Chapter 1

Emerging Food Contaminants:

An Overview of the Growing Threat to Human Health

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ABSTRACT

Food safety has traditionally focused on visible contaminants like bacteria, pesticides, and heavy metals. However, as food systems evolve and the use of industrial chemicals increases, new, often invisible risks have emerged. These risks, which can be characterized as ghost molecules or emerging contaminants, that may be present in trace amounts, often undetectable by traditional food safety protocols,

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yet potentially hazardous. Microplastics, PFAS and pharmaceutical residues are leading examples of such contaminants that have infiltrated the modern food supply. The implications of their presence in food ranging from endocrine disruption to carcinogenic effects are still being explored. With increasing consumer awareness and regulatory concerns, the need to address these invisible contaminants is more urgent than ever. This chapter focuses on source, occurrence, detection methods and toxicity of these emerging contaminants in the food chain.

1. INTRODUCTION

Emerging contaminants (ECs) represent a wide range of chemical substances that have recently become a focus of environmental concern. These pollutants, although increasingly detected in various ecosystems, are not yet comprehensively included in standard regulatory frameworks or environmental monitoring programs. ECs typically consist of compounds such as pharmaceuticals, components of personal care products, synthetic industrial chemicals, nanomaterials, and other newly developed substances associated with modern human activity. What distinguishes these contaminants from conventional pollutants is their resistance to degradation, ability to accumulate in living organisms, and potential to pose unknown or long-term health and ecological risks. Since many ECs are not efficiently removed by conventional wastewater treatment facilities, they often find their way into natural water bodies, sediments, and even the food web, leading to ongoing environmental exposure. These substances enter the environment through multiple pathways, including runoff from agricultural fields, effluents from industrial processes, household wastewater, leachate from solid waste disposal sites, and urban drainage systems. In many cases, these chemicals were not originally considered hazardous, which is why they were neither closely studied nor regulated until recent technological advances made their detection possible.

Urbanization, industrial development, and the widespread use of chemicals in agriculture and manufacturing are accelerating the release of ECs into the environment. For example, heavy metals such as arsenic are naturally present in the Earth's crust but have become more prevalent due to mining activities, use in agrochemicals, and industrial applications. Arsenic, a metalloid with significant industrial value, is used in the production of semiconductors, pesticides, paints, glass products, and even cosmetics. Despite its utility, arsenic is a known human carcinogen and toxicant. In its inorganic form, it is classified as a Group 1 carcinogen by the International Agency for Research on Cancer. Chronic exposure to arsenic can lead to serious health issues including cancer, neurotoxicity, and developmental problems (Singh, Yadav, Sharma, & Singh, 2023).

The mobility of arsenic in the environment is facilitated by various geochemical and biological processes. In agroecosystems, arsenic can bind to soil particles and be taken up by crop roots through mineral uptake pathways. This transfer to edible plant parts makes it a critical food safety issue, especially in regions dependent on contaminated groundwater for irrigation. Additionally, arsenic can bioaccumulate in the tissues of animals consuming contaminated feed or water. Products like milk, eggs, meat, and fish from these animals can serve as secondary sources of arsenic exposure in the human diet (Zakhar, Derco, & Cacho, 2018).

Another major category of emerging contaminants is microplastics (MPs). These are plastic particles smaller than 5 millimeters that result from the breakdown of larger plastic waste or are manufactured at a micro scale for use in various products. Although microplastics are primarily associated with marine pollution, their presence in terrestrial ecosystems and agricultural soils has become an increasing concern. Plastic particles can enter soil through the application of sewage sludge, plastic mulching in agriculture, or littering. Once in the environment, microplastics can alter soil structure, affect microbial communities, and potentially carry toxic chemicals that adsorb onto their surfaces. (Singh, Yadav, Sharma, & Singh, 2023; Zakhar, Derco, & Cacho, 2018)

The COVID-19 pandemic has contributed to a surge in plastic waste generation due to the extensive use of disposable personal protective equipment (PPE), such as face masks, gloves, and plastic containers. Much of this waste has not been properly managed and has made its way into natural ecosystems, exacerbating the problem of microplastic pollution.

2. MICROPLASTICS

Plastics are now a significant component of everyday life and activities. Because of their mobility, elasticity, compact size, and simplicity of delivery, these artificial polymers are widely used in a variety of consumer care items. Due to these special qualities, plastics are especially appealing to the commercial packaging sector. Plastics' non-biodegradability and waste management may be issues, despite the fact that their uses in everyday products have increased (Sridhar, Kannan, Kapoor, & Prabhakar, 2022). Nearly 370 million tons of plastic were produced worldwide in 2019, with more than one-third of that plastic utilized in the US and Europe in throwaway items like garbage bags, eating utensils, and packaging that are intended to be thrown away within three years of manufacture. Despite recycling efforts, a significant amount of waste has collected in the environment and is gradually deteriorated by weathering and aging to micro and nanoscale sizes (Udovicki, Andjelkovic, Cirkovic-Velickovic, & Rajkovic, 2022).

The modern world's increased usage of plastic items has contaminated almost every environmental medium with microplastics, or synthetic plastic particles smaller than 5 mm. Beaches, seas, soils, sediments, and freshwater systems have all been found to accumulate microplastics. Therefore, it is possible that the intake of different foods will eventually bring the global contamination of microplastics back to our dinner table (Kwon et al., 2020).

The general definition of microplastics is synthetic polymers with a maximum size of 5 mm and no lesser limit (Li, Liu, & Chen, 2018). Plastic particles can enter the environment directly or indirectly through the movement of MPs throughout the ecosystem, contaminating human food. Microplastics have a significant impact on the environment as a whole by contaminating food and posing health risks to consumers. Because they are consumed by both marine and terrestrial creatures, microplastics are readily making their way into the human food chain (Al Mamun, Prasetya, Dewi, & Ahmad, 2023).

Drinking water may contain MPs. Additionally, they are present in fish, shellfish, poultry, milk, honey, eggs, salt, sugar, fruits, vegetables, wine, beer, tea, energy drinks, and soft drinks. Plastics in food pose health problems because of their makeup. Furthermore, MPs' toxicity varies according to their sizes and forms (Kadac-Czapska, Trzebiatowska, Knez, Zaleska-Medynska, & Grembecka, 2023).

2.1 Classification of Microplastics

It is classified into two types. Primary and secondary microplastics.

Primary Microplastics: The bigger plastic granules used as starter materials for goods fabrication, sandblasting media, and scrubs in personal care products are all examples of primary microplastics (MPs), which are produced industrially as microbeads of various sizes. When these pellets are manufactured, transported, or used, they “leak” into the environment (Andrady, 2017).

Secondary Microplastics: The destruction of larger objects that have somehow found their way into the marine ecosystem is the source of secondary MPs. It is widely believed that the majority of MPs in the environment are secondary MPs due to the significant volume of macroplastics entering the environment (Efimova, Bagaeva, Bagaev, Kileso, & Chubarenko, 2018).

2.2. Occurrence of Microplastics in Food

Human beings are primarily contaminated with MPs through the consumption of food, such as commercially processed fish, seafood tainted with microplastics, salt from the sea, nectar, alcohol, and culinary ingredients. Additionally, pollutants found in containers and impurities from processing materials might occasionally infect the majority of these food products. Inhaling MP-containing dust and air is the second way to become exposed. Seafood is an essential part of the human diet due to its high nutritional value, so eating these tainted items increases the risk of illness, particularly for little fish consumed whole (Ziani et al., 2023).

2.2. Salt

In addition to being utilized in food preservation, salts are vital components of the diet of humans. As a result, everyday salt intake is unavoidable, just like air and water. According to reports, around 11.6% of the 300 million tons of salt consumed worldwide in 2018 (including table salts and food processing) was consumed for human consumption (Taghipour, Ghayebzadeh, Mousavi, Sharifi, & Payandeh, 2023). The main sources of these are the sea, salty lakes, salty rocks, and salty wells. Usually, the combined effects of sunlight and evaporation cause sea salts to crystallize in salinas, also known as solar work ponds. Numerous saltworks can be found in waters that have been touched by human activity in a number of places, including Europe. As a result, they frequently come into contact with various pollutants. Many saltworks are probably affected by MPs since these regions are also thought to be hotspots for MP pollution of the environment (Peixoto et al., 2019).

2.3. Drinking Water

Numerous investigations worldwide have documented the pollution of water resources with various MP kinds in recent decades. Primary and secondary MPs entering the environment and moving to the aquatic environment are the causes of these diseases. The amount of of MPs in various water supplies vary, nevertheless, and there is a noticeable variance in the concentrations that have been observed (Babaei, Reshadatian, & Feizi, 2024). The United States had the most concentration of MPs in tap water, while Italy and Denmark had the lowest.

2.4. Air

Traffic dust, rubber tire erosion, and synthetic fabrics (such as plastic fibers or pieces of clothing) are thought to be the main sources of primary atmospheric MPs, which winds can carry to other environmental areas. Since 2015, the occurrence of MPs in the atmosphere has drawn more attention. Wet and dry deposition, atmospheric sampling, and dust collection are the three sample techniques that have been utilized to gather atmospheric MPs. As a result, it is not possible to directly compare studies using various sampling techniques (Zhang et al., 2020).

2.5. Detection of Microplastics

Common methods employed for the detection of microplastics are Nile red staining, scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS), visual identification (with the aid of a microscope), Fourier Transform Infrared (FT-IR) spectroscopy. But none of the aforementioned methods can simultaneously provide the chemical (polymer type) and physical (size, color, and form) characteristics. Time constraints, size restrictions, and interference concerns can all restrict the use of a single technique (Ding et al., 2019).

2.6. SEM-EDS

Scanning electron microscopy plus energy-dispersive X-ray spectroscopy (SEM/EDS) and optical microscopy work together to screen a large number of microplastic particles rapidly and effectively with a lower chance of misidentification mistakes. Because it can easily separate plastic material from other substances including lipids, mineral particles, and cellulose fibers—all of which can be separated from plastics under optical microscopy—optical microscopy is the most effective method for analyzing microplastics. However, because certain particles can be mistakenly classified as plastics or as other materials, optical microscope imaging must be used carefully (Wang, Wagner, Ghosal, Bedi, & Wall, 2017).

2.7. FT-IR

By revealing details about the particular interactions found in plastics, FTIR is a potent method for the diagnostic investigation of synthetic polymers. Traditional FTIR is typically used to identify plastic debris and visible MPs, whereas micro-FTIR (μ-FTIR), which is fitted with a microscope to localize MPs on filters, is needed for smaller particles. Theoretically, μ-FTIR can detect MPs as small as 10 μm in diameter (Chen et al., 2020). It measures the amount of infrared (IR) light that the MP sample absorbs, enabling the analysis of its molecular makeup. The unique identification of a sample (MP) is represented by an infrared spectrum, where the absorption peaks match the frequencies of vibration between the atoms' bonds. Since every polymer material is a distinct atom-by-atom arrangement, no two compounds have precisely the same infrared spectra (Veerasingam et al., 2021).

2.8. SERS

The most commonly method used for the detection of chemical composition of microplastic is raman spectroscopy. This reliable technique is frequently used to detect trace amounts of a wide range of chemicals, including pharmaceuticals, contaminants, biological molecules dynamite, and microscopic plastic particles. SERS's 1974 revelation garnered a lot of interest due to its powerful augmentation of the inadequate Raman signal (Mikac et al., 2023).

Because of its exceptional chemical specificity and high sensitivity, surface-enhanced Raman spectroscopy (SERS) finds extensive application in ecological, food safety, and health surveillance. When the specimen's molecules are adsorbed on the perforated metal surface (often gold or silver nanoparticles), the Raman signal of the sample itself—which is typically quite weak—can be significantly increased. Based on this idea, it appears that SERS technology may detect microplastics and nanoplastics with smaller sizes and low concentrations in aqueous solutions (Lv et al., 2020).

2.9. Nail red Staining

Environmental specimens can be quickly screened for the occurrence of MPs using fluorescence microscopy when MPs are fluorescently stained with the hydrophobic dye Nile red (NR), which is widely used in histopathology. MPs can be categorized as “polar” or “hydrophobic” based on their polymer properties and the solvatochromic nature of NR, which causes its emission spectra to change based on the polarity of its surroundings. Because NR's interactions with various polymers varied depending on the plastic's chemical makeup, NR staining of particles has proven to be an effective method for polymer identification based on fluorescence (Meyers et al., 2022). Even though NR by itself is currently unable to identify particles (i.e., distinguish between different types of polymers), it is recognized as the most effective straightforward strategy for reducing the number of particles that require confirmation by more reliable methods like FTIR or Raman spectroscopies. Despite its widespread use in studies pertaining to the detection and measurement of MPs in various sample types (mostly environmental), there is no accepted technique for applying NR (Ribeiro, Duarte, & da Costa, 2024).

2.10. Toxicity of Microplastics on Organisms

A wide variety of aquatic taxa are vulnerable to these new contaminants due to the abundance of microplastics in aquatic settings. There have been reports of over 690 aquatic wildlife species consuming macro- or microplastics. Following ingestion, microplastics may have unknown effects on aquatic organisms' health (Wang, Gao, Jin, Li, & Na, 2019). The consumption of microplastic particles by marine animals may result in both deadly and sublethal consequences, including toxicosis in freshwater and marine fish species, according to recent ecotoxicological studies. Numerous researchers have documented a number of detrimental impacts on both freshwater and marine animals, such as altered fertility, abnormal reproduction, inflammatory reactions, gut inflammation, metabolic disorders, immune response impairments, hormonal interruption, and decreased mortality rates (Benson et al., 2022). It is possible for people to absorb MP particles by food or breathing. Eating seafood represents a single way that people can be exposed to MP. The majority of people eat bivalves, oysters, and tiny fish as entire creatures (such as sardines, anchovies, and sprat), and microplastic particles are frequently discovered concentrated in the digestive track (Jinadasa, Uddin, & Fowler, 2023).

3. PFAS

The heterogeneous group of fluorinated synthetic compounds known as per-and polyfluoroalkyl substances (PFAS) are distinguished by the presence of a perfluorinated methylene group (−CF2−) or at least one perfluorinated methyl group (−CF3), as well as a variable number of carbon atoms, fluorination degree, and other chemical groups. Since PFAS can be found in a wide range of consumer goods and industrial industries, they are practically always present in the environment (Panieri, Baralic, Djukic-Cosic, Buha Djordjevic, & Saso, 2022). The two most prevalent PFAS, per-fluorooctanoic acid (PFOA) and per-fluorooctane sulfonic acid (PFOS), are found in a variety of environmental matrices across the globe (Podder, Sadmani, Reinhart, Chang, & Goel, 2021).

3.1. Characteristics

The excellent chemical and thermal stability of PFAS is one of their defining characteristics. They are interesting for many technological applications since they do not break down at temperatures of several hundred degrees or when exposed to harsh chemicals. The remarkable stability of the carbon–fluorine bond, for instance, is the cause of this feature. It is much higher than the bond energy of the carbon–oxygen single bond. In addition to making the trifluoromethyl groups (-CF3) useful building blocks, the fluorine atom's strong electronegative characteristic also explains why many PFAS are water, oil, and dirt resistant (Brunn et al., 2023).

3.2. Sources and Occurrence

Both commercial and residential sources emit PFAS into the atmosphere. PFAS are found in everyday items such as industrial domestic goods and food processing. Chemicals used in food packaging are the main source of PFAS. These include noodle cups, popcorn bags, grease-resistant paper, candy wrappers, and containers and wrappers for fast food (O'Connor et al., 2022). One significant way that humans come into contact to PFAS is through the consumption of polluted water, agricultural products, and poultry. According to numerous studies, PFAS can build up in animals, soil and water used for food production, and other food packaging materials and/or processing machinery that contain PFAS can all contaminate food (Eze et al., 2024).

According to recent research, PFAS species can bioaccumulate in agricultural crops, which helps spread the chemicals to people and animals through food consumption. Hydrophobic interactions with organic materials dominate the sorption behavior of PFAS. Numerous investigations have demonstrated that whereas less hydrophobic PFASs are more common in aqueous solutions, highly hydrophobic PFASs have a tendency to sorb to suspended solids (TSS).

Because various PFASs have been found in PFAS-impregnated clothing, shoes, and upholstery, humans are susceptible to PFAS exposure. Furthermore, it has been demonstrated that humans are exposed to PFAS through the ambient intake of fish, shellfish, fruits, and their products (Nahar, Zulkarnain, & Niven, 2023; Johnson, 2022; Shen, Lee, Ra, Suk, & Moon, 2018).

3.3. Detection and Analysis

GC-MS, LC-MS, and HPLC-MS/MS are examples of chromatographic techniques combined with mass spectrometry that are the foundation of the current gold standard detection procedures for PFASs. In 2009, the EPA established "Method 537," an official analytical technique that uses liquid chromatography-tandem mass spectrometry (LC-MS/MS) enabled by solid phase extraction (SPE) to analyze 14 distinct PFASs, including PFOA and PFOS, in drinking water. The EPA announced "Method 533," a revised analytical technique, in November 2019 to focus more on the detection of "short chain" PFASs (Ryu, Li, De Guise, McCutcheon, & Lei, 2021).

The gold-standard method for determining targeted PFAS has been liquid chromatography (LC) in conjunction with mass spectrometric (MS) or tandem mass spectrometric (MS/MS) detection. Novel PFASs have been consistently found in a range of natural matrices thanks to recent advancements in high resolution mass spectrometry (HRMS). The structure of unknown PFAS molecules from over twenty established classes16 has recently been proposed using time-of-flight mass spectrometry (TOF-MS), Fourier transform ion cyclotron resonance mass spectrometry (FTICR-MS), and orbitrap instruments. These methods also contribute to the growing field of arising PFAS discovery through suspect and non-target screening (Androulakakis, Alygizakis, Bizani, & Thomaidis, 2022).

One strategy to manage PFAS collectively is combustion ion chromatography (CIC). More precise techniques are required to quantify all forms of PFAS entirely because CIC is able to determine the overall quantity of thermally degraded fluorine and cannot differentiate between inorganic and organic sources. There aren't many options besides LC-MS and CIC. Notably, by generating volatile derivatives, certain non-volatile substances can be examined using traditional GC (Yanagisawa, Obayashi, Furuta, & Fujimaki, 2025).

3.4. Toxicity

One significant way that humans are exposed to PFAS is through the consumption of tainted water, crops, and livestock. Many studies demonstrate that PFAS buildup in animals, soil and water used to grow food, and other food packaging materials and/or processing equipment/machines that contain PFAS can all contaminate food (Eze et al., 2024). Harmful consequences of newly discovered per- and polyfluoroalkyl compounds. The renal glands, hepatocytes lymph nodes, and brain of many living things are among the organs where PFAS tend to build up. PFAS have a number of negative health effects on humans, including immune-mediated (asthma, reduced vaccination response), heart disease (hypertension), cancer (breast, liver, testicular, kidney), endocrine (thyroid disease), fertile (decreased fertility), and developmental (Manojkumar, Pilli, Rao, & Tyagi, 2023). Kids are affected by the effects of PFASs. Children who are exposed to PFOA have an increased chance of acquiring asthma. The same is true for PFOS exposure, which has been linked to documented pulmonary function impairment. Young children are more likely than adults to be exposed to PFASs because of their smaller stature, greater respiratory rates, and hand-to-mouth and crawling habits that necessitate contact with contaminated surfaces, like floors. Children are exposed to PFASs primarily through inhalation, ingestion of dust, dirt, food, water, and breast milk, and cutaneous exposure to contaminated air or materials. There have also been reports of children's serum having higher levels of PFASs than adults (Lee, Smaoui, Duffill, Marandi, & Varzakas, 2025; Starnes, Rock, Jackson, & Belcher, 2022).

Because PFAS interfere with testosterone signaling, they are frequently linked to reproductive disorders such male infertility. The substantial burden of PFAS on the fetus throughout crucial phases of development is demonstrated by the increased risk of adipokine hormone dysregulation and lower levels of growth factors and sex hormones during fetal and postnatal development that result from prenatal exposure to PFAS. Pregnancy-related placental transfer of PFAS is also visible, and the offspring may have metabolic syndromes, chronic renal disorders, and abnormal thyroid signaling. When PFAS in breastmilk are passed from mother to kid through infant feeding, it is anticipated that an infant's exposure to PFAS will increase even more (Baluyot, Reyes, & Velarde, 2021).

Because of their extensive production and strong tendency to migrate from their source locations, PFAS are found in soil and water bodies all over the world. The apoplastic, symplastic, and transmembrane pathways are the three routes via which nutrients can reach plant roots. Additionally, foreign chemicals like PFAS can enter plant roots through similar mechanisms. Apart from the buildup of PFAS in plants, their possible phytotoxicity might have detrimental effects on the health of the ecosystem and food security, so it is important to pay attention to this. Values like IC50 or EC50, which represent the concentration of PFAS that results in a 50% reduction or inhibitory impact on plant growth, can be used to demonstrate the phytotoxicity of PFAS (Adu, Ma, & Sharma, 2023).

In the United States, water samples from military installations were found to contain PFAS pollution in 2337 locations across 49 states as of January 2021. Because PFOA and PFOS molecules are found in blood, serum, and urine, the majority of people in the US are exposed to PFAS. With measurable amounts of PFAS in soils, hay, milk, and human blood samples, a nearby ICLS was shut down in 2017 after PFAS were found in water samples from a well water district in Maine. Levels of PFAS in milk samples from one of the New Mexico dairies have been identified by the US Food and Drug Administration to pose a risk to human health (Jha et al., 2021).

3.5. Mitigation

Reducing the amount of PFAS in food products is beneficial for public health since most human cultures have a strong tradition of consuming animal products, and this is unlikely to change very soon. The effects of thermal processing (such as boiling, steaming, and frying) on PFAS loads in a range of blue food species (freshwater fish and shellfish) have been the subject of numerous research. Given PFAS's chemical stability and heat tolerance, it seems unlikely that they will break down under typical cooking circumstances. But according to the theories of Del Gobbo et al. (2008), Kim et al. (2020), Luo et al. (2019), and Sungur et al. (2018), cooking heat breaks the protein-PFAS connection in animal tissue, causing PFAS to be released (Vendl et al., 2022)

PFAS pollution prevention measures are highly sought after and should be implemented at the sources of pollution rather than after PFAS have entered marine and estuarine environments. Water treatment facilities, as well as factories and enterprises that utilize and generate PFAS, are responsible for handling PFAS waste. Although there are a number of PFAS remediation strategies available today, adsorption on natural and renewable material-based adsorbents, agricultural wastes, biochar, and several combinations of materials are some of the most widely utilized and acknowledged approaches for PFAS contamination mitigation (Bilela et al., 2023).

Lowering the amount of PFAS in drinking water is necessary to lower the risk of female PFAS intake. Because MPs adsorb to PFAS, improving the removal of MPs from drinking water has proven to be an effective way to lower PFAS. Eliminating PFAS from drinking water is a difficult task because it is a newly discovered water contaminant. PFAS are hard to get rid of with conventional drinking water treatment (Du et al., 2023). One of the most significant and useful of them for treating PFAS in drinking water is the adsorption of PFAS by activated carbon (AC) (Pranić, Carlucci, van der Wal, & Dykstra, 2025).

In a mixture of phosphate buffer (pH 7.2), the photo-transformation rates in aqueous solutions and the mineral content of clay of PFOSA, a sulfonamide precursor to the more stable carboxylated PFAS, were assessed and contrasted. By interacting with superoxide anions and hydroxide radicals, the natural clay mineral montmorillonite promoted the breakdown of PFOA to the shorter chain carboxylates (Dickman & Aga, 2022).

The granular byproduct of the thermochemical conversion of biomass in a low-oxygen environment (pyrolysis) is called biochar. In addition to its potential for carbon sequestration and, particularly in agriculture, its capacity to rebuild and support soil health, it has been acknowledged for its capacity to eliminate new pollutants like heavy metals and trace organic compounds from environmental media (Ramos & Ashworth, 2024).

3.6. Future Challenges

The restriction of historical PFAS, including PFOA and PFOS, has led to the development of new per and polyfluorinated species. Furthermore, because long-chain PFAS can persist in the environment, build up in lifeforms, and cause adverse effects, their manufacture has been reduced or stopped in the United States (Ehsan et al., 2023).

4. PHARMACEUTICALS AND RESIDUE CONTAMINATION IN FOOD PRODUCTS

4.1. Antibiotic Residues in Food-Producing Animals

The persistence of antibiotic residues in edible animal products has emerged as a significant food safety concern within the domain of food technology. These residues, when not adequately managed through withdrawal periods and proper veterinary oversight, can pose serious health risks to consumers (Singh, Shukla, Tandia, Kumar, & Paliwal, 2014). Among the most well-documented effects are allergic and anaphylactic responses, particularly in individuals with hypersensitivity to specific antibiotics such as penicillin. Studies estimate that approximately 7% of the general population may be susceptible to drug-induced hypersensitivity, with even trace concentrations (e.g., 0.6 μg of penicillin) being sufficient to trigger reactions in sensitive individuals (Kempe et al., 1999). The presence of such residues in milk (as low as 0.01 IU/mL) is especially concerning from a food processing and public health standpoint.

Chronic dietary intake of residues from antibiotics like oxytetracycline (OTC) can lead to hematological and hepatic alterations, including leucocytosis, atypical lymphocyte development, toxic granulations in granulocytes, and impaired coagulation. Additionally, OTC has a strong affinity for calcium-rich tissues, contributing to dental discoloration in children and prenatal exposure effects in neonates. These factors raise critical challenges for food technologists responsible for quality assurance and consumer safety (Lee SueJan, Lin ChinShiung, & Chen MaoChiang, 1996).

From a food toxicology and risk assessment perspective, β-lactam antibiotics are known to accumulate at significantly higher concentrations in liver and kidney tissues compared to muscle, emphasizing the need for rigorous residue monitoring in organ meats. Furthermore, fluoroquinolone antibiotics such as enrofloxacin—used in poultry production—act through bacterial DNA gyrase inhibition and have demonstrated teratogenic and embryotoxic effects in laboratory models (Kempe et al., 1999). This has prompted regulatory actions by agencies such as the U.S. FDA, which proposed banning enrofloxacin use in poultry not due to direct toxicity but due to its role in fostering antimicrobial resistance in zoonotic pathogens.

Environmental contamination through improperly disposed carcasses has also been observed to impact wildlife. Field studies have shown accumulation of enrofloxacin and ciprofloxacin in avian scavengers like cinereous and Egyptian vultures, correlating with significant mortality. These findings underscore the broader ecological and food chain risks associated with residual antibiotics in animal-derived foods (Lemus, Blanco, Grande, Arroyo, & Garcia-Montijano, 2008).

For food technologists, the mitigation of such risks requires integrated residue control strategies, robust screening techniques, and compliance with international residue limit standards to ensure the production of microbiologically and chemically safe food products for consumers (Singh, Shukla, Tandia, Kumar, & Paliwal, 2014).

4.1.1 Antibiotic Resistance: A Food Technological Perspective on Human Health Risks

Antibiotic resistance has become a significant public health crisis with direct implications for food safety and food processing. Regulatory bodies such as the World Health Organization (WHO) and the U.S. Centers for Disease Control and Prevention (CDC) have classified antibiotic resistance as one of the most urgent global health threats. From a food technology standpoint, the issue is particularly concerning due to the integration of antibiotics into food production systems, especially within animal husbandry and intensive livestock farming.

Bacterial resistance develops as a direct result of antimicrobial misuse or overuse in both clinical and agricultural contexts. The introduction of antibiotics in animal feed as growth promoters and for prophylactic use has accelerated the selection pressure on microbial populations. Consequently, many bacterial strains—once responsive to conventional treatments—have developed multidrug resistance. Infections caused by resistant pathogens such as Salmonella, Escherichia coli, Staphylococcus aureus, and Campylobacter jejuni are increasingly linked to contaminated food products, creating severe challenges for food technologists, quality control specialists, and public health authorities.

Antibiotics used in food-producing animals are often the same or structurally similar to those used in human medicine. Therefore, cross-resistance between human and animal bacterial pathogens is inevitable. Resistant strains may be transferred to humans through the food chain, especially when meat, milk, or eggs are not processed, handled, or cooked correctly. For instance, foodborne outbreaks of Salmonella typhimurium DT104, resistant to multiple antibiotics like tetracyclines, chloramphenicol, and ampicillin, have been traced back to livestock treated with these drugs. A similar trend has been seen in Campylobacter species resistant to fluoroquinolones, correlating with their use in poultry production.

The emergence of vancomycin-resistant enterococci (VRE) is a direct result of the use of avoparcin, a glycopeptide antibiotic, as a feed additive in animal production. These resistant bacteria colonize animal intestines and can transfer resistance genes to human pathogens via the food chain, particularly affecting immunocompromised individuals in clinical settings. From a food microbiology standpoint, such developments increase the complexity of ensuring microbial safety in food products.

Regulatory frameworks in food technology emphasize adherence to Maximum Residue Limits (MRLs) and enforcement of appropriate withdrawal intervals. For example, antibiotics like lincomycin and spectinomycin—used to treat mycoplasma infections in poultry—must be discontinued at least 48 hours before slaughter to avoid contamination in final products. Inadequate adherence to such guidelines contributes to the accumulation of antimicrobial-resistant bacteria in the food supply.

WHO and other international food safety agencies have recommended restricting the use of antibiotics critical for human health in food animals, especially as growth promoters. Food technologists and meat processors must integrate robust residue monitoring programs, enforce withdrawal periods, and adopt alternative biosecurity and husbandry practices to minimize antimicrobial usage.

The ongoing challenge of antimicrobial resistance underscores the need for multidisciplinary action across food processing, veterinary science, public health, and regulatory sectors. Ensuring microbiological integrity in animal-derived food products is essential to safeguard both consumer health and the efficacy of therapeutic agents. (Lemus, Blanco, Grande, Arroyo, & Garcia-Montijano, 2008)

4.2. Veterinary Pharmaceuticals and Residue Contamination in Animal-Derived Food Products

Veterinary pharmaceuticals constitute a broad class of bioactive compounds specifically formulated for therapeutic, prophylactic, and nutritional applications in animal health management. These compounds encompass antimicrobials, antiparasitics, hormones, vaccines, and immunomodulators, and are integral to maintaining homeostasis, optimizing productivity, and enhancing the physiological performance of domesticated and farmed animals. Their utilization is particularly critical in high-density livestock production systems where pathogenic exposure is elevated due to intensified animal husbandry practices.

A significant biotechnological concern associated with veterinary drug administration is the persistence of pharmacological residues in edible animal tissues and by-products. These xenobiotic residues may be traced in meat, milk, eggs, and aquatic products, often resulting from suboptimal compliance with established pharmacokinetic withdrawal intervals. Veterinary drug residues are defined as any pharmacologically active substance, including parent compounds, metabolites, excipients, or degradation intermediates, that persist post-therapy within biological matrices of treated animals. The bioaccumulation and biomagnification of such residues have raised public health concerns due to their potential to induce cytotoxic, genotoxic, immunotoxic, and endocrinological perturbations in human consumers.

In intensive animal agriculture, antimicrobial agents are routinely administered not only for curative interventions but also as metaphylactic and growth-promoting agents. According to global predictive models, the annual consumption of veterinary antibiotics is projected to escalate significantly—from approximately 63,151 metric tons in 2010 to over 105,596 metric tons by the year 2030—reflecting the intensification of biotechnological inputs in animal agriculture. This surge underscores the necessity for robust pharmacovigilance frameworks and residue surveillance systems to mitigate the risk of chemical contaminants in the food supply chain.

Regulatory authorities have instituted rigorous residue monitoring protocols and established maximum residue limits (MRLs) based on toxicological thresholds and acceptable daily intake (ADI) values. In the United States, the Food and Drug Administration (FDA) enforces veterinary drug tolerances under Title 21 CFR Part 556, while the European Medicines Agency (EMA) regulates residue levels in accordance with Commission Regulation (EU) No. 37/2010. These regulations rely on biotechnological methodologies including enzyme-linked immunosorbent assay (ELISA), liquid chromatography-mass spectrometry (LC-MS/MS), and radioimmunoassay for residue quantification.

Moreover, environmental ecotoxicology studies have shown that veterinary drug residues, excreted via urine and feces, may infiltrate aquatic and terrestrial ecosystems. Such contamination can alter microbial diversity, interfere with biogeochemical cycles, and facilitate the development of resistant environmental microbiota, further complicating the biosphere-human interface.

To address these challenges, integrative strategies involving pharmacogenomics, molecular diagnostics, residue biosensors, and bioremediation are being explored. A comprehensive biotechnological review encompassing residue sources, detection methodologies, risk assessments, and regulatory interventions is essential to inform policy formulation and ensure biosafety in the agro-food sector. Bridging the current knowledge gaps through advanced research will fortify our ability to manage veterinary pharmaceutical residues as a pressing public health concern and preserve ecological integrity in the face of intensifying agricultural biotechnology.

4.3. Pharmaceuticals and Personal Care Products (PPCPS): Environmental Presence and Impact

Pharmaceuticals and personal care products (PPCPs) refer to a diverse group of chemical substances, including human and veterinary medicines such as pain relievers, antibiotics, contraceptives, and cholesterol-lowering drugs. The constant introduction of these substances into the environment—through household use, industrial discharge, and improper disposal—poses a growing concern due to their bioactive nature and potential ecological and human health risks (Li et al., 2024; Singh, Yadav, Sharma, & Singh, 2023; Zakhar, Derco, & Cacho, 2018; Rubio-Armendáriz et al., 2022; Briffa, Sinagra, & Blundell, 2020; Silva et al., 2021). Ebele et al. (Hawthorne, Grabanski, Martin, & Miller, 2000) describe pharmaceuticals as therapeutic agents used to treat or prevent diseases in humans and animals, which may sometimes be misused or overprescribed.

Collectively, PPCPs consist of compounds with diverse biological effects, many of which can interfere with hormonal systems or exert toxic effects even at low concentrations (Selvaraj, Shanmugam, Sampath, Larsson, & Ramaswamy, 2014). The pharmaceutical category includes substances such as antihyperlipidemic agents, stimulants (e.g., caffeine), painkillers (e.g., ibuprofen, paracetamol, ketoprofen, naproxen), psychiatric medications (e.g., carbamazepine, primidone), and antibiotics (e.g., sulfamethoxazole, chloramphenicol, trimethoprim, ciprofloxacin). Cardiovascular drugs such as propranolol, atenolol, and metoprolol, as well as lipid regulators like gemfibrozil and bezafibrate, are also common. On the personal care side, compounds include synthetic fragrances (e.g., polycyclic musks), antimicrobial agents (e.g., triclosan), sunscreen ingredients (e.g., methylbenzylidene camphor), preservatives (e.g., parabens), insect repellents (e.g., DEET), and hormones such as estrone (E1), estradiol (E2), and ethinylestradiol (EE2) (Omar, Ahmad, Aris, & Yusoff, 2016). These substances are frequently detected in various environmental compartments, primarily due to widespread daily usage. Research conducted by Yang et al. At a wastewater treatment plant in Gwinnett County identified common PPCPs like sulfamethoxazole, primidone, caffeine, and DEET in treated effluent, with concentrations between 10 and 100 nanograms per liter. Similarly, findings by Vlachagrammi and Athanasios (Petrovic & Barceló, 2006) highlight the frequent presence of compounds such as DEET, caffeine, triclosan, coprostanol, cholesterol, tri(2-chloroethyl) phosphate, and 4-nonylphenol in environmental samples, with non-prescription medications and steroids among the most commonly detected

4.4. Detection Techniques for PPCPS in Environmental Analysis

The detection of trace levels of endocrine-disrupting compounds (EDCs), which include pharmaceuticals and personal care products (PPCPs), has long relied on two primary analytical approaches: gas chromatography (GC) and liquid chromatography (LC). GC is typically paired with detectors such as flame ionization (FID), electron capture (ECD), or mass spectrometry (MS), whereas LC is often used alongside detectors like diode array (DAD), fluorescence, or MS . Each technique offers specific advantages depending on the analyte's chemical behavior. However, traditional methods sometimes lack the sensitivity or selectivity needed for accurate detection in complex environmental samples. To overcome these limitations, researchers have increasingly turned to advanced MS-based techniques—such as ion trap MS, triple quadrupole MS, Orbitrap, and time-of-flight MS—for improved precision and lower detection thresholds. Of these, GC-MS and LC-MS/MS remain the most widely used tools for monitoring pharmaceutical residues, estrogenic compounds, and alkylphenols in environmental contexts . Identifying these compounds in clean water is a complex task due to the wide array of potential contaminants and the low concentrations at which they appear . Mass spectrometry has emerged as the leading technique in this field, largely because of its capability to both identify and quantify trace pollutants in matrices like wastewater sludge. While earlier studies employed single-quadrupole LC-MS systems with some success, modern environmental monitoring often depends on more advanced setups like triple quadrupole mass spectrometers (QqQ) for accurate and specific detection of target substances [189,190]. Tandem mass spectrometry (MS/MS), including QqQ and quadrupole time-of-flight (QTOF), is widely implemented in PPCP analysis, frequently in combination with methods such as pressurized liquid extraction (PLE), LC, and either single or double-stage MS. This combination allows for the detection of compounds at very low concentrations, often in the microgram-per-kilogram (µg/kg) range when analyzing dry weight samples . As noted by Diaz-Cruz et al, LC-MS^2 systems operating in selected reaction monitoring (SRM) mode typically offer better detection limits than GC-MS systems, although LC-MS techniques may require more adaptable sample preparation protocols.

4.5. ELISA Method for Detecting SEM Contaminants in Food

The analytical process used in this ELISA-based screening method for semicarbazide (SEM) detection parallels key steps in conventional LC–MS/MS analysis. Traditional methods involve breaking down animal tissue, releasing bound SEM through acid hydrolysis, chemically tagging SEM with o-nitrobenzaldehyde (o-NBA), followed by neutralization and extraction using ethyl acetate. The ELISA protocol streamlines this process by integrating two important modifications that significantly reduce sample preparation time. Key Improvements in Sample Processing (Cooper, Samsonova, Plumpton, Elliott, & Kennedy, 2007)

4.5.1. Elimination of Full Tissue Homogenization

Unlike LC–MS/MS, which typically requires complete tissue homogenization, the ELISA method allows for only coarse mincing of samples. This is made possible through the use of Protease Type XIII, derived from Aspergillus saitoi, which remains active even in highly acidic environments (pH ~1.4). During the acid hydrolysis and derivatization step, this enzyme breaks down the tissue, allowing complete solubilization of both free and bound SEM. This approach not only shortens preparation time but also reduces the risk of false negatives, as SEM from all cellular compartments is released effectively. Although derivatization is commonly carried out overnight to ease workflow management, this duration could be shortened to 2–3 hours with occasional mixing, which helps speed up the tissue degradation. Further improvements, such as reducing the ELISA incubation period, could allow the entire assay to be completed in a single working day.

4.5.2. Efficient Extraction via Solid-Phase Columns:

Instead of using conventional liquid–liquid extraction with ethyl acetate, this method employs solid-phase extraction (SPE) using mixed-mode cation exchange columns. These columns are suitable for use under acidic conditions, allowing the sample supernatant to be applied directly without the need to adjust the pH

4.5.3. Relevance to Composite Food Testing

In 2003, it was discovered that SEM in processed meat products often originated not from the meat itself but from external ingredients such as coatings (e.g., breadcrumbs). In response, the AFSSA (French Agency for Food Safety), along with the RIKILT Institute of Food Safety in the Netherlands, issued a recommendation that when analyzing processed foods, only the animal-derived portion should be tested. For example, in breaded meat products, the focus should be solely on the meat component. They also advised that when a sample exceeds SEM limits in initial screening, further analysis should target only bound SEM. This involves removing any free SEM before performing the confirmatory test (Cooper, Samsonova, Plumpton, Elliott, & Kennedy, 2007). The ELISA method described here is ideal for this type of screening, as it accurately measures total SEM (free and bound) without requiring the time-consuming pre-washing steps needed for confirmation of tissue-bound SEM.

4.5.4. Detection of SEM From Different Sources

Research indicates that in poultry meat exposed to nitrofurazone, about 75% of the SEM present is in the tissue-bound form (Cooper, Samsonova, Plumpton, Elliott, & Kennedy, 2007). However, SEM can also originate from other sources, such as food additives like carrageenan or azodicarbonamide, where it generally appears in a free (extractable) form. In some cases, SEM has been found in unexpected places—for instance, in crayfish meat where known contaminants weren't suspected. In one such study, the total SEM concentration averaged 4.2 µg/kg, while the bound SEM accounted for just 0.5 µg/kg (Saari & Peltonen, 2004). This highlights the versatility of the ELISA method, making it suitable not only for detecting

SEM resulting from nitrofuran drug use but also for screening contamination from alternative or unknown sources.

4.6. Chromatography Technique

Gas chromatography (GC) is the most widely applied technique for isolating compounds with moderate to low polarity and semi-volatile properties, making it suitable for many POPs. GC separation efficiency depends on the compound's volatility and its interaction with the column's stationary phase. However, complex food samples often contain structurally similar compounds, making complete separation a challenge. In such cases, comprehensive two-dimensional gas chromatography (GC×GC) significantly enhances separation by incorporating two distinct columns based on different physicochemical principles, improving peak capacity and resolution.

Although GC is effective for many POPs, per- and polyfluoroalkyl substances (PFAS), due to their unique chemical characteristics, require analysis using liquid chromatography–tandem mass spectrometry (LC–MS/MS) (Alqarni, 2024). LC techniques are often paired with atmospheric pressure ionization methods such as electrospray ionization (ESI) and atmospheric pressure chemical ionization (APCI), which are suitable for non-volatile, thermally unstable compounds often found in food matrices.

In POP detection, mass spectrometry can be operated in various ionization modes. The electron capture detector (ECD) is cost-effective and still employed for detecting halogenated contaminants such as polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs). However, MS, particularly in selected ion monitoring (SIM) mode, has largely replaced conventional detectors due to its superior specificity. While electron ionization (EI) provides reproducible spectra, it may lead to excessive fragmentation in sensitive food samples (Alqarni, 2024). In such cases, negative chemical ionization (NCI) offers a gentler alternative with enhanced selectivity.

Recent advances such as triple quadrupole tandem MS (MS/MS) and atmospheric pressure gas chromatography (APGC) have further enhanced detection sensitivity and selectivity, particularly for dioxins, PCBs, and pharmaceutical residues in high-fat food matrices like vegetable oils and fish (Alqarni, 2024). These innovations are crucial in ensuring compliance with food safety regulations and maintaining public health standards

4.7. Persistent Organic Pollutants (POPS) and Their Impact on Food Safety

In recent years, growing concern has emerged over chemical contamination in the food supply, particularly from pesticide residues and environmental pollutants. Industrial expansion and the intensification of agriculture have contributed significantly to the release of various contaminants into the environment, many of which eventually enter the food chain. Because of their widespread presence and potential to cause serious health issues, managing chemical contaminants in food has become a global public health priority (Hojjati-Najafabadi, Mansoorianfar, Liang, Shahin, & Karimi-Maleh, 2022). A significant focus has been directed toward a particular class of harmful synthetic chemicals known as Persistent Organic Pollutants (POPs). These substances, primarily generated through human activities, are organic in nature, resistant to degradation, capable of long-distance transport, and tend to accumulate in living organisms over time. Types and Sources of POPs POPs are generally categorized into three main groups: Pesticides: This includes organochlorine pesticides (OCPs) like DDT and its derivatives. (Hojjati-Najafabadi, Mansoorianfar, Liang, Shahin, & Karimi-Maleh, 2022)

By-products: Substances unintentionally generated from manufacturing or combustion processes, such as dioxins (PCDDs), furans (PCDFs), and polycyclic aromatic hydrocarbons (PAHs). Although PAHs are not classified as POPs under the Stockholm Convention, they are included under the Aarhus Protocol and often considered POPs in various scientific assessments due to their environmental persistence and fat-solubility. Environmental Stability and Bioaccumulation Many POPs are halogenated compounds—containing chlorine, bromine, or fluorine—which strengthens their resistance to chemical, biological, and photolytic breakdown. Even non-halogenated POPs are extremely stable due to their molecular structure. As a result, once introduced into the environment, these compounds persist for years or even decades. These pollutants are capable of long-range transport via atmospheric and water pathways, often reaching remote locations like the Arctic where they were never directly used. This widespread distribution means that both humans and wildlife across the globe are at risk of chronic exposure to POPs, sometimes for an entire lifetime.

4.7.1 Health Risks Associated With Pops

POPs are linked to numerous adverse health outcomes, particularly with long-term or high-level exposure. These include hormonal imbalances, cardiovascular disease, reproductive disorders, immune dysfunction, developmental abnormalities, diabetes, and various forms of cancer. Although the use of many POPs peaked during the 1970s, stringent regulations have since led to substantial declines in their levels, especially in industrialized countries. Nevertheless, ongoing exposure—especially in developing nations—remains a major concern due to the persistent nature of these compounds and their presence in commonly consumed foods. Fish and seafood are among the most contaminated sources (Hojjati-Najafabadi, Mansoorianfar, Liang, Shahin, & Karimi-Maleh, 2022). POPs enter the food chain through environmental contamination caused by agricultural practices, industrial discharge, and pesticide use. For instance, legacy pesticides like DDT and dieldrin, once widely used to boost agricultural productivity, have left persistent residues in soil, water, and crops. Similarly, chemicals like PCBs, hexachlorobenzene (HCB), dioxins, and furans are often detected in food products due to their environmental ubiquity and resistance to degradation. Regulatory and International Efforts To reduce public health risks, several national and global regulatory bodies—including the WHO, EPA, EFSA, and FDA—have established strict guidelines and safety limits for POPs in food. The Stockholm Convention on POPs, initiated in 2001, provides a legally binding global framework for eliminating or restricting the production and release of these toxic substances. Initially addressing 12 POPs known as the "dirty dozen," the list has expanded to include additional compounds over the years. Programs like the Global Monitoring Plan by the United Nations Environment Programme (UNEP) have shown measurable reductions in contaminants such as DDT, PCBs, and dioxins, especially in breast milk samples from monitored populations. (Hojjati-Najafabadi, Mansoorianfar, Liang, Shahin, & Karimi-Maleh, 2022)

4.7.2. Challenges in Risk Assessment

One major challenge in food safety today is evaluating the health risks posed by dietary exposure to POPs. This requires comprehensive data on their toxicity and the levels at which they are present in food. However, for many POPs, toxicological data is limited, often derived from predictive models, lab animal research, or observational human studies. While acute toxicity levels can help determine safety thresholds for some compounds, chronic low-level exposure makes it difficult to establish clear cause-effect relationships for others. For genotoxic substances like some PAHs, no safe exposure level can be confidently established, and a margin of exposure model is typically used instead. (Hojjati-Najafabadi, Mansoorianfar, Liang, Shahin, & Karimi-Maleh, 2022) In response, the European Commission has set legal maximum levels for several PAHs across different food categories to mitigate potential health impacts. Analytical Techniques for POP Detection To estimate dietary intake of POPs, many nations conduct Total Diet Studies (TDS) using advanced analytical techniques. These methods must be sensitive enough to detect contaminants at trace levels while also being reliable and reproducible. Sample preparation is a critical step and varies depending on the type of food being tested.

5. CONCLUSION

Numerous emerging contaminants are introduced to people and the natural environment at large through a variety of identified and unidentified means. These pollutants consistently create new and pressing problems for ecosystems, including soil, water, and air, as well as for human health. Furthermore, novel chemical outputs proliferate and typically surpass the capabilities of risk assessment, inspection, hazard remediation, and existing prevention strategies. Additionally, as a result of innovative farming methods, polluted environments, technological progress, and global warming, the range of harmful residues in food is always growing which has potential risk in human health. To reduce potential risks and ensure proper tracking of all kinds of chemicals in the surroundings, which will aid in improving laws on this issue, it is therefore becoming more and more crucial to learn about developing contaminants.

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