

Review

Ultrasound-Assisted Microextraction for Food Chemical Contaminant Analysis: A Review

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Abstract

Ultrasound-assisted microextraction (UAME) has emerged as a powerful and sustainable technique for food chemical contaminant analysis, offering a rapid, efficient, and environmentally friendly alternative to conventional extraction methods. This review provides a comprehensive overview of recent advancements in the application of UAME for the determination of various food chemical contaminants, including pesticide residues, potentially toxic elements, mycotoxins, veterinary drugs, and other chemical contaminants. The fundamental principles of ultrasound-assisted extraction are discussed, with an emphasis on the mechanisms of acoustic cavitation and mass transfer enhancement that enable improved analyte recovery from complex food matrices. Key factors influencing extraction efficiency (solvent selection, ultrasonic frequency and power, extraction time, and sample characteristics) were critically analyzed. Additionally, the integration of UAME with modern analytical platforms, such as LC-MS, GC-MS, and ICP-MS, was explored, highlighting its compatibility with high-throughput and multiresidue detection. Compared with traditional techniques, UAME offers significant benefits, including reduced solvent consumption, shorter extraction times, and improved analytical performance. This review also addresses current limitations and future perspectives, particularly regarding standardization, automation, and application in routine food safety monitoring. Overall, UAME represents a promising direction for more sustainable and efficient food chemical contaminant analysis, aligning with the growing demand for green analytical chemistry approaches.

Keywords: UAME; UA-DLLME; dispersive; pesticides; heavy metals; mycotoxins; deep eutectic solvents; greenness



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1. Introduction

Contamination of food with toxic substances is a major global concern, posing significant risks to human and animal health as well as to overall food security. Food safety involves identifying and preventing potential hazards throughout the food supply chain, from primary production to the consumer [1]. Ensuring food safety remains a global public health priority because of the widespread presence of chemical contaminants such as pesticide residues, potentially toxic elements (PTEs), mycotoxins, veterinary antibiotics, and industrial pollutants [2–4]. These contaminants can accumulate in a wide range of food products because of intensive agricultural practices, environmental pollution, and inadequate post-harvest handling. Although multiple factors contribute to food contamination,

agricultural activities are frequently identified as the main source [5–7]. These pollutants can be introduced into the environment and later transferred to crops, water supplies, and animal feed through various routes such as excessive use of pesticides and synthetic fertilizers, improper use of veterinary drugs, irrigation with contaminated water, application of polluted fertilizers or soil amendments, and inadequate storage or handling of agricultural inputs [8–11]. To comply with the increasingly stringent food safety regulations set by authorities such as the European Food Safety Authority (EFSA) [12], the U.S. Environmental Protection Agency (EPA) [13], and Codex Alimentarius [14], reliable and sensitive analytical methods are essential for monitoring trace levels of these harmful substances.

The precision and efficacy of analytical methods are significantly affected by the quality of sample preparation, especially in complex food matrices, such as fruits, vegetables, cereals, dairy, and meat products. This step directly affects the sensitivity and reliability of the results by ensuring target analyte isolation, elimination of matrix interference, and instrument compatibility [15–17]. Traditional methods such as solid–liquid extraction (SLE), Soxhlet extraction, and liquid–liquid extraction (LLE) have been widely used but are often time-consuming, solvent-intensive, and environmentally unfriendly [17–19]. Furthermore, the multistep nature of conventional extraction can introduce variability and reduce analyte recovery, making reliable food safety monitoring challenging [20,21]. Although advanced techniques, such as solid-phase extraction (SPE), ultrasound-assisted extraction (UAE), and QuEChERS, have improved selectivity and operational simplicity, they are not without limitations. Matrix effects, recovery variability, and the need for method optimization still pose significant challenges [22,23]. For example, SPE reduces solvent use somewhat but still involves expensive cartridges and multiple conditioning, loading, and elution phases [19,24]. The effectiveness of any sample preparation strategy depends on the chemical nature of the analytes, matrix complexity, and analytical goals, making this step one of the most critical steps in food chemical contaminant analysis.

In response to these limitations, the field has shifted toward green analytical chemistry (GAC) and microextraction methods. GAC emphasizes sample preparation procedures that use minimal solvents, energy, and time, aligning with sustainability goals [25,26]. Microextraction techniques fulfill the GAC principles by drastically reducing the solvent and sample volumes and simplifying the workflows [27–30]. In recent years, ultrasound-assisted microextraction (UAME) has gained prominence as a powerful green sample-preparation approach [31,32]. UAE utilizes high-frequency sound waves to enhance the extraction efficiency of target analytes from solid samples in a liquid medium. The acoustic cavitation generated by ultrasound creates microscopic bubbles that implode, producing localized high temperatures and pressures. This phenomenon facilitates the breakdown of sample matrices, increases mass transfer between phases, and improves solvent penetration, resulting in faster and more efficient analyte extraction compared to conventional methods [33–36]. For example, in ultrasound-assisted dispersive liquid–liquid microextraction (UA-DLLME), ultrasonic irradiation creates a fine emulsion of the extracting solvent in an aqueous sample, preserving a high analyte partition coefficient. This acoustic agitation often enables complete extraction within minutes using only microliters of the solvent [37,38]. UAME offers several advantages, including reduced solvent usage, shorter extraction times, lower energy consumption, and compatibility with eco-friendly solvents, making it particularly appealing for sustainable and high-throughput analytical workflows [39–41]. The versatility of this method enables its application across various sample types, from solid to liquid matrices [36,41–43]. Additionally, ultrasound extraction can be performed at low temperatures, which is particularly beneficial for thermally sensitive compounds, preserving their integrity during the extraction process. This non-destructive approach also maintains the sample structure, allowing for further analyses if

needed [41,44–47]. Numerous formats of UAME (e.g., ultrasound-assisted emulsification microextraction (UA-EMA), ultrasound-assisted hollow fiber liquid phase microextraction) and the use of novel solvents (ionic liquids (ILs), deep eutectic solvents (DESs) further enhance selectivity and greenness [48–51]. Such approaches enable the routine monitoring of pesticides, mycotoxins, veterinary drugs, and other residues in food with a minimal analytical footprint.

This review provides a comprehensive survey of the UAME techniques applied to food chemical contaminant analysis. Special emphasis was placed on the principles and configurations of UAME methods and the integration of green solvents (ILs, DESs, and supramolecular solvents). This review highlights recent applications of UAME for key classes of food chemical contaminants (pesticides, mycotoxins, additives, pollutants, and environmental pollutants). This study aimed to evaluate how UAME advances the goals of GAC in food safety. Finally, this article identifies current challenges and potential future directions for UAME, including automation and in situ analysis, to guide researchers in implementing greener, more efficient sample-preparation strategies for safe food monitoring.

2. Principles of Ultrasound-Assisted Microextraction (UAME)

UAME has emerged as an effective approach for food analysis, offering superior efficiency and sensitivity compared to conventional extraction techniques. It relies on ultrasonic waves to enhance analyte transfer from the sample matrix to the extraction solvent, thereby improving the extraction yields and reducing the processing time. Typically operating at frequencies between 20 and 500 kHz [52], ultrasound propagates through liquids in compression–rarefaction cycles that generate cavitation, such as the formation, growth, and implosive collapse of microscopic bubbles (Figure 1) [53,54]. Bubble collapse releases concentrated energy, producing localized high temperatures (up to 5000 K) and pressures (100 MPa), along with intense mechanical effects such as shock waves, microjets, and shear forces [54,55]. These phenomena disrupt cellular structures, increase solvent penetration, open microchannels in materials, and generate reactive radicals (e.g., $\text{OH}\cdot$ and $\text{H}\cdot$), which can further facilitate analyte release [53,55].

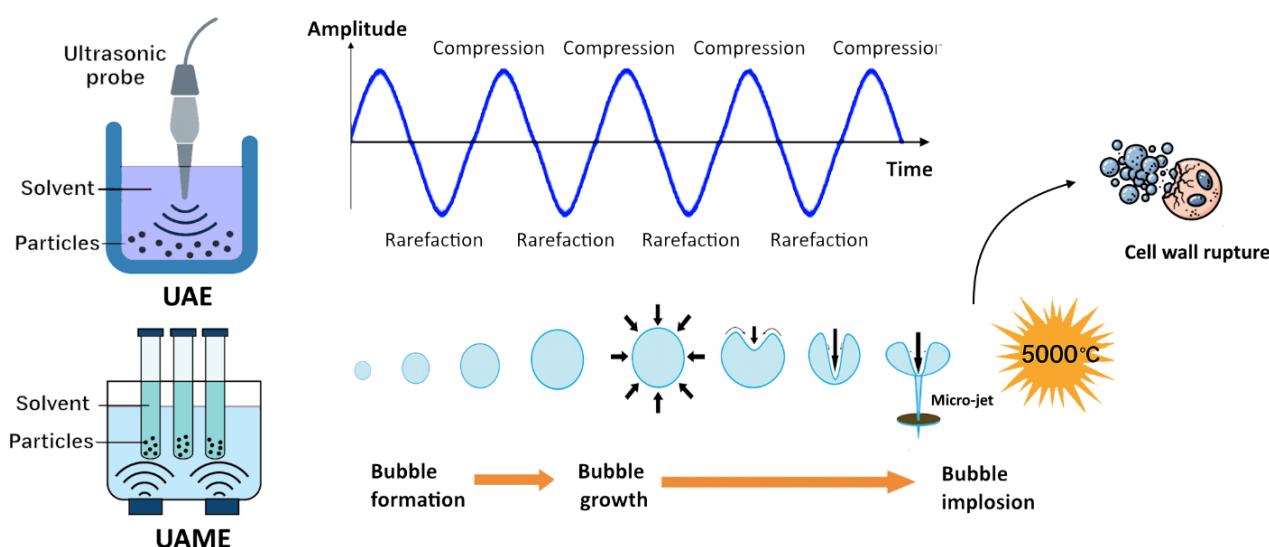


Figure 1. Schematic illustration of the ultrasound-assisted extraction (UAE) and ultrasound-assisted microextraction (UAME) mechanisms.

In UAME systems, cavitation generated by ultrasound promotes efficient analyte release from the sample matrix, allowing extraction with minimal solvent use and often at lower temperatures, which helps preserve thermally labile compounds [54,56]. In liquid–

liquid formats, ultrasound induces emulsification, dispersing one phase into another as fine droplets, which exponentially increases the solvent–sample interface and accelerates analyte partitioning [52,56,57]. Overall, these combined physical, mechanical, and sonochemical effects allow UAME to achieve rapid extraction without prolonged soaking while maintaining high recoveries and reduced environmental impact.

UAME simultaneously integrates the advantages of microextraction and ultrasonic radiation, making it highly effective for one-step derivatization, extraction, and preconcentration of various analytes [31,53,58]. As a miniaturized version of conventional ultrasound-assisted extraction, UAME drastically reduces the solvent and sample volumes to the micro-liter scale, making the process more environmentally friendly and cost-effective. Although conventional UAE also relies on acoustic cavitation to enhance extraction, it generally requires significantly larger volumes of solvent. In both techniques, the collapse of cavitation bubbles disrupts cell structures and improves solvent penetration, resulting in improved extraction yields and shorter extraction times compared with traditional methods [44].

However, UAME has clear benefits. Intense cavitation and microscale solvent dispersion enable rapid analyte transfer and near-quantitative recovery within minutes [52,59]. In some cases, centrifugation and filtration can be omitted because ultrasound promotes spontaneous phase separation [60]. Tailored microscale solvents or sorbents, combined with the inherent preconcentration effect, yield cleaner extracts with reduced matrix interference and allow detection of analytes at extremely low concentrations [59,61,62]. Overall, UAME delivers faster, more efficient, and more selective extraction with minimal solvent use, representing a significant advantage over conventional UAE techniques while maintaining its nonthermal, energy-efficient nature [52–54,60].

This method can achieve quantitative analyte recoveries that exceed those of solid-phase microextraction (SPME), a fiber-based microextraction technique, while still maintaining good precision and sensitivity [58,63–65]. All microextraction techniques drastically minimize solvent and sample consumption, in line with green chemistry [66,67]. SPME is solvent-free, where a thin coated fiber is exposed to the sample or its headspace, and analytes are adsorbed until equilibrium is reached. This single-step process is simple, highly sensitive, and automated [68]. However, the SPME has certain limitations. The sorbent coating has finite capacity and selectivity, meaning that heavy analyte loads or high-molecular-mass substances can saturate the fiber [69–71]. Fibers are also relatively expensive, have a limited lifetime, and can be fouled or broken, thus limiting the throughput [72]. In contrast, UAME uses an organic solvent (usually low-toxicity) as the extractant, which can accommodate a larger analyte mass and broader polarity range than thin fibers [52,73]. Ultrasound agitation provides faster kinetics than passive SPME; analytes flood the solvent droplets almost immediately, whereas SPME requires waiting for fiber equilibration. Of course, UAME requires handling and subsequent evaporation or analysis of the solvent extract, whereas SPME is solventless. In practice, this choice depends on the task [50,52,53]. SPME is ideal for trace volatile organics with minimal preparation, owing to its clean and solvent-free nature [69]. In contrast, UAME is better for aqueous samples, where rapid preconcentration of moderately polar analytes is desired. In brief, UAME extends the green, miniaturized principles of microextraction into the ultrasonic domain, achieving high enrichment and speed through cavitation-enhanced mass transfer at the expense of a small solvent handling step [52,56,74]. UAME and SPME are powerful microextraction strategies that complement each other's strengths and weaknesses. Conventional stirring-extraction recoveries often depend strongly on the solvent/sample volume ratio, whereas Takahashi et al. [60] found that UAME recoveries were essentially independent of the ratio. Their UAME method yielded > 80% analyte recovery with a 40× enrichment factor at any tested ratio. In essence, UAME combines the high cavitation

efficiency of UAE with the inherent concentration benefit of microextraction. This technique is particularly valuable for isolating trace compounds and contaminants from complex food matrices such as pesticides, mycotoxins, and heavy metals.

Compared to other miniaturized methods, UAME offers a fast, high-throughput alternative at the expense of a small amount of extractant. For example, UA-DLLME has been shown to achieve much shorter extraction times and higher efficiency than hollow-fiber liquid phase microextraction (HF-LPME) [75]. HF-LPME is a solvent-minimized extraction method that employs a porous polypropylene fiber to immobilize a small volume of organic solvent, allowing selective extraction and preconcentration of contaminants from complex food matrices [76,77]. The hollow fiber functions simultaneously as a physical barrier and extraction interface, yielding very clean extracts, high enrichment factors, and good compatibility with chromatographic and mass spectrometry techniques [78,79]. However, the method typically requires several tens of minutes to reach equilibrium and may suffer from issues such as fiber wetting or bubble formation [78]. This technique is considered a greener alternative to conventional solid-phase extraction [79]. Stir-bar sorptive extraction (SBSE) represents a solventless alternative in which a magnetic stir bar coated with polydimethylsiloxane (PDMS) is immersed or exposed to the sample; the thick coating (0.5–1 mm) provides an extracting phase volume 50–250× greater than SPME fibers, leading to higher sensitivity and excellent enrichment [80,81]. SBSE is robust and environmentally friendly, but it requires thermal or liquid desorption to transfer analytes from the stir bar to the analytical system and exhibits low recoveries for highly polar analytes because PDMS is non-polar [80]. In addition, commercially available SBSE coatings are limited, so only a few sorbent chemistries are available [80]. Consequently, the choice between UAME and other microextraction techniques should consider the sample matrix, analyte polarity and required throughput: UAME offers rapid extraction and broad analyte applicability at the cost of using a small solvent volume, HF-LPME provides exceptional enrichment but requires longer extraction times and careful handling, while SBSE is solventless and highly sensitive for non-polar analytes but requires specialized desorption equipment and has limited sorbent options.

Types of UAME Techniques

UAME techniques have emerged as a versatile class of sample preparation methods for analyzing food chemical contaminants. These techniques take advantage of sonic cavitation to accelerate analyte release while drastically reducing solvent consumption compared with conventional extraction methods. Over the past decade, UAME has been increasingly applied to a wide range of contaminants, including pesticides, veterinary drugs, mycotoxins, heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other contaminants, across diverse food matrices.

Several formats of UAME have been developed, each tailored to specific matrix challenges and analytical requirements (Figure 2). The main types include Ultrasound-Assisted Liquid–Liquid Microextraction (UA-LLME), UA-DLLME, UA-EMA, Ultrasound-Assisted Solid–Liquid Microextraction (UA-SLME), Ultrasound-Assisted Dispersive micro-Solid Phase Extraction (UA-D μ SPE) or often Ultrasound-Assisted Dispersive Solid Phase Microextraction (UA-DSPME), Ultrasound-Assisted Solid Phase Microextraction (UA-SPME), Ultrasound-Assisted Matrix Solid-Phase Dispersion (UA-MSPD), Ultrasound-Assisted Cloud Point Extraction (UA-CPE), Ultrasound-Assisted Surfactant-Enhanced Microextraction (UA-SEME), Ultrasound-Assisted Ionic Liquid-Based Microextraction (UA-ILME), and Ultrasound-Assisted Magnetic Solid Phase Extraction (UA-MSPE). UA-LLME combines classical liquid–liquid microextraction (LLME) with ultrasound irradiation. In these approaches, only the extraction solvent is introduced into the aqueous sample, whereas

cavitation and bubble agitation generated by ultrasound promote the formation of fine solvent droplets that enhance mass transfer [82,83]. UA-DLLME (Figure 3) represents an improved version of conventional DLLME, where ultrasound energy accelerates emulsification and analyte migration into the extraction solvent. The combined action of ultrasound and a disperser solvent produces a finer and more stable emulsion, reducing the extraction time and improving the recovery, especially in complex food matrices. Under ultrasonic irradiation, cavitation events generate countless DES droplets, resulting in the formation of a stable cloudy dispersion that maximizes interfacial contact and facilitates efficient analyte transfer [62,84,85]. Unlike UA-LLME, which relies solely on ultrasound to disperse the extraction solvent, UA-DLLME employs a disperser solvent in combination with ultrasound, resulting in a much finer and more stable emulsion [41,86,87]. UA-EME is similar to UA-DLLME but uses low-energy ultrasound to form emulsions without a dispersive solvent [88,89], making it conceptually closer to UA-LLME while simplifying the procedure and reducing solvent consumption. UA-SLME is designed to extract analytes from solid and semi-solid food matrices using small amounts of solvents. Ultrasound promotes cavitation and mechanical disruption, increasing contact surface and accelerating analyte transfer into the extractant [90–92]. UA-D μ SPE is a miniaturized sample preparation technique that couples dispersive solid-phase extraction with ultrasound to enhance the mass transfer and analyte adsorption. A small amount of sorbent is dispersed in the sample solution, and ultrasonic cavitation promotes uniform particle distribution while accelerating analyte migration onto the sorbent surface [93,94]. The sorbent, which is often composed of nanomaterials or functionalized particles with a high surface area, is subsequently separated, and analytes are desorbed with a minimal volume of solvent for instrumental analysis [65,94–96]. UA-SPME is a solvent-free technique that employs a microfiber coating (SPME fiber) to selectively adsorb analytes, making it particularly suitable for trace contaminant analysis and enabling direct coupling with analytical instruments. However, its application in food chemical contaminant analysis remains rare because ultrasound is more commonly used in solvent-based extraction prior to SPME (UAE + SPME) [97,98]. In the UA-MSPD procedure, the sample is homogenized with a solid sorbent (such as C18, Florisil, or polymeric materials), which effectively disperses the matrix and increases the surface area available for extraction. The analytes were subsequently eluted with an appropriate solvent under optimized conditions [43,99,100]. The application of ultrasound enhances the interaction between the solvent and solid phase, accelerates the release of target compounds, and improves the overall recovery. Because of these advantages, UA-MSPD has been widely applied for the determination of pesticides and mycotoxins in food [43,99,101,102]. UA-CPE combines ultrasound with extraction using nonionic surfactants at cloud-point temperature. This approach exploits the formation of a surfactant-rich phase that concentrates the analytes from the sample matrix. Ultrasound significantly shortens the extraction time and improves recovery by enhancing micellar solubilization and promoting more efficient interaction between phases. This extraction procedure was effective for both polar and nonpolar contaminants. It is frequently used for the extraction of metals and organic pollutants [103–105]. In UA-SEME, a surfactant is used as an emulsifier, while ultrasound accelerates micelle formation and extraction. This synergy improves the dispersion of the extracting phase, enhances analyte solubilization, and reduces the need for large volumes of organic solvents [106].

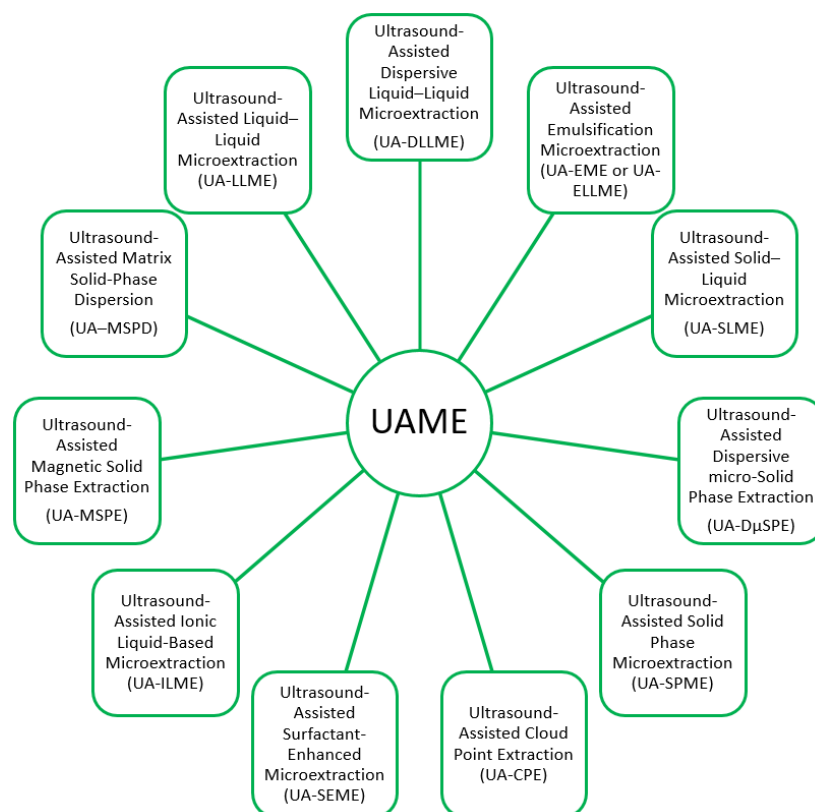


Figure 2. Types of ultrasound-assisted microextraction (UAME) techniques applied in food chemical contaminant analyses.

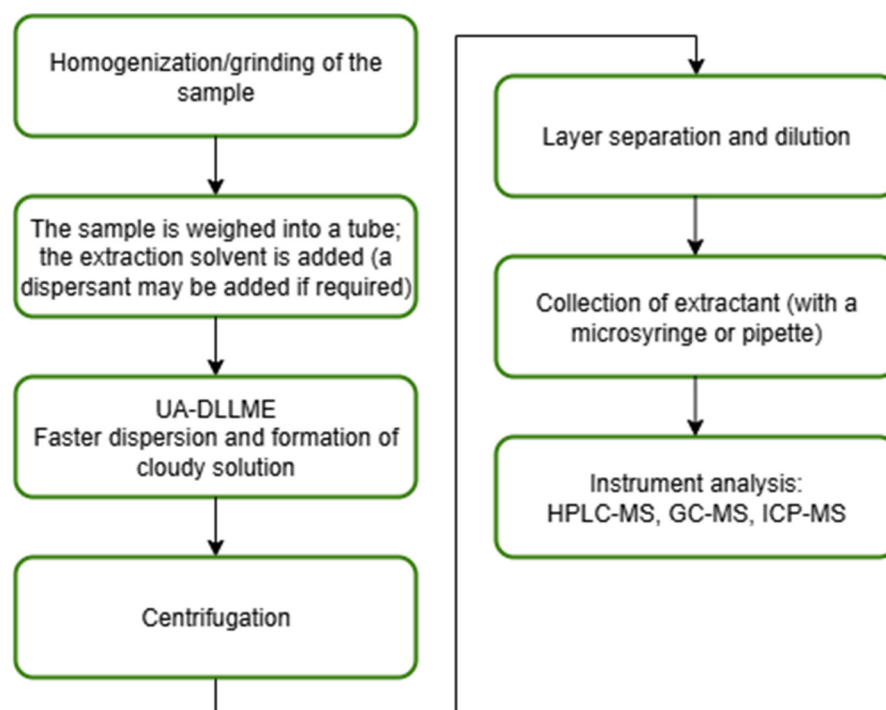


Figure 3. Flow chart of ultrasound-assisted dispersive liquid–liquid microextraction (UA-DLLME) applied for food chemical contaminant analysis.

UA-ILME utilizes ILs as extractants, assisted by ultrasound [107]. This extraction technique can be regarded as a subcategory of UA-LLME, since both rely on ultrasound-assisted liquid–liquid partitioning. However, while UA-LLME typically employs conventional or-

ganic solvents, UA-ILME makes use of ILs, which offer lower volatility, higher thermal stability, and improved selectivity owing to specific intermolecular interactions [107,108]. For UA-MSPE (Figure 4), magnetic nanoparticles are used as sorbents, and ultrasound improves the dispersion and extraction [109,110]. The combination of ultrasound and magnetic sorbents enhances surface contact, accelerates analyte adsorption, and ensures a high extraction efficiency, even in complex matrices. UA-MSPE has been applied to monitor trace metals [110], pesticides [111,112], and PAHs [24,109] in food and environmental samples. This method provides rapid separation using a magnet that is suitable for automation. Overall, emulsification is a defining feature only of certain UAME techniques such as UA-DLLME, UA-EME, and occasionally UA-ILME, while in methods like UA-SLME, UA-SPME, and UA-MSPE, extraction proceeds through solid–liquid transfer or sorbent–analyte interactions without the formation of emulsions.

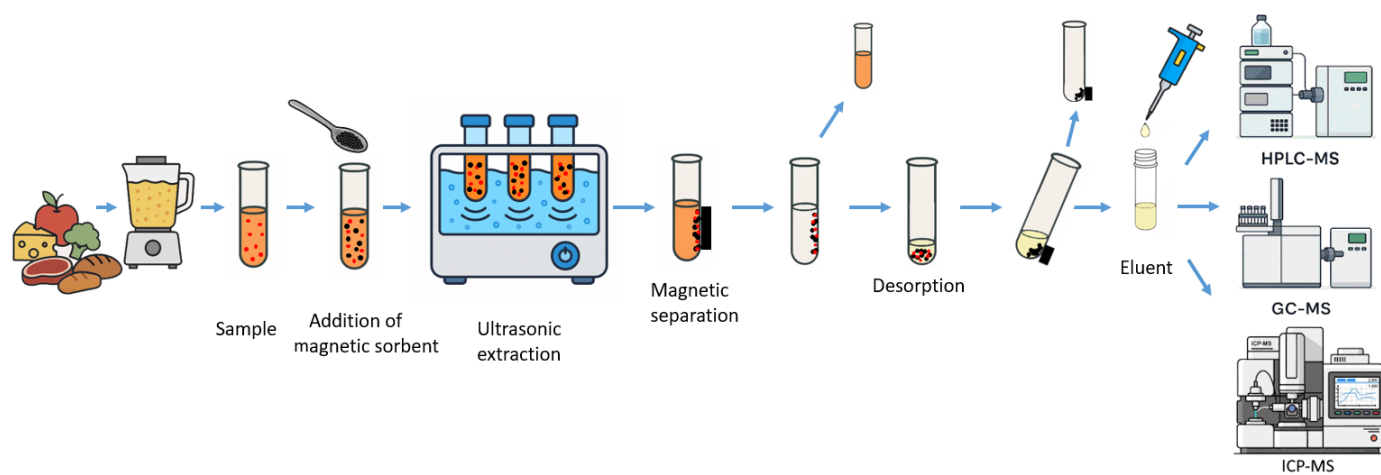


Figure 4. General schematic representation of an ultrasound-assisted magnetic solid phase extraction (UA-MSPE) applied for food chemical contaminant analysis.

3. Optimization Parameters Influencing UAME Performance

The choice of solvent for UAE/UAME has a critical impact on the extraction efficiency. Solvent polarity, viscosity, and surface tension affect the solubility of the target analytes and the intensity of ultrasonic cavitation in the medium [113]. The efficiency of extracting different contaminants is strongly influenced by the polarity of the solvent because the contaminants themselves vary in polarity. Ultrasound-assisted techniques accommodate this variability by enabling the extraction of a wide range of compounds using either polar or nonpolar solvents [113,114]. A higher solution viscosity imposes a greater viscous resistance, thereby slowing the mass transfer of analytes into the organic phase [115]. An increase in the solvent viscosity or surface tension modifies the acoustic environment, raising the cavitation threshold and minimizing the possibility of bubble formation and collapse. Consequently, solvents with lower viscosities and surface tensions promote more efficient bubble dynamics, leading to intensified cavitation and improved extraction yields [116,117]. For green extraction, DESs and edible oils have been successfully used as ultrasound media. Conventional organic solvents such as ethanol, methanol, hexane, petroleum ether, ethyl acetate, chloroform, and dichloromethane are traditionally selected based on the polarity of the target compounds. Polar solvents are used for polar analytes, nonpolar solvents for nonpolar analytes, and intermediate-polarity solvents for compounds with moderate polarity. Despite their extraction versatility, these petrochemical-derived solvents are volatile, flammable, and potentially harmful to human health and the environment [118]. In response to these drawbacks, the search for alternative and greener solvents has intensified, with DESs and their natural counterparts (NADESs) emerging as promising candidates for

microextraction applications [82,87]. DESs are typically formed by combining a hydrogen bond acceptor (HBA) and a hydrogen bond donor (HBD) in specific molar ratios to yield a eutectic mixture that is stabilized through hydrogen bonding [86,119]. NADESs, composed of naturally occurring compounds, such as organic acids, sugars, amino acids, and alcohols, offer tunable polarity, negligible vapor pressure, low toxicity, and biodegradability, making them suitable replacements for conventional organic solvents and, in many cases, ILs [87]. Recent developments have explored the use of hydrophobic DESs (HDESs) for the extraction of pesticides and other contaminants from food matrices. For instance, in one study, a combination of menthol (HBA) and decanoic acid (HBD) yielded an HDES with a polar hydroxyl group capable of hydrogen bonding to polar analytes and a long alkyl chain that enhanced the solubility of nonpolar and semi-polar compounds. This dual affinity enables efficient extraction across a broad polarity range, improving the recovery of diverse pesticide classes without the need for additional disperser solvents [86,118]. One of the notable advantages of UAME, as previously highlighted, is its reliance on relatively small amounts of solvent, and in some cases, the absence of dispersive solvents [42]. Consequently, this extraction strategy not only facilitates the use of novel green solvents but also significantly reduces the overall solvent consumption. The solvent volume (liquid-to-solid or liquid-to-liquid ratio) is another key variable. Generally, increasing the solvent volume initially increases the yield by maintaining concentration gradients, but beyond an optimum yield plateaus or falls due to the dilution of analytes and reduced ultrasonic energy density. In one study, pesticide yield from water increased as the solvent ratio rose to 200 μL and then declined with further dilution [32]. Similarly, in UA-LLME, a solvent volume that is too small can enhance enrichment factors due to reduced sediment phase volume, whereas excessive volume decreases enrichment because of dilution effects [82]. Thus, solvent selection and volume must be tailored to ensure efficient phase contact and analyte transfer, but not so high as to reduce cavitation intensity or cause dilution of the extract.

The ultrasonic frequency and power determine the cavitation intensity and, thus, the extraction efficiency. Lower frequencies (typically 20–40 kHz) produce larger cavitation bubbles that implode more violently, resulting in greater cell disruption and mass transfer [53,108,110]. In practice, frequencies in the tens of kilohertz range are most common in UAME [65,110,119]. In most studies where UAME was used for the extraction of contaminants from food matrices, the ultrasound frequency was kept constant rather than optimized. One of the few studies that investigated this parameter found that increasing the frequency from 45 kHz to 55 kHz reduced the extraction of PAHs from tomato paste, likely owing to altered sonochemical conditions [24].

The extraction time and temperature exhibited typical kinetic and thermodynamic characteristics. Longer sonication times provide more time for solute diffusion out of the matrix and solvent penetration, so the yield usually increases with time until equilibrium is reached. However, excessively long exposures may result in analyte loss [32,86,115]. For example, UA-EMA of triazine herbicides showed maximal yield at 10 min, while beyond optimal sonication time, yields began to decline, likely as a result of back-extraction [115]. In contrast, in the UA-LLME of Cd^{2+} , Pb^{2+} , Zn^{2+} , and Mn^{2+} from water and vegetable samples, recoveries increased with sonication time up to 7 min, after which they plateaued, providing consistent quantitative values [87]. Temperature has a dual effect: raising the temperature generally improves solute solubility and lowers solvent viscosity, accelerating extraction, but it also raises vapor pressure and reduces the intensity of cavitation. Thus, moderate heating often boosts yields, whereas excessively high temperatures degrade cavitation and harm thermolabile compounds [107,108]. In practice, UAME typically uses mild temperatures (often 25–50 $^{\circ}\text{C}$). For instance, triazole pesticide residues were best

extracted at 50 °C, whereas higher temperatures reduced the recovery by disrupting the effective structure of the switchable deep eutectic solvent (SDES) and promoting aggregation between the SDES and analytes [32]. Likewise, the optimal microextraction temperature for metal ions with NADESs was 35 °C, beyond which recoveries gradually decreased with increasing temperature up to 55 °C [87]. Thus, both time and temperature must be optimized to achieve a high recovery, but below the thresholds where diminishing returns or analyte loss occur.

UAME techniques have been successfully applied to the extraction of contaminants from both liquid and solid matrices [82,87,108,119]. Accordingly, different variants of UAME have been developed and adapted to address the specific challenges associated with extracting contaminants from diverse food samples [24,56,82,87,108,115,119]. The matrix effect and particle size represent key challenges in the application of UAME techniques for determining food chemical contaminants because the composition and complexity of the sample directly influence the extraction efficiency and quantification reliability [41,120]. The composition and properties of the matrix (e.g., water, fat, and fiber content) can either facilitate or hinder the release of trace contaminants during sonication. Shirani et al. (2023) confirmed that additional cleanup steps in US-DuSPE are crucial for minimizing matrix effects and achieving high recoveries of tetracyclines in milk, eggs, and honey [93], as well as β -lactam antibiotics in chicken meat, eggs, and honey [121]. Vegetables, for instance, exemplify highly complex matrices due to the presence of pigments and secondary metabolites, such as chlorophylls, carotenoids, and flavonoids, along with numerous other co-extractives that complicate analyte recovery and quantification. These interferences often pose additional challenges to analysts during contaminant determination. To address this, different sorbents and dispersive media were tested using ultrasound-assisted protocols. Dos Santos et al. (2019) demonstrated that the use of sand as a solid support in UA-MSPD significantly improves the extraction of pesticides from vegetables [120]. In the case of dried food, samples are usually powdered because fine particles facilitate ultrasound penetration and improve the extraction efficiency [122].

In summary, maximizing UAME performance requires careful balancing of the solvent properties and volume, ultrasonic frequency and power, time and temperature, and sample preparation. The optimal conditions are highly case specific. Polar analytes typically require polar solvents (or hydro-alcohol mixes) at moderate volumes, moderate frequencies (20–40 kHz), power to induce strong cavitation without overheating, and sufficient time/temperature to reach equilibrium without degradation. Minimizing particle size and removing interfering components enhance yields, as does adjusting the solid–liquid ratio to a level that saturates the matrix without excess dilution. By systematically varying these factors, researchers can “tune” UAME systems to achieve high extraction efficiency and reproducibility across diverse sample types.

4. UAME in Food Chemical Contaminant Analysis

The analysis of chemical contaminants in food has undergone a significant transformation over the past two decades, with increasing demands for analytical procedures that are not only accurate and sensitive but also environmentally sustainable and operationally efficient. Among the various sample preparation strategies developed in recent years, UAME has gained increasing attention as a promising and versatile technique. Through acoustic cavitation, UAME enables efficient disruption of complex food matrices and promotes the migration of target analytes into a limited volume of extraction solvent, thereby offering high enrichment efficiency with reduced solvent consumption. UAME has been applied to key groups of food chemical contaminants, including pesticides, heavy metals, mycotoxins, veterinary drugs, and other contaminants, often achieving high recoveries and method

performance comparable to or better than that of conventional methods. Method validation typically shows recovery rates within acceptable ranges (often 70–120%) and good precision, demonstrating that UAME is a viable alternative sample preparation approach for contaminant analysis. This section provides a comprehensive examination of the role of UAME in the extraction and quantification of these food chemical contaminants, drawing on recent literature to illustrate its performance, validation parameters, and analytical advantages over conventional techniques.

4.1. Pesticide Residues

UAME has been widely applied for the analysis of pesticide residues in food and environmental samples (Table 1). These approaches enable rapid multiresidue extraction from fruits, vegetables, and herbs, with high recoveries and minimal solvents. Its high acoustic energy accelerates solvent penetration into plant cells, significantly reducing the extraction time and solvent volume compared to conventional methods. UAME has been widely applied for pesticide residue determination in diverse food and environmental matrices, offering high recovery and low detection limits. The most common modes are UA-DLLME [61,86,123,124], UA-EME [106,115,125,126], and UA-LLME [82,83,127]. These approaches rely on acoustic cavitation to generate fine solvent droplets, which greatly enlarge the contact surface between phases and thereby enhance extraction efficiency. For instance, UA-DLLME based on the solidification of floating organic droplets and DESs achieved recoveries of 83–115% for multi-class pesticides such as organochlorines, organophosphates, pyrethroids, and organonitrogen compounds in agricultural waters, with LODs as low as 0.2 ng/mL [86]. Similarly, UA-EMA using DESs has been successfully applied to triazine herbicides in fruit, honey, and water, providing recoveries of 72–119%, RSD values below 8%, and LODs as low as 0.04 µg/L [115]. In fruit juice matrices, DES-based UA-LLME (DES-UA-LLME) enabled the quantification of organophosphorus pesticides (phosalone and chlorpyrifos) with recoveries in the range of 87–117% and low detection limits (0.07–0.09 ng/mL) [82]. Other studies have demonstrated the applicability of UA-SEME for fungicides in juices and wines, reporting recoveries between 79% and 113% [106], whereas carbamates in wines were quantified with recoveries of 74–102% and LOQs below 1 µg/L [126]. These methods are commonly coupled with gas chromatography—mass spectrometry (GC-MS) [63,86], gas chromatography—flame photometric detection (GC-FPD), liquid chromatography—tandem mass spectrometry (LC-MS/MS) [43,128], high-performance liquid chromatography—ultraviolet detection (HPLC-UV) [32,82], high-performance liquid chromatography—diode array detection (HPLC-DAD) [106,115] and ultra-high-performance liquid chromatography—tandem mass spectrometry (UHPLC-MS/MS) [126] to ensure high sensitivity and selectivity [82,83,86,115]. A notable advantage is the alignment of UAME approaches with GAC principles, as DESs provide biodegradable, low-toxicity alternatives to conventional solvents, whereas ultra-sonication reduces the extraction time to a few minutes [82,115]. Overall, UAME represents a versatile and sustainable platform for pesticide residue analysis across multiple food matrices, thereby ensuring both analytical performance and environmental safety.

Table 1. Selected applications of ultrasound-assisted microextraction (UAME) techniques for pesticide determination in food and water matrices.

Analytes/Examples	Sample Matrix	UAME Approach	Recovery (%)	Detection	Reference
Pesticides					
Organophosphorus pesticides: phorate, diazinon, parathion methyl, fenitrothion, and malathion, chlorpyrifos	Water and juice	UA-EMA	80.0–110.0	GC-FPD	[125]
Pyrethroid pesticides: ethofenprox, tetramethrin, meperfluthrin, and alpha-cypermethrin	Honey	UA-DLLME	101.2–103.0	HPLC-DAD	[123]
Fungicides: pyrimethanil, fludioxonil, procymidone, cyprodinil, kresoxim-methyl, pyraclostrobin	Fruit juices and red wine	UA-EME	79.5–113.4	HPLC-DAD	[106]
Carbamates: asulam, aldicarb-sulfoxide, aldicarb-sulfone, oxamyl, methomyl, ethiofencarb-sulfone, pirimicarb-desmethyl, ethiofencarb-sulfoxide, methio-carbsulfoxide, carbofuran-3-hidroxy, cymoxanil, aldicarb, metolcarb, propoxur, carbofuran, carbaryl, ethiofencarb, thiodicarb, isoprocarb, fenobucarb, diethofencarb, methiocarb, promecarb, napropamid and benthocarb	Wines	UA-EME	74–102	UHPLC-MS/MS	[126]
Organophosphorus pesticides: diazinon, chlorpyrifos	Rice	UA-DLLME	58.0–66.0	HPLC-UV	[124]
Organophosphorus pesticides: phosalone, chlorpyrifos	Fruit juice	DES-UA-LLME	87.3–116.7	HPLC-UV	[82]
Organophosphorus pesticides: malathion, fenthion, dimethoate, imidan, phosphamidon, fenitrothion, and isocarbophos	Water	UE-AA-LLME	75.4–112.6	UPLC	[83]
Strobilurin fungicides: azoxystrobin, pyrimethanil and kresoxim-methyl	Apple	UA-DLLME	76–92	HPLC-UV	[61]
Organochlorine pesticides: endosulfan, aldrin, dieldrin, dichlorodiphenyldi-chloroethylene (DDE), and dichlorodiphenyltrichloroethane (DDT)	Cheese	UA-LLME	57–79	GC-MS	[127]
Thiamethoxam, thiacloprid, pirimicarb, acetamiprid, tebuconazole	Pears	UA-MSPD	78.5–120	LC-MS/MS	[43]
Triazine herbicides: atrazine, simazine, deisopro-pylatrazine, deethylatrazine, propazine, prometryn and terbutryn	Water, fruit and honey	UA-EME	71.90–119.25	HPLC-DAD	[115]
Ovex, oxidiazon, tetrasul, buprofezin, sulprophos, tebufenpyrad, cis-permethrin	Agricultural waters	UA-DLLME	83–115	GC-MS	[86]
Metalaxyl, napropamide and epoxiconazol	Tea	UA-MSPE	75.1–101.2	UHPLC-MS/MS	[112]
Acetamiprid and Imidacloprid	Fruit and water	UA-MSPE	82.13–102.27		[111]

4.2. Potentially Toxic Elements (PTEs)

UAME has been increasingly applied to the determination of elements in food matrices, offering a green, rapid, and highly efficient alternative to conventional digestion and extraction procedures (Table 2). Among the most commonly employed approaches are UA-D μ SPE [65,96], UA-DLLME [62,87], and UA-CPE [103–105]. These techniques have been successfully utilized for trace-level determination of toxic and essential elements, including Sb, As, Al, Cd, Pb, Hg, and other elements, in diverse food products such as beverages [65], edible oils [129], dairy products [62], fish [94,105], rice, edible mushrooms [94,96], sunflower seeds [96], wheat, honey, eggs, red meat, white meat, salami, sausage, black tea, green tea, tomato, pepper, flour, cabbage, carrot, parsley, and mint [94].

The primary advantages of UAME-based methods lie in their ability to achieve high extraction recoveries (often above 90–95%) with low relative standard deviations while drastically reducing solvent and reagent consumption compared to conventional wet digestion. Cavitation induced by ultrasound accelerates mass transfer, disrupts complex food matrices, and allows for shorter extraction times, often within a few minutes. A representative example is the analysis of rice, where an optimized UAME protocol with low acid volumes achieved the efficient extraction of As, Pb, Cu, and Cd prior to inductively coupled plasma optical emission spectroscopy (ICP-OES) determination. The method, validated with certified reference material, demonstrated accuracy comparable to microwave digestion and enabled the reliable detection of Pb and Cd residues in real samples at the $\mu\text{g}/\text{kg}$ level [57]. UAE has also been successfully applied in complex foods. For example, Savić et al. [36]

applied UAE to coffee beans to determine rare-earth elements using ICP-MS. The recoveries for 14 elements ranged from 80.1% to 112% with RSDs below 14%, demonstrating excellent precision. The limits of detection were remarkably low (pg-ng/kg range), and the method compared favorably with microwave-assisted digestion. In addition, these methods align with the principles of GAC, as many recent protocols employ eco-friendly extractants such as DESs or surfactant-based emulsions instead of toxic organic solvents [62,104,130]. Among the most prominent are DESs, successfully applied for the UA-DLLME of Al in milk [62], ILs [74], and magnetic ILs such as [C₄mim][FeCl₄] [131], which have been used in surfactant-enhanced emulsification procedures for Cd and Pb in edible oils. Nonionic surfactants, including Triton X-100 and Igepal CO-630, are frequently used in UA-CPE for trace elements, such as Sb, Sn, Tl, Zn, Ni, and Co [104,130]. Surfactants used in CPE are characterized by low toxicity and minimal dosage, making them sustainable substitutes for harmful organic solvents [130]. In addition, diluted mineral acids (HNO₃, HCl) and water are used in the UAE to extract nutritional elements such as Fe, Mn, Mg, and Ca from plant-based foods [39]. Collectively, these solvent systems provide both high analytical performance and a transition toward greener, safer, and more sustainable methodologies for the elemental analysis of food. Another relevant feature is the compatibility of UAME with detection systems such as ICP-OES [130], inductively coupled plasma mass spectrometry (ICP-MS) [129], flame atomic absorption spectroscopy (FAAS) [104], graphite furnace atomic absorption spectroscopy (GFAAS) [131], hydride generation atomic absorption spectroscopy HGAAS [65], UV-VIS spectrophotometer, and slurry vapor generation atomic fluorescence spectroscopy (SVG-AFS), enabling reliable quantification at ultra-trace levels with excellent enrichment factors.

Table 2. Selected applications of ultrasound-assisted microextraction (UAME) for the determination of potentially toxic elements (PTEs) in food and water matrices.

Analytes/Examples	Sample Matrix	UAME Approach	Recovery (%)	Detection	Reference
Potentially toxic elements					
Al, Ca, Cd, Cu, Mg, Mn, Ni, Ti, V, Zn	Edible oils	UA-EME	92.9–109.1	ICP-MS	[129]
As	Rice and flour	UA-EH-WPME *	98–107	ICP-MS	[132]
Se	Organic rice	UAME	85.5–106.7	ICP-MS	[133]
Hg (CH ₃ Hg ⁺ and Hg ²⁺)	Fish	UA-CPE	91.5–96.5	UV-VIS	[105]
Zn, Ni, Co	Foods and vegetables	UA-CPE	>94	FAAS	[104]
Cd and Pb	Edible vegetable oils	UA-SEME	95.8–105.8	GFAAS	[131]
Co, Ni, Pb, Hg, Cd	Rice	UA-EME	88.6–107.0	ICP-OES	[57]
Sb, Sn and Tl	Food and water	UA-CPE	98–100	ICP-OES	[130]
iAs (As ³⁺ and As ⁵⁺)	Food and water	UA-D μ SPE	>95	ICP-OES	[96]
Trace mercury (Hg ²⁺)	Water	UA-MSPE	>90	SVG-AFS	[110]
Sb ³⁺	Bottled beverages	UA-D μ SPE	96	HGAAS	[65]
Al	Whey milk	UA-DLLME	>98	ICP-OES	[62]
Total As	Food	UA-D μ SPE	96.0–98.5	HG-AAS	[94]
Cu ²⁺	Beverages	UA-CPE	94–103	UV-VIS	[103]
Pb, Cd, Zn, Mn	Water and vegetables	UA-DLLME	94.3–97.9	FAAS	[87]

* ultrasound assisted-enzyme based hydrolytic water phase microextraction method.

Overall, the application of UAME techniques for elemental analysis of food offers a robust, miniaturized, and environmentally sustainable strategy. Their versatility across different food matrices and compatibility with multivariate optimization approaches make

them especially valuable for routine monitoring of both nutritional and toxic elements, thereby ensuring food quality and safety in line with international regulatory standards.

4.3. Mycotoxins

Given the chemical stability and low concentration levels of mycotoxins in food, rapid and efficient extraction methods are essential, and UAME has emerged as a particularly suitable approach for addressing these analytical challenges [18,70]. Some mycotoxins are heat-sensitive, and UAE methods operate at ambient or mildly elevated temperatures while still achieving trace level enrichment [70]. The applied variants were UA-DLLME [119], UA-MSPD [99,101], and DES-based UAME (DES-UAME) [134]. There are also studies (Table 3) where ultrasound-assisted solvent extraction has been combined with, for example, magnetic ionic liquid-based DLLME [49] or vortex-assisted LLME [135]. These approaches have been successfully employed across diverse food matrices, including milk [119], black beans, black sesame seeds [136], pistachio nut [99], rice [101], tea [49], and seafood [135]. Their major benefits include high extraction recoveries, typically ranging from 70 to 96%, substantial enrichment factors, low detection limits (often below 1 ng g^{−1}), and short extraction times compared to conventional solid–liquid extraction or Soxhlet-based protocols [101,119,122].

Table 3. Selected applications of ultrasound-assisted microextraction (UAME) for the determination of mycotoxins in food and water matrices.

Analytes/Examples	Sample Matrix	UAME Approach	Recovery (%)	Detection	Reference
Mycotoxins					
Aflatoxins (B1, B2, G1 and G2)	Pistachio nut	UA-MSPD	74–78	LC-FLD	[99]
Aflatoxins (B1, B2, G1 and G2)	Rice	UA-MSPD	78–83	HPLC-FLD	[101]
Patulin	Fruit juices	UA-EMA	90.2–106.9	UV-VIS	[137]
		Ultrasound extraction + MIL-based DLLME *			
Aflatoxins B1, B2, G1, and G2 and ochratoxin A	Tea		76–88	LC-FLD	[49]
Aflatoxin M1	Milk	UA-DLLME	91.4	UV-VIS	[119]
Aflatoxins B1, B2, G1, G2, and M1, ochratoxin A, zearalenone, deoxynivalenol and patulin	Medicinal and edible foods	UA Organic Drop- DLLME **	82.77–103.2	HPLC-DAD-FLD	[136]
Aflatoxins G1, G2, B1, and B2, citrinin (CIT), HT-2, roquefortin C (ROQ C), T-2, ochratoxin A (OTA), sterigmatocystin (ST)	Chili powder	CI-LLE-MSPE ***	70.6–111.7	UPLC-Q-TOF/MS	[40]
Beauvericin and enniatins A1, B, and B1, aflatoxin B1, zearalenone, deoxynivalenol	Gluten-free flours	UA-MSPD	84.8–121.7	LC-MS/MS	[102]
Zearalenone	Food	DES-UA-ME	96–98	UV-VIS	[134]

* UA Solvent Extraction Combined with Magnetic Ionic Liquid Based-DLLME. ** UA Aqueous Two-phase Extraction with Solidifying Organic Drop-DLLME. *** Cold-induced liquid–liquid extraction-MSPE.

A further advantage is the compatibility with green solvents, such as magnetic ILs [49] and sugar-based DESs [119], which not only reduces environmental impact but also maintains excellent analytical performance. For mycotoxin analysis, UAME procedures are coupled with a UV-VIS spectrophotometer [119,134], high-performance liquid chromatography–fluorescence detector (HPLC–FLD) [99] or HPLC coupled to in-series FLD and DAD [136], liquid chromatography–fluorescence detector (LC-FLD), and ultra-performance liquid chromatography–quadrupole time-of-flight mass spectrometry (UPLC-Q-TOF/MS). These miniaturized methods allow for simultaneous multi-mycotoxin determination, for example, aflatoxins B₁, B₂, G₁, G₂, M₁, ochratoxin A, zearalenone, deoxynivalenol, and patulin [136], or different aflatoxins (B₁, B₂, G₁, and G₂) [99]. An example of such UAME applications is the study by Gürsoy et al. (2022), who developed an ultrasound-assisted sugar-based deep eutectic solvent DLLME (UA-sugar-DES-DLLME) for the extraction of aflatoxin M1 in

milk [119]. Under optimized conditions, this method achieved recoveries of 91–107%, an enrichment factor of 328, and a detection limit of 6.1 ng/L, confirming the efficiency of DES-based UAME in complex dairy matrices [119]. Another notable example was provided by Gholizadeh et al. (2022), who combined ultrasound-assisted mixed solvent extraction with magnetic IL effervescent DLLME for tea samples, enabling the simultaneous determination of aflatoxins B1, B2, G1, G2, and ochratoxin A [49]. Their approach yielded recoveries of 76–88%, enrichment factors of 300–350, and LODs as low as 0.15–0.28 ng/g, with RSD values $\leq 3.5\%$, all within a procedure lasting only a few minutes at 35 °C, thereby preserving thermolabile analytes [49]. However, only a limited number of studies have focused on the development of UAME techniques for the determination of mycotoxins in food, indicating that further research is still required to establish their full potential and broaden their application.

4.4. Veterinary Drug Residues

Veterinary drugs (e.g., antibiotics, antiparasitics, etc.) encompass a variety of chemical classes (β -lactams, tetracyclines, macrolides, sulfonamides, avermectins) that accumulate in animal-derived foods [89,93,121,138]. Ultrasound-based microextraction has been applied to these compounds to expedite sample pretreatment of complex matrices (muscle, fat, milk, and fruit juice) [89,95,138–140]. The targeted analytes in many UAME studies include major antibiotics, such as tetracyclines and macrolides (Table 4).

Several methodological variants have been developed, depending on the antibiotic class and matrix. For instance, UA-DLLME has been successfully applied to sulfonamides in water and seafood [140], chloramphenicol in honey [85], and β -lactam antibiotics in chicken, eggs, and honey [93] using HDEs. Similarly, DES-based ferrofluid UA-LLME has enabled efficient extraction of quinolones from milk [139], while DES-DLLME coupled with ^{19}F qNMR has been used to detect fluoroquinolones illegally added to herbal medicines [141]. For sulfonamides, UA-D μ SPE with polymeric IL-based chitosan has been proposed, which shows high selectivity and sensitivity in milk and eggs [95]. Across these approaches, recoveries typically range between 80 and 98% with low RSD values ($<6\%$), while detection limits often fall in the sub- $\mu\text{g L}^{-1}$ or low $\mu\text{g kg}^{-1}$ range, demonstrating the robustness of UAME as a pretreatment step prior to chromatographic or electrophoretic analysis. For example, Lorenzetti et al. [89] developed a “reverse” UA-EME for extracting the macrolide antibiotics tylosin and tilmicosin from fatty chicken tissues. They used an aqueous IL solution ([Bmim]Cl with tartrate/phosphate) and a 7.5 min ultrasound probe exposure to form an emulsion that extracted the drugs. The method yielded linear calibrations (35–200 $\mu\text{g/kg}$), and recoveries were 73–117%, with LOQs in the range of 17–55 $\mu\text{g/kg}$. This simple two-step method (sonication in an IL solution, followed by phase separation) allowed capillary electrophoresis-UV detection without further clean-up. Importantly, such UAME approaches simplify the pretreatment of greasy matrices: ultrasound disperses the sample and emulates the extractant, even in the presence of lipids. Karageorgou et al. [100] demonstrated another UAME variant for veterinary drugs: they performed UA-DLLME for tetracyclines in milk. In their protocol, acetonitrile/methanol (2:1) was blended with milk and a C18 sorbent under ultrasonic vibration to effectively bind the lipids to the sorbent. The tetracyclines (oxytetracycline, tetracycline, doxycycline, etc.) were eluted and quantified by HPLC–DAD. Method validation showed LOQs of 14–57 $\mu\text{g/kg}$ (below EU MRLs) and recoveries of 82–108% with RSDs $< 8\%$. These figures meet the regulatory requirements and were confirmed using a bovine milk certified reference material (CRM). Notably, this UA-MSPD approach eliminated the separate fat removal step by fixing lipids on the sorbent under ultrasonic agitation.

Overall, the UAME of veterinary drugs consistently yields quantitative recoveries (often 70–110%) for a broad range of veterinary compounds. Coupling to sensitive detectors, ultra-high-performance liquid chromatography—tandem mass spectrometry (UHPLC MS/MS) [85], HPLC-DAD [140], high-performance liquid chromatography—photodiode array detector (HPLC-PDA) [95,121]) is standard; for instance, Lorenzetti et al. [89] noted that LC-MS/MS is now the “most common technique” for antibiotic residue analysis in milk, muscle, egg, etc. In many cases, only simple filtration or centrifugation follows the extraction [95,141]; in others, dispersive SPE (QuEChERS) is used to clean the residual matrix [142]. The key point is that ultrasound greatly accelerates extraction from tight or fatty tissues and often allows miniaturized green solvents (ILs, DES) to be used effectively. This high-throughput method satisfies the stringent accuracy, precision, and low LOQ demands of veterinary residue monitoring.

Table 4. Selected applications of ultrasound-assisted microextraction (UAME) for the determination of veterinary drug residues in food matrices.

Analytes/Examples	Sample Matrix	UAME Approach	Recovery (%)	Detection	Reference
Veterinary drugs					
Oxytetracycline, tetracycline, epi-chlorotetracycline, chlorotetracycline and, doxycycline	Milk	UA- MSPD	82–108	HPLC-DAD	[100]
Tilmicosin and tylosin	Chicken fat	UA-EME	73–117	CE *	[89]
Chloramphenicol	Honey	UA-DLLME	/	UHPLC MS/MS	[85]
Sulfonamides: sulfapyridine, sulfamethazine, sulfadimethoxine	Fruit juices	UA-LLME	88.09–97.84	HPLC-UV	[138]
Quinolones: enrofloxacin, ciprofloxacin	Milk	UA-LLME	84.4–95.4	HPLC-UV	[139]
Sulfonamides: sulfacetamide, sulfamerazine, sulfanilamide pyridine, sulfadizine, sulfamonomethoxine, sulfamethoxazole, and sulfadimethoxine.	Water and seafood	UA-DLLME	80.0–116.0	HPLC-DAD	[140]
β -Lactam antibiotics: penicillin G, ampicillin, and amoxicillin	Egg, honey, and chicken muscle	UA-DLLME	>97	HPLC-PDA	[121]
Sulfamethizole, sulfadiazine, sulphamethoxazole, sulfachloropyridazine, sulfisoxazole and sulfadimethoxin	Milk and egg	UA-D μ SPE	79.1–100.0	HPLC-DAD	[95]
Tetracyclines, oxytetracycline, chlortetracycline, and doxycycline	Milk, egg, and honey	UA-D μ SPE	95.2–99.3	HPLC-PDA	[93]

* capillary electrophoresis analysis.

4.5. Other Contaminants

In addition to pesticides, toxic elements, mycotoxins, and veterinary drug residues, UAME has been widely applied to a broad spectrum of chemical contaminants, reflecting its versatility and adaptability across diverse food safety challenges. Emerging contaminants of concern include synthetic dyes [90,92], endocrine-disrupting chemicals [84,143,144], preservatives [103,144], plasticizers [145], PAHs [24,109], and polychlorinated biphenyls (PCBs) [4], many of which are present at trace levels and within complex food matrices (Table 5).

Persistent organic pollutants (POPs), particularly PAHs and PCBs, have been successfully addressed using UAME. Low-density UA-EME has been applied for trace PCB determination in water, yielding recoveries of 87–93% and limits of quantification as low as 10 ng/L [146]. Similarly, ultrasound-based solid phase or emulsification methods have been employed for PAHs in various food matrices, including tomato paste [24], soft drinks [109], and eggs exposed to fire contamination [98]. These studies demonstrated consistently low

detection limits (0.02–0.5 ng g^{−1}), high recoveries (88–98%), and short extraction times (typically < 30 min), highlighting UAME as a powerful strategy for monitoring toxic, lipophilic contaminants that tend to bioaccumulate in fatty foods. In addition, the integration of advanced sorbents such as graphene oxide–Fe₃O₄ and magnetite biochar with ultrasonication has enabled efficient magnetic separation, minimized solvent use, and improved reusability, thereby reinforcing the alignment of UAME with GAC principles [24,109].

UAME has also been used for the extraction of illegal colorants such as Sudan dyes from spices, where UA DES-based SLME achieved recoveries of 85–99% and low RSD values (<3.2%), enabling the sensitive detection of carcinogenic dyes in paprika, chili, cumin, and sumac [90]. Similarly, parabens and phenolic preservatives in edible oils and beverages have been effectively identified using UA-DLLME and UA-LLME with green solvents, with recoveries typically above 90% and detection limits at ng/L levels. These results highlight the role of UAME in the monitoring of both regulated and emerging food additives [144,147].

One of the most extensively studied plasticizers in food is bisphenol A (BPA), an endocrine disruptor that can migrate from plastic packaging into food products. Its extraction and determination in beverage samples have been successfully achieved using UA-EME with in situ derivatization, which enabled simultaneous derivatization, preconcentration, and rapid sample preparation for GC–MS analysis [145]. The method demonstrated a detection limit of 38 ng/L and recoveries higher than 82%, confirming that UAME ensures high efficiency and reliability for the quantification of BPA in complex food matrices. These results highlight the potential of UAME techniques to control the migration of plasticizers from packaging into food and beverages, which represents a critical aspect of food safety assessment.

Table 5. Selected applications of ultrasound-assisted microextraction (UAME) for the determination of representative analytes (contaminants) in food and water.

Analytes/Examples	Sample Matrix	UAME Approach	Recovery (%)	Detection	Reference
Bisphenol A	Beverage	UA-EME	≥82	GC-MS	[145]
PCBs	Tap waters	UA-EME	87.29–92.83	GC-MS	[146]
<i>tert</i> -butylhydroquinone (TBHQ)	Soybean oils	UA-LLME	93.4–108.8	HPLC-UV	[147]
Sudan dyes	Spice	UA-SLME	85.55–99.29	HPLC-UV	[90]
Non-steroidal anti-inflammatory drugs	Water and milk	UA-DLLME	79.42–107.52	HPLC-UV	[148]
PAHs	Soft drinks and non-alcoholic beers	UA-MSPE	94.67–109.45	GC-MS	[109]
Endocrine-disrupting phenols	Water, milk and beverage	UA-DLLME	81.79–109.82	HPLC-UV	[84]
Benzotriazole (BTRs) and benzothiazole (BTHs) derivatives	Tea beverages	UA-LPME	65–107	UHPLC	[143]
Parabens	Edible oil	UA-LLME	85.1–106.8	HPLC-UV	[144]
5-hydroxymethylfurfural (5-HMF)	Honey	UA-DLLME	92–103	UV-VIS	[149]
PAHs	Tomato paste	UA-MSPE	88.03–98.52	GC-MS	[24]
Illegal colorants	Traditional Chinese medicines	UA-SLME	94.2–103.1	HPLC-DAD	[92]
Formaldehyde	Milk-based products	UA-CPE	90.8–97.4	UV-VIS	[103]
Bisphenol A	Milk	UA-MSPE	89.1–99.4	HPLC-UV	[150]

5. Emerging Technologies and Future Perspectives

Over the past decade, UAME has undergone significant development to meet the demand for rapid, sustainable, and highly sensitive analytical methods. The use of ultra-

sound enhances solvent–matrix interaction via acoustic cavitation, which facilitates the release of analytes at trace levels within short processing times and with reduced reagent consumption [138]. This aligns well with the GAC principles, which prioritize reducing hazardous solvent usage and improving safety [17]. Ultrasound has thus become recognized as a versatile tool that improves analyte recovery while reducing ecological impact [51,55,137]. Recent technological advances have improved these benefits by combining ultrasonication with novel microextraction formats and materials to improve detection and sustainability.

Compared with other microextraction methods, such as HF-LPME and SBSE, UAME offers faster extraction and reduced solvent consumption, although it may involve minor handling of extractants. These characteristics make it ideal for rapid, high-throughput analyses. Nevertheless, future research should quantitatively benchmark UAME against other microextraction approaches by using measurable performance metrics. A comparison of the key analytical performance parameters between UAME and other emerging microextraction techniques is summarized in Table 6.

Table 6. Comparison of emerging microextraction techniques used for food contaminant analysis.

Technique	Food Matrix	Target Contaminants	LOD	Enrichment Factor	Extraction Time	Solvent Consumption	Reference
UA-LLME	Fruit juices	Diphenylamine	0.05 µg/L	/	11 min	500 µL of HP-DES	[151]
UA-EME	Water and juice	Organophosphorus pesticides	5.3–10.0 ng/L	241–311	10 min	50 µL chlorobenzene	[125]
UA-LLME	Oils, fish, milk	Ni(II), Zn(II)	0.029 µg/kg (Ni); 1.5 µg/kg (Zn)	/	5 min	8 mL of DES	[31]
UA-DSPME	Bottled beverages	Sb(III)	1.5 ng/L	90	15–20 min	6 mL, 3.0 mol/L HNO ₃ and 4 mL, 2.0 mol/L H ₂ O ₂ 3.5 mL of ACN:H ₂ O:acetic acid (79:20:1, v/v/v) in	[65]
UA-MSPD	Gluten-Free Flours	Mycotoxins	1–100 µg/kg *	/	20 min	Microliter-scale extractant after preconcentration	[102]
UA-CPE	Milk-based products	Formaldehyde	0.501 µg/L	55.6	17 min	50 µL HP-DES and 150 µL acetonitrile	[103]
USA-DLLME	Egg, honey, and chicken muscle	β-Lactam Antibiotics Residues	In µg/kg	29.1–74.6	7 min	Solvent-free (thermal desorption)	[121]
SBSE	Fish	Quinolone antibiotics	0.48–0.8 ng ng/mL	/	>1 h		[152]
HF-LPME	Fruits and vegetable juices	Pyrethroid pesticides	0.02–0.07 ng/mL	519–528	41 min optimum	24 µL organic phase in fiber	[153]
HF-LPME	Drinking water	Disinfection by-products	10–220 ng/L	13.1–140.1	30 min	20 µL of octanol	[154]
HS-SPME	Biscuits	Acrylamide	27.4 µg/kg	/	45 min	30 mL of propanol	[155]
SBSE	Milk samples	Fluoroquinolones	1.20–2.62 µg/L	56.2–61.5	60 min	1 mL of organic solvent for elution	[156]
SBSE	Seafood	Heavy metal and arsenic ions	<0.08 µg/kg	/	30 min	10 mL 1 M HNO ₃	[157]

*LOQ

A clear trend in recent years is the integration of UAE with novel solvents and sorbents designed for a minimal environmental footprint. Traditional organic solvents are increasingly being replaced by green solvents, such as ILs and NADES, in UAME protocols [43,87,95,131]. ILs have attracted attention because of their negligible vapor pressure, but concerns over poor biodegradability and aquatic toxicity have limited their “greenness” [115]. In contrast, DES, often composed of benign food-grade components, has gained popularity as an extraction medium [118,139]. For example, Legesse et al. (2025) developed a UA-EMA using a DES to selectively isolate triazine herbicide residues from fruit and honey samples, achieving detection limits down to 0.04 µg/L with excellent recoveries [115]. Similarly, Heidari et al. (2020) optimized DES-based UA-LLME for organophosphate pesticides in fruit juices, demonstrating high enrichment factors and

low $\mu\text{g/L}$ detection [82]. These cases illustrate how greener solvents, when combined with ultrasound agitation, can maintain the analytical performance while replacing toxic organic solvents. Future developments may even leverage artificial intelligence (AI) and machine-learning tools to design or select optimal solvent–sorbent systems and further streamline method development [158].

In tandem with solvent innovation, novel sorbent materials have been introduced into UAME methods to enhance the selectivity and extraction efficiency. Magnetic nanoparticles (MNPs), metal–organic frameworks (MOFs), molecularly imprinted polymers (MIPs), and covalent organic frameworks (COFs) are emerging as high-surface-area sorbents that can be dispersed in a sample during ultrasonic treatment and then easily retrieved magnetically or by filtration [41,159,160]. For instance, Zhao et al. (2020) reported a UAME using a DES as the medium combined with functionalized magnetic carbon nanotubes as a sorbent to extract multiple pesticide residues from foods [45]. The approach leveraged ultrasonication to rapidly disperse the magnetic nanomaterial and DES throughout the sample, achieving efficient contaminant adsorption. Subsequent magnetic separation yielded a clean extract for analysis [45]. In another study, Shirani et al. (2019) developed a magnetic nanofluid-based UAME for pyrethroid insecticides; an iron oxide nanofluid stabilized with biocompatible surfactants was emulsified into the sample under ultrasound, then retrieved with a magnet, enabling pesticide determination in fruit and vegetable extracts with minimal solvent use [161]. These examples highlight a future direction in which advanced nanostructured sorbents, designed to be ultrasound-dispersible, can significantly improve extraction efficiency and selectivity. Furthermore, such sorbents can often be reused and crafted from inexpensive or bio-derived materials, reinforcing the green ethos [41]. We can expect continued growth in this area, with more MIPs, MOF/COF sorbents, and enzymatic materials adapted for ultrasonic microextraction to target specific contaminant classes.

By definition, microextraction techniques use very small sample and solvent volumes, and new designs miniaturize the extraction hardware itself. One example is the use of microscale emulsions and droplets in the UAME. UA-DLLME has been widely applied to foods, wherein a few hundred microliters (or less) of solvent is ultrasonically dispersed as fine droplets into the sample. This dramatically increases the surface area for partitioning and accelerates equilibrium [62,86]. Various creative UA-DLLME variants have been developed. Jouyban et al. (2020) introduced the in situ formation of a DES extractant within milk, followed by UA-DLLME and cooling-induced phase separation, to extract multiple pesticides in a single step [162]. Other researchers have exploited ultrasonic emulsification to create smaller extractant droplets. Legesse et al. (2025), for example, used ultrasonic energy to emulsify a DES in aqueous fruit extracts, forming a microemulsion that could trap herbicides efficiently [115]. Ultrasonic probe systems allow these emulsions to form quickly, even at the microliter scale [115]. An innovative technique is ultrasound-assisted single-drop microextraction (UA-SDME). For example, Almeida et al. (2015) demonstrated that suspending a single microliter-level drop of an acidic extractant in a vegetable oil sample and irradiating it with ultrasound could efficiently extract trace cadmium, after which the enriched drop was directly analyzed using atomic absorption spectroscopy (AAS) [163]. Because ultrasonic treatment significantly increases the mass transfer of analytes into the drop, the UA-SDME technique achieves remarkable miniaturization; it only requires a small drop of solvent and is still effective. A further step toward miniaturization was achieved using in-syringe UA-DLLME. In this approach, the entire extraction process takes place inside a disposable syringe, where ultrasonic energy facilitates the dispersion of microliter amounts of the extractant directly into the food matrix. Gómez et al. (2022) [164] demonstrated this concept for trace contaminant analysis in milk, showing that the self-

contained syringe format reduces solvent consumption, simplifies handling, and renders the method highly compatible with automation.

As UAME techniques improve, they are better integrated with modern analytical tools, which improves the overall workflow from extraction to detection. One clear trend is the coupling of UAME with sensitive chromatographic techniques such as LC–MS/MS [43,85]. There has been a clear shift toward pairing these greener extraction methods with high-sensitivity detectors to meet regulatory limits. For instance, multi-residue methods often combine a UAE step with LC–tandem MS detection, allowing dozens of contaminants to be identified and quantified in one run with sub-ng/mL detection limits [43,102,126]. García-Valcárcel et al. (2025) [43] recently reported an NADES-based UA-MSPD followed by LC–MS/MS capable of simultaneously measuring various pesticides in pears. The ability to enrich multiple classes of compounds via ultrasonically enhanced microextraction and then detect them in one instrumental run is highly attractive for regulatory laboratories. For example, Yao et al. (2018) developed a UA-SEME with a magnetic IL combined with micro-solid phase extraction (μ SPE) using Fe_3O_4 nanoparticles, and subsequently introduced the concentrate into a graphite furnace AAS for Cd and Pb determination in edible oils [131]. Such hybrid strategies reduce manual handling, streamline sample preparation, and enhance the detection limits of trace metals [131]. In the near future, it is conceivable to have integrated devices in which an ultrasonic microextractor is built into the inlet of an LC or GC system, performing extraction *in situ* just before injection.

The trajectory of UAME development clearly indicates a more sustainable, efficient, and integrated approach. Several key areas will shape future applications. Solvent innovation continues with the increasing use of truly natural eutectic mixtures (e.g., NADES made from plant-derived components) and even switchable solvents that can alter polarity with a trigger to selectively extract targets [32,87]. Advances in sorbents are expected to focus on cost-effective and biodegradable materials. For instance, researchers are exploring sorbents derived from agro-waste or biopolymers that can perform as well as synthetic sorbents, but degrade benignly after use. Improving sorbent selectivity (through molecular imprinting or functionalization) is a parallel goal aimed at eliminating laborious cleanup steps and enabling direct analysis of extracts without extensive chromatography [41,165]. Ultimately, the combination of highly selective microextraction and a specific detector (such as a biosensor) could allow the measurement of certain contaminants in complex food matrices with minimal sample preparation [166,167].

Although comprehensive life cycle assessments (LCA) of UAME are still limited, existing studies have consistently highlighted its superior energy efficiency compared to conventional extraction methods. The reduced solvent consumption, shorter extraction times, and lower operating temperatures contribute to a smaller environmental footprint [31,49,52,138]. The reported energy savings reached 50–70% per analytical cycle owing to shorter extraction times (typically 3–7 min), reduced solvent volumes, and lower ultrasonic power requirements (30–60%) [32,40,119]. Moreover, temperature-switchable DES and sugar-based DES systems have demonstrated excellent green performance, as they facilitate efficient phase transitions without external dispersants, further decreasing energy input and waste generation [32,119]. These improvements, coupled with the absence of intensive centrifugation or heating, make UAME one of the most energy-efficient and sustainable extraction strategies currently available. Future life cycle assessments (LCA) integrating energy balance, solvent footprint, and waste minimization metrics are expected to further confirm the ecological and economic advantages of ultrasound-assisted microextraction.

Future developments may focus on hybrid systems that combine ultrasound with complementary green technologies such as microwave irradiation and deep eutectic solvents

(DES), thereby improving extraction kinetics, reducing solvent use, and enhancing matrix adaptability [113,151,168]. In parallel, advances in automation and sensor integration could enable the real-time monitoring of food contaminants at industrial scale, ensuring standardized and reliable analytical workflows.

In the future, the automation of UAME is expected to advance considerably. Such integration would not only streamline enrichment and cleanup steps but also reduce analysis time and minimize human error [165]. Moreover, the inherently small-scale and rapid nature of UAME makes it highly compatible with modern laboratory automation, and even adaptable to portable field devices designed for on-site contaminant monitoring. Integrating automated platforms can streamline enrichment and cleanup steps, dramatically reducing analysis time and human error [169,170]. Machine learning (ML) and AI will enable data-driven optimization of UAME parameters: for example, ML algorithms can analyze complex extraction data to predict optimal conditions, and AI-based models can provide real-time adaptive control of the extraction process [171]. These advancements lay out a clear roadmap for UAME: automated, intelligent workflows with ML-assisted optimization and AI-guided process design, implemented in miniaturized, portable devices. Indeed, the compact, rapid nature of UAME makes it ideal for field deployment, recent trends emphasize compact, portable analyzers that combine microextraction with on-board detection for on-site monitoring [158,169,171].

However, from a regulatory perspective, there are challenges to address before these emerging techniques are widely adopted in routine food safety monitoring. Regulatory agencies require robust validation of methods across diverse matrices and laboratories. Many UAME methods reported in the literature are proof-of-concept in single laboratories; moving toward standardization will require interlaboratory studies and perhaps collaborative efforts to draft official methods. The success of QuEChERS (a dispersive microextraction method) as an AOAC/ISO standard for pesticide residues underscores the importance of demonstrating versatility and reliability [172–174]. UAME could follow suit by proving its effectiveness for a broad array of analytes and foods under standardized conditions. Indeed, some UAME methods have already shown multiresidue capabilities [61,102,127], which is encouraging. Another regulatory consideration is ensuring that any novel solvents or materials used (e.g., DES components or nanoparticle sorbents) do not themselves introduce toxicity or interfere with analyte detection, a principle that is well in line with green chemistry [49,50,137]. Thus far, studies have indicated that carefully chosen NADES and biodegradable sorbents meet these criteria [45,137].

The use of UAME for food chemical contaminant analysis is exceedingly promising. Emerging technologies are making these methods faster, greener, and more compatible with modern analytical instruments and on-site testing requirements. Miniaturization and automation are expected to increase throughput and consistency, while integration with green solvents and advanced materials will continue to reduce environmental impact. Equally important, the principles of GAC guide these innovations, ensuring that future methods protect both consumer health and the ecosystem [17,41,53]. With ongoing research, UAME techniques are well positioned for the transition from academic research to routine practice. Their eventual inclusion in regulatory monitoring systems represents a substantial advancement in ensuring food safety through sustainable, modern analytical technology.

6. Limitations and Challenges

Although UAME techniques have emerged as rapid, efficient, and environmentally friendly approaches for sample preparation, numerous studies have consistently emphasized certain limitations that must be addressed before these methods can be universally adopted. Some of the advantages and limitations are presented in Table 7. One recurring

issue is the persistence of matrix effects and co-extractive interferences, particularly in complex biological or food substrates, such as milk [100,142,164], eggs [95], honey [85], fruit juices [82,138], chicken fat [89], and other lipid-rich or protein-rich samples. These interferences can lower recoveries, reduce enrichment factors, and compromise reproducibility, unless additional cleanup steps (e.g., dispersive SPE, immunoaffinity columns, or multistep workflows) are introduced.

Another common limitation is the nature and stability of extraction solvents. Although volatile organic solvents remain efficient, they conflict with the principles of green chemistry. DESs, hydrophobic DESs, and polymeric ILs have been proposed as greener alternatives; however, their universality across diverse matrices remains limited, and issues such as viscosity, phase separation efficiency, and possible analyte interactions can impair recovery [121,138,139,141]. Similarly, when nanostructured sorbents or magnetic nanogels are employed, their aggregation tendency and variable stability often require precise ultrasonic control and careful optimization to avoid efficiency loss [93,110,139].

Table 7. Advantages and Disadvantages of Ultrasound-Assisted Microextraction Methods (UAME) in Food Analysis.

Extraction Method	Advantages	Disadvantages
UA-LLME	Rapid mass transfer Minimal solvent High enrichment Simple setup	Emulsion separation can be difficult Heat can degrade analytes Choice of solvent is limited
UA-DLLME	Fast and efficient Uses little sample/solvent High enrichment	Requires phase separation Emulsions may trap analytes Risk of analyte loss with over-sonication
UA-EME	Fine emulsions efficiently extract hydrophobic/volatile compounds Extremely rapid and simple Low solvent uses	Less effective for highly polar analytes Phase separation can be slow Limited solvent compatibility
UA-SLME	Speeds extraction of solids Shorter time and less solvent Suitable for complex matrices	Needs post-extraction solid removal Dependent on particle size and mixing May miss strongly bound analytes
UA-D μ SPE	High efficiency Little sorbent/solvent needed Fast enrichment of trace analytes	Requires sorbent separation Limited sorbent capacity Optimization needed for each matrix
UA-SPME	Greatly reduces SPME time Solvent-free High sensitivity for volatiles/pollutants	Requires specialized fibers and desorption Fibers are fragile Single-sample processing
UA-CPE	Uses mild surfactants High enrichment Fast cloud formation	Requires heating and centrifugation Surfactant cleanup needed Risk of micelle disruption
UA-SEME	Safe surfactants Works for polar and non-polar analytes Quick dispersion	Surfactant removal needed Optimization can be time-consuming Matrix effects possible

Table 7. *Cont.*

Extraction Method	Advantages	Disadvantages
UA-ILME	Tunable selectivity Non-volatile and reusable solvents Broad polarity range	Ionic liquids can be expensive/toxic High viscosity slows extraction Requires solvent to remove IL phase
UA-MSPE	Magnetic separation simplifies cleanup High recovery and sensitivity Good for trace contaminants	Magnetic sorbents can be complex/costly Limited to analytes that bind sorbent Extra desorption step required
UA-MSPD	Integrates grinding, extraction, and cleanup Minimal solvent Rapid analyte release	Labor-intensive homogenization Reproducibility depends on uniform blending Requires matrix-specific optimization

In addition, while ultrasound significantly enhances analyte transfer and accelerates extraction, inconsistent outcomes can arise owing to variability in frequency, power, irradiation time, and temperature, sometimes even leading to analyte degradation in sensitive classes such as tetracyclines, sulfonamides, and macrolides [89,93,100,142]. Complex hybrid methods, such as reverse-USAEME, effervescent tablet-assisted DLLME, or aqueous two-phase combined with DLLME, have shown improved sensitivity and greener profiles, yet they introduce greater procedural complexity and potential analyte loss during multistep handling [89,121,136].

Even under optimized conditions, recoveries below 70% or RSDs above 15% have been reported for certain contaminants in difficult matrices, falling short of the EU SANTE or FDA validation guidelines [124,127,143]. Furthermore, although innovative strategies such as DES-ferrofluids, polymeric IL-based sorbents, and magnetic nanogels have broadened their applicability, these approaches often lack inter-laboratory validation, and their performance remains matrix- and analyte-dependent [93,95,139].

Collectively, these findings highlight that, while UAME represents a versatile and powerful tool for trace contaminant determination, its routine implementation in official monitoring programs will require (i) standardization of ultrasonic parameters, (ii) development of more universal and greener extractants, and (iii) systematic interlaboratory studies to ensure reproducibility and robustness across a wide spectrum of food and environmental samples.

7. Conclusions

UAME has emerged as a powerful and sustainable alternative to conventional extraction methods in food chemical contaminant analysis. Leveraging acoustic cavitation enables the efficient release of analytes from complex matrices while reducing solvent consumption, analysis time, and environmental impact. Its adaptability to different food types, various contaminants, and compatibility with advanced analytical platforms underscore its practical potential for regulatory monitoring.

The advantages of UAME extend beyond its speed and efficiency. Miniaturized solvent consumption reduces exposure to hazardous chemicals, while the use of green solvents such as NADES or biocompatible surfactants further minimizes environmental impact. Its versatility enables its application across diverse food matrices, including those that are particularly challenging due to their high fat, protein, or pigment content. UAME is also easily integrated with modern analytical platforms such as LC-MS/MS, GC-MS, and ICP-MS, supporting high-throughput and multiresidue workflows that are essential for regulatory compliance. Furthermore, the ultrasound-driven dispersion of sophisticated sorbents and nanomaterials, including magnetic nanoparticles, covalent organic frameworks, and molecularly imprinted polymers, opens the door for more sensitive and focused contaminant monitoring.

However, broader implementation requires further work. Standardization of protocols, validation across multiple laboratories, and refinement of green solvents and advanced sorbents are essential steps. Future directions include automation, integration with portable field devices, and the design of new extraction materials that enhance selectivity and robustness. In this way, UAME not only advances the reliability of food safety testing but also represents a model of how analytical chemistry can align efficiency with sustainability.

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