. Tramadol hydrochloride in water samples has also been detected using the three-phase DSDME mode in conjunction with UV-Vis spectrophotometry. Nevertheless, a significant drawback of DSDME is the challenge of gathering the

enhanced microdrop following extraction. Furthermore, the technique's dependence on solvents that are less dense than water and hence water-immiscible may have an impact on the extraction effectiveness for specific analytes [20].

Table 4: Liquid sample micro-extraction using SDME and DSDME [20].

Analyte detected	Employed analytical method	Environmental sample analyzed	Sensitivity
Residual phenoxyethanol	2- HS-SDME/GC-MS	Marine Fish tissue	High
Volatile compound	SDME	Water bodies	Moderate
Silver nanoparticles	DSDME	Ambient water samples	High
Tramadol hydrochloride	Three-phase DSDME with UV-Vis spectrophotometry	Water samples	High

3.2.3. Dispersive Liquid-Liquid Microextraction (DLLME) and Related Techniques

The Liquid-Phase Microextraction (LPME) methodologies have struggled with significant issues related to sensitivity and analytical duration owing to the precarious stability of the extractant phase. The introduction of Dispersive Liquid-Liquid Microextraction (DLLME) by Rezaee et al. in 2006 represented a substantial advancement in this domain. In the context of the Dispersive Liquid-Liquid Microextraction (DLLME) process, a combination of an immiscible organic solvent—essentially a halogenated solvent with a density greater than that of water and a dispersive solvent like methanol, acetone, or acetonitrile, which is miscible with both the sample and the organic solvent is swiftly introduced into the sample, leading to the creation of a turbid solution. Mass transfer rates between the liquids are improved as a result of the significant increase in interfacial area. Subsequent to the emulsion's breakdown (typically via solvent-based de-emulsification or centrifugation), the enhanced extractant phase is collected. Enrichment and cleanup of a wide range of CECs such as pharmaceuticals, personal care items, UV filters, illegal substances, pesticides, rare earth elements, nano materials, and disinfection by products have been extensively accomplished by the application of DLLME [21].

3.2.4. Membrane-Assisted Liquid-Phase Microextraction

LPME procedures have been made more stable and reliable with the introduction of microporous hollow fiber membranes confirming the membrane assisted liquid phase extraction (MALPE). These membranes permit microfiltration through the hollow fiber's pores while offering the acceptor phase more protection. Cleaner extracts and better enrichment factors are the outcomes of this. An achievable setup for Hollow Fiber Liquid-Phase Microextraction (HF-LPME) consists of a bifurcated phase sampling system. In this arrangement, target analytes are extracted from an aqueous sample and subsequently placed in a water-immiscible extraction solvent that is confined within the lumen and pores of the hollow fiber. Upon the extraction of the acceptor solution, it may be subjected to immediate analysis through Gas Chromatography (GC) or Liquid Chromatography (LC); alternatively, after solvent evaporation and reconstitution in an aqueous medium, it can be assessed using Capillary Electrophoresis (CE) in conjunction with MALPE.

The extraction of PAEs and beta-blockers from environmental fluids, as well as the assessment of developing iodinated trihalomethanes and controlled disinfection byproducts in water samples treated with various methods, are examples of CECs evaluated utilizing this two-phase design. Although the use of this sample preparation technique for analyzing mixtures of various CEC families is still limited, HF-LPME has been effectively applied to detect 27 different CECs in effluents from sewage treatment plants (STPs) and surface water. The method achieved enrichment factors between 6 and 4177, with detection limits (LODs) ranging from 1.09 to 98.15 ng/L. To enhance the extraction efficiency in LPME, nine hollow fibers were tightly bundled into a polypropylene hollow fiber array (BHF), which

was used to extract estrogens from both influent and effluent samples from a wastewater treatment plant (WWTP). This method provided LODs ranging from 0.251 to 0.440 ng/L, which were either comparable to or superior to those achieved by other microextraction techniques or traditional Solid-Phase Extraction (SPE) methods [22].

Table 5: Liquid phase extraction using DLLME and MALPE techniques [22].

Analyte detected	Employed analytical method	Environmental sample analyzed	Sensitivity
Pharmaceuticals	DLLME	Marine samples	Low
Rare earth metals	DLLME	Liquid samples	Moderate
PAEs and beta-blockers	MALPE	Environmental fluids	High
Iodinated trihalomethanes and disinfection byproducts	CE-MALPE	Water samples	Low

3.4. Mass Spectroscopy for the detection of Emerging contaminants

3.4.1. Liquid chromatography (LC)–mass spectrometry

Directing attention to liquid chromatography (LC)–mass spectrometry (MS) methodologies, a significant number of reviews have extensively investigated the contributions of various research groups in the analysis of emerging contaminants and their transformation products (TPs), thereby evaluating the contemporary state of the field and emphasizing existing shortcomings and prospective demands. Reviews that offer current knowledge on the fate, incidence, and dispersion of new pollutants have recently been published. Previous analyses have concentrated on the primary analytical techniques for identifying newly developing pollutants and associated TPs. Thin-layer chromatography (LC) with conventional detectors, gas chromatography, radiolabeled substances, and other techniques were traditionally used to identify TPs. Mass spectrometry is crucial since these techniques lack the specificity required for precise TP identification. Because of recent developments, LC-MS is now an essential instrument for assessing pollutants in the environment. The need for improved environmental analysis skills is propelling the creation of fresh approaches and advancements in technology. These include techniques to improve chromatographic separation, like the use of quadrupole time-of-flight (QqTOF) and time-of-flight (TOF) instruments, high-precision mass measurements, and ultra-performance liquid chromatography (UPLC). The use of tandem mass spectrometers (MS) such as triple quadrupole (QqQ) systems and LC-hybrid mass spectrometers (MS) such as QqTOF and quadrupole linear ion trap (QqLIT) instruments is a significant development in improving the sensitivity and specificity of environmental assessments. However, occasionally the target compound fragments poorly, resulting in only one transition that receives 2.5 IP, or the second transition is weak and stops the compounds from being confirmed at the level of interest. Using TOF and QqTOF equipment, which offer precise mass measurement, is one method to increase selectivity and reduce false-positive results. The identification of target compounds and unknowns is therefore far more confident.

Excellent sensitivity is attained in the selected reaction monitoring (SRM) mode when employing LC–MS with triple quadrupole (QqQ) equipment. Target chemical identification is verified by monitoring two distinct precursor-product transitions, yielding four identification points (IP) that satisfy the requirements for environmental contamination detection and confirmation. Because TPs are polar, separation is typically accomplished using high-performance liquid chromatography, or LC. The majority of the work has been done using standards or high concentrations of clean water solutions since quadrupoles are not sensitive enough in full-scan mode to detect unknowns, even if nominal mass can be utilized to identify TPs. Traditional LC–MS interfaces use gentle ionization methods that offer minimal fragmentation but provide molecular information. Collision-induced dissociation is a common method of fragmentation used in structural elucidation. It can take place in the mass spectrometer's intermediate-pressure section or in a specialized collision cell. Following thorough processing and

confirmatory analyses, fragmentation pattern analysis aids in the identification of unknown TPs. Unlike in gas chromatography, a problem in this field is the absence of extensive standard libraries for TP identification. Furthermore, nominal-mass LC-MS techniques are restricted to target methods, which means that the majority of the analytical information is lost in the process and they can only detect pre-specified analytes [23].

3.4.2. High resolution Mass spectroscopy (HRMS)

Targeted MS/MS and non-target LC-MS technologies have significant limitations that are addressed by high-resolution MS (HRMS). HRMS instruments with high mass resolution and precision, including Orbitrap and time-of-flight (TOF), provide sensitive full-spectrum data. Theoretically, HRMS eliminates the necessity for reference standards or pre-selected analytes by enabling the identification of an infinite number of molecules with adequate sensitivity. With accurate mass measurements, HRMS can identify ions with slightly varying m/z ratios and ascertain the molecular formulae of analytes. These devices can be used to add MS/MS or MSⁿ capabilities by coupling them with quadrupoles and ion traps. This enables precise mass measurements of several product ions. For swiftly identifying and screening a broad variety of chemicals and unknowns, this makes HRMS a viable method. TPs have not been specifically addressed by several writers who have examined the trends and new uses of HRMS in micropollutant analysis. In activated sludge batch tests, biodegradability is typically evaluated under a range of treatment scenarios. While sterile controls are autoclaved to account for abiotic processes, the sludge is aerated in these tests to suspend microorganisms, which are employed for biodegradation. To avoid interference, parallel batch tests are carried out using and without the spiking analyte. Phosphorus, dissolved oxygen, temperature, and total suspended particles can all be changed in these studies to match the ambient conditions, whether they are conducted in anoxic, aerobic, or both. Following techniques based on multiple OECD rules, the sorption behavior of chemicals in soils or sewage sludge is ascertained. Through the use of activated sludge in laboratory trials as well as field investigations at wastewater treatment plants, recent research have detected micropollutant total pollutants (TPs) and have revealed both hydrolytic and oxidative reaction pathways. However, because it is difficult to detect TPs (due to a lack of defined methodologies, procedures, and spectrum libraries) and quantify them (because to a lack of analytical standards), determining the relative relevance of various pathways is difficult. In soils and sediments, where microorganisms are important, batch tests have also been employed to evaluate biodegradation.

All precursor ions are fragmented without quadrupole preselection using the data-independent acquisition (DIA) technique known as all-ion fragmentation (AIF), which is employed in Orbitrap devices. In the higher-energy collisional dissociation (HCD) cell, ions are broken up in this fashion. Because AIF allows for greater in-depth analysis, it is comparable to the MSE approach in that it breaks up ions at different energies. The sensitivity of LC-HRMS over a broad range of m/z values makes it possible to detect a large number of polar pollutants and associated TPs. Suspect screening and post-target analysis are made possible by this technique, which not only identifies pre-specified target compounds but also makes it possible to identify unexpected molecules. A wide-target and suspicious screening algorithm, either home-brewed or supplied by the instrument manufacturer, is used to extract m/z values from a database. These databases consider features such as the isotopic pattern, double bond equivalents, and MS/MS data to improve chemical identification, automatically comparing the accurate mass of peaks with those from known compounds [24].

4. Determination of CECs and comparison with chromatographic methods coupled to mass spectrometry

Most people agree that the best way to identify CECs in environmental samples is to use mass spectrometry in conjunction with chromatographic procedures. But given their shortcomings, these methods should be compared to portable and point-of-need technologies. Preparing the samples is an essential step. Little preparation is preferred in portable approaches so that on-site installation can be more straightforward. In contrast, massive sample preparation is necessary for chromatographic methods using mass spectrometry detectors in order to minimize matrix effects by removing interfering materials and obtaining the necessary low detection limits, which are frequently in the range of nanograms per liter. Point-of-need or portable devices often face difficulties in achieving the low detection limits required for CEC detection due to colorimetric detection's inability to reach the sensitivity required. Potential approaches to improve detection sensitivity in this area include fluorescence and electrochemical technologies combined with biochemical sensors (biosensors, for example). Another chance exists to create novel materials that can function as platforms for detection in addition to serving to concentrate the analytes. Cost is yet another crucial aspect to take into account. In order to maintain reliable detection at low CEC levels, gas and liquid chromatography coupled with mass spectrometry entails high continuing costs, not only for the equipment acquisition but also for maintenance and operation. Furthermore, these techniques need individuals with the necessary skills to operate the equipment and evaluate the data. On the other hand, portable gadgets are typically made to be inexpensive and simple to operate, even for those with little experience. These gadgets might help "citizen science" projects, in which members of the public gather environmental data and assist in monitoring CECs. Even with continuous efforts to make these systems more portable, GC/LC-MS techniques are still primarily restricted to laboratory application [25].

Well-established principles for quality assurance and control (QA/QC) complement the precision and robustness of GC/LC-MS technologies, which continue to be exceptional. GC/LC-MS equipment is also offered in a variety of commercial configurations. The lack of regulatory clearance and commercial availability, however, for portable and point-of-need CEC detection devices presents a chance for innovation in this area. Comparing GC/LC-MS to portable equipment, a deeper level of information is also available. With the use of multiple analyte capabilities, these techniques, for example, enable the examination of contaminant degradation pathways in a single run for both qualitative and quantitative analysis. Usually, this calls either tandem mass spectrometry or high-resolution mass spectrometry, which are not common in everyday labs. Within this framework, portable devices may prove to be useful screening instruments, detecting samples that require in-depth examination in the laboratory, therefore decreasing the analytical burden of the lab [26].

5. Conclusions

The latest developments in the downsizing of analytical techniques for identifying contaminants of emergent concern (CECs) in environmental sample analysis are summarized in this overview. It discusses current advancements in the field and highlights a variety of analytical systems, including both miniature analytical flow systems and scaled-down sample preparation approaches. Even with these successes, there are still a number of obstacles to overcome, necessitating the continued development of smaller systems in the years to come. Considerable work has been done to use tiny technologies to determine CECs. However, the kind of analyte can affect how successful these systems are. Although numerous techniques have been created for certain CECs, there is still a great need for techniques that can reliably identify other kinds, like designed nanoparticles and specific disinfection byproducts (DBPs). Furthermore, there are particular difficulties in creating techniques for trace and ultratrace CEC detection in matrices that are getting more and more complicated. To guarantee the dependability of these methods, validation is essential; yet, for many CECs, this can be impeded by the absence of established reference methods and certified reference materials (CRMs). Therefore, it would be quite helpful to create candidate CRMs to aid in quality control in these procedures. Furthermore,

tackling environmental and health issues associated with unregulated substances may benefit greatly from more selective and sensitive technologies, especially those that make use of reduced sample preparation procedures. It's crucial to keep an eye on these substances in environmental compartments and research how possible CECs, like DBPs, originate and degrade. According to the principles of "green analytical chemistry," researchers should also give top priority to replacing or getting rid of any hazardous compounds used in these techniques. This emphasis should encompass every step of the procedure, not only the approaches' application, such as the creation of cutting-edge materials for usage in compact systems. To guarantee that procedures intended to identify CECs do not worsen the environment, more environmentally friendly approaches must be developed.

6. References

- (1) Huidobro-López, Blanca, Isabel López-Heras, Covadonga Alonso-Alonso, Virtudes Martínez-Hernández, Leonor Nozal, and Irene de Bustamante. "Analytical method to monitor contaminants of emerging concern in water and soil samples from a non-conventional wastewater treatment system." *Journal of Chromatography A* 1671 (2022): pp.463006.
- (2) Shi, Wei, and Haoyue Tan. "Mechanisms of Action of Emerging Contaminants: Pharmaceuticals and Personal Care Products (PPCP)." In *Advances in Toxicology and Risk Assessment of Nanomaterials and Emerging Contaminants*. Singapore: Springer Singapore, (2022): pp. 255-276.
- (3) Kang, Ju-Seop. "Principles and applications of LC-MS/MS for the quantitative bioanalysis of analytes in various biological samples." *Tandem Mass Spectrometry–Applications and Principles* 29 (2012): pp. 441-92.
- (4) Gogoi, Anindita, Payal Mazumder, Vinay Kumar Tyagi, GG Tushara Chaminda, Alicia Kyoungjin An, and Manish Kumar. "Occurrence and fate of emerging contaminants in water environment: a review." *Groundwater for Sustainable Development* 6 (2018): pp.169-180.
- (5) Pena-Pereira, Francisco, Carlos Bendicho, Dragana Mutavdžić Pavlović, Antonio Martín-Esteban, Myriam Díaz-Álvarez, Yuwei Pan, Jon Cooper et al. "Miniaturized analytical methods for determination of environmental contaminants of emerging concern—a review." *Analytica chimica acta* 1158 (2021): pp. 238108.
- (6) Dhangar, Kiran, and Manish Kumar. "Tricks and tracks in removal of emerging contaminants from the wastewater through hybrid treatment systems: a review." *Science of the Total Environment* 738 (2020): pp. 140320.
- (7) Oliver, Miquel, Błażej Kudłak, Monika Wiczerzak, Salette Reis, Sofia AC Lima, Marcela A. Segundo, and Manuel Miro. "Ecotoxicological equilibria of triclosan in Microtox, XenoScreen YES/YAS, Caco2, HEPG2 and liposomal systems are affected by the occurrence of other pharmaceutical and personal care emerging contaminants." *Science of The Total Environment* 719 (2020): pp. 137358.
- (8) Ahmed, Mohammad Boshir, Md Abu Hasan Johir, John L. Zhou, Huu Hao Ngo, Wenshan Guo, and Kireesan Sornalingam. "Photolytic and photocatalytic degradation of organic UV filters in contaminated water." *Current Opinion in Green and Sustainable Chemistry* 6 (2017): pp. 85-92.

- (9) Gorga, Marina, Sara Insa, Mira Petrovic, and Damià Barceló. "Occurrence and spatial distribution of EDCs and related compounds in waters and sediments of Iberian rivers." *Science of the Total Environment* 503 (2015): pp. 69-86.
- (10) Pietrzak, Damian, Jarosław Kania, Grzegorz Malina, Ewa Kmiecik, and Katarzyna Wątor. "Pesticides from the EU first and second watch lists in the water environment." *Clean–Soil, Air, Water* 47, no. 7 (2019): pp. 1800376.
- (11) Gusmaroli, Lucia, Gianluigi Buttiglieri, and Mira Petrovic. "The EU watch list compounds in the Ebro delta region: Assessment of sources, river transport, and seasonal variations." *Environmental pollution* 253 (2019): pp. 606-615.
- (12) Gwenzi, Willis, Lynda Mangori, Concilia Danha, Nhamo Chaukura, Nothando Dunjana, and Edmond Sanganyado. "Sources, behaviour, and environmental and human health risks of high-technology rare earth elements as emerging contaminants." *Science of the Total Environment* 636 (2018): pp. 299-313.
- (13) Espina-Benitez, Maria, Lilia Araujo, Avismelsi Prieto, Alberto Navalón, José Luis Vílchez, Paola Valera, Ana Zambrano, and Vincent Dugas. "Development of a new microextraction fiber combined to on-line sample stacking capillary electrophoresis UV detection for acidic drugs determination in real water samples." *International Journal of Environmental Research and Public Health* 14, no. 7 (2017): pp. 739.
- (14) Calza, Paola, Claudio Medana, E. Padovano, V. Giancotti, and Claudio Minero. "Fate of selected pharmaceuticals in river waters." *Environmental Science and Pollution Research* 20 (2013): pp. 2262-2270.
- (15) Vila, Marlene, Maria Celeiro, J. Pablo Lamas, Carmen Garcia-Jares, Thierry Dagnac, and Maria Llupart. "Simultaneous in-vial acetylation solid-phase microextraction followed by gas chromatography tandem mass spectrometry for the analysis of multiclass organic UV filters in water." *Journal of Hazardous Materials* 323 (2017): pp. 45-55.
- (16) Kirschner, Nicolas, Adriana Neves Dias, Dilma Budziak, Cristian Berto da Silveira, Josias Merib, and Eduardo Carasek. "Novel approach to high-throughput determination of endocrine disruptors using recycled diatomaceous earth as a green sorbent phase for thin-film solid-phase microextraction combined with 96-well plate system." *Analytica chimica acta* 996 (2017): pp. 29-37.
- (17) Cheng, Wen-Hsi, Ding-Yang Tsai, Jia-Yu Lu, and Jen-Wei Lee. "Extracting emissions from air fresheners using solid phase microextraction devices." *Aerosol and Air Quality Research* 16, no. 10 (2016): pp. 2362-2367.
- (18) Elmongy, Hatem, Hytham Ahmed, Abdel-Aziz Wahbi, Ahmad Amini, Anders Colmsjö, and Mohamed Abdel-Rehim. "Determination of metoprolol enantiomers in human plasma and saliva samples utilizing microextraction by packed sorbent and liquid chromatography–tandem mass spectrometry." *Biomedical Chromatography* 30, no. 8 (2016): pp. 1309-1317.
- (19) Kiszkiel-Taudul, Ilona, and Barbara Starczewska. "Single drop microextraction coupled with liquid chromatography-tandem mass spectrometry (SDME-LC-MS/MS) for determination of ranitidine in water samples." *Microchemical Journal* 145 (2019): 936-941.
- (20) Yangcheng, Lu, Lin Quan, Luo Guangsheng, and Dai Youyuan. "Directly suspended droplet microextraction." *Analytica Chimica Acta* 566, no. 2 (2006): 259-264.
- (21) Rykowska, Iwona, J. Ziemblińska, and Iwona Nowak. "Modern approaches in dispersive liquid-liquid microextraction (DLLME) based on ionic liquids: A review." *Journal of molecular liquids* 259 (2018): 319-339.
- (22) Ocaña-González, Juan Antonio, Noemí Aranda-Merino, Juan Luis Pérez-Bernal, and María Ramos-Payán. "Solid supports and supported liquid membranes for different liquid phase microextraction and electromembrane extraction configurations. A review." *Journal of Chromatography A* 1691 (2023): 463825.
- (23) Hernandez, Felix, Maria Ibáñez, Richard Bade, Lubertus Bijlsma, and Juan V. Sancho. "Investigation of pharmaceuticals and illicit drugs in waters by liquid chromatography-high-resolution mass spectrometry." *TrAC Trends in Analytical Chemistry* 63 (2014): pp. 140-157.
- (24) Zonja, Bozo, Jaume Aceña, Sandra Pérez, and Damià Barceló. "Methods for Elucidation of

Transformation Pathways: Identification of Intermediate Products, Chiral, and Isotope-Ratio Mass Spectrometry Analysis." *Comprehensive Analytical Chemistry* 62 (2013): pp. 593-610.

- (25) Rodriguez-Mozaz, Sara, Maria J. Lopez de Alda, and Damià Barceló. "Advantages and limitations of on-line solid phase extraction coupled to liquid chromatography–mass spectrometry technologies versus biosensors for monitoring of emerging contaminants in water." *Journal of chromatography A* 1152, no. 1-2 (2007): pp. 97-115.
- (26) Zarrouk, Eliès, Marie Lenski, Clément Bruno, Valérie Thibert, Paul Contreras, Kevin Privat, Alice Ameline, and Nicolas Fabresse. "High-resolution mass spectrometry: Theoretical and technological aspects." *Toxicologie Analytique et Clinique* 34, no. 1 (2022): pp. 3-18.