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Solid Phase Extraction as a Sample Preparation Technique

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ABSTRACT
Sample preparation is the process of extracting and concentrating targeted components or target compounds from complex mixtures to improve their suitability for subsequent separation, detection, and quantification. It plays a crucial role in analytical chemistry, given its direct effect on the accuracy, reactivity, as well as reliability of analytical results. Various sample preparation methods have evolved over time, such as liquid phase extraction method (L.P.E), liquid liquid extraction method (L.L.E), and liquid solid extraction method (L.S.E). Among these, solid phase extraction (S.P.E) has emerged as one of the most powerful and versatile techniques for rapid, selective, and efficient sample cleanup and analyte enrichment. SPE utilizes the solid sorbent as well as a liquid phase for isolating and purifying analytes, minimizing solvent use and reducing matrix interferences. Since its introduction in the 1940s and widespread adoption in the 1970s, SPE has evolved significantly, driven by advancements in sorbent materials and cartridge formats. Modern innovations such as mixed-mode SPE (MM-SPE) and solid phase micro extraction method (S.P.M.E) have further enhanced extraction efficiency, selectivity, as well as environmental sustainability. This review provides a comprehensive overview of sample preparation techniques with a primary focus on SPE covering its history, principle, mechanisms, and types along with its wide-ranging applications in environmental, pharmaceutical, biological, and food analysis. The continuous evolution of SPE technologies demonstrates its indispensable role in modern analytical workflows, bridging the gap between sample collection and precise instrumental analysis.

KEYWORDS: Sample Preparation, Solid-Phase Extraction (SPE), Solid-Phase Microextraction (SPME), Ion-Exchange Extraction (IEE), Reversed-Phase Extraction(RPE), Normal-Phase Extraction Mixed-Mode SPE, Analytical Chemistry, Sorbent Materials,Chromatographic Analysis.

I. INTRODUCTION

The process of separating and concentrating certain target compounds from different samples to improve their suitability for separation and detection is known as sample preparation. In order to prepare a sample for easy isolation, simple separation and detection later on, chemical protection, or molecular analysis the interesting analytes may need to undergo chemical modification. Sample preparation is essential for the unambiguous detection, verification and confirmation of analytes since it affects almost all subsequent assay stages. Generally speaking, a purified sample helps to enhance isolation and measurement whereas an improperly prepared sample could render the entire experiment incorrect. Using samples that have been properly cleaned also cuts down on instrument maintenance time, which lowers assay costs. This review seeks to organize the sample preparation methods in order to provide an overview of the area, with an emphasis on certain promising methods that have emerged and/or rapidly evolved in recent periods. These advanced methods aimed at such cell and particle preparation are just in short described, whereas tissues and organ form are often excluded. For reference, a few standards have been put out to assess or validate a technique for improved sample preparation of complex materials. It shows the method for completely preparing complex protein specimens (used in proteomics research) via polysaccharide fractions obtained from dehydrated herb sources (For reference purposes only).It contains various types of methods for example, extraction methods such as LPE, LLE, and LSE etc.[1]

Solid-phase extraction (SPE) is a sample preparation technique in which analytes are separated from a solution using interactions between a solid sorbent and a liquid phase. It is commonly applied to clean and prepare samples prior to chromatographic analysis or other quantitative methods.[3]SPE has become one of the most widely used approaches for rapid and selective sample preparation due to its flexibility and efficiency. This technique can serve multiple

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purposes, including purification, concentration of trace compounds, and removal of salts, derivatization, and fractionation of analytes. Over recent years, interest in SPE has grown significantly, leading to numerous studies and method developments. [4] The major surge in SPE research began in the late 1960s and continued into the early 1980s, driven by the creation of innovative sorbent materials. The incorporation of diverse adsorptive phases into analytical workflows greatly advanced the evolution and applicability of SPE methodology.[2]

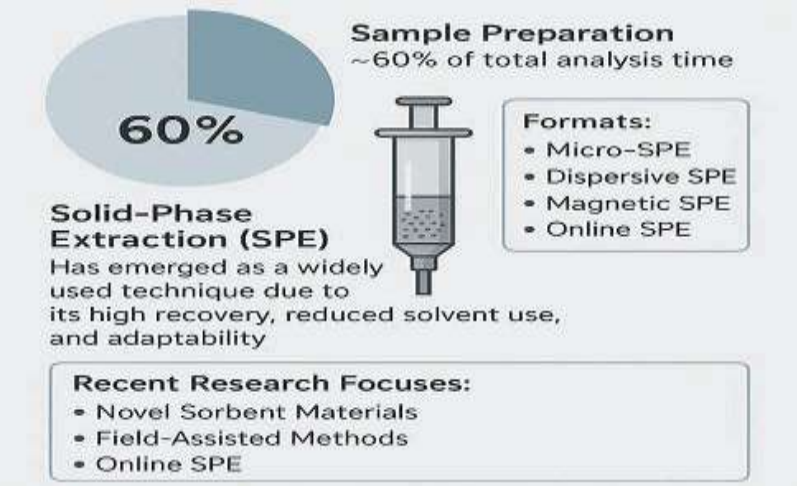

Fig.1 Sample preparation

HISTORY

The analysis of sample preparation (SP) can be dated to early days in analytical chemistry, at the time when scientists first began working with complex samples. Following the rapid advancements in analytical techniques after World War II, there was a growing demand for high-quality samples. This was particularly important as specimens obtained from natural sources, the human tissue and additional sources often featured complex sample matrices, preventing effective analysis without some form of pre-processing. In the context of liquid chromatography coupled with mass spectrometry (LC-MS), the sample matrix continues to present significant challenges. It can reduce the resolution of the chromatography, lower the ionization efficiency of mass spectrometry, increase measurement noise, finally affect detection limits. [1]

Solid phase extraction method (S.P.E.), which provides numerous benefits compared to conventional methods, was first introduced in the 1940s [5]and has grown rapidly in popularity since the 1970s. The earliest adsorbent used in SPE columns, animal charcoal, was employed to remove pigmented products of reactions. In the 1970s, SPE started to gain recognition in the form of legitimate analytical methods. Over the years, three distinct procedures involved in sample preparation have been established: 1968 to 1977, 1977 to 1989, and 1989 to the current. [7] In these periods, the popularity of adsorbent materials has increased, and technological innovations have resulted in the creation of new types as well as forms of sorbents. Early applications of SPE involved synthetic polymers such as styrene-divinylbenzene resins[8], which appeared in the initial publications on S.P.E. That initial investigative use of S.P.E, dating back to the 1950s, focused on analyzing organic trace substances in water. Many scientific papers have since been published, describing SPE as an effective method for quantifying organic compounds in water.[6,9]

A significant advancement in the development of SPE occurred in October 1977 with the use of pre-loaded cartridges or columns filled with silica-based sorbents, which simplified the procedure. This innovation marked the beginning of a new phase in SPE creation. As of May 1978, the method was featured in the covering laboratory equipment magazine. One of the initial published studies on S.P.E. using silicon sorb.[10]

PRINCIPLE

Solid-phase extraction is an extensively applied and efficient method for sample preparation in chemical analysis. It helps integrate sample collection with analytical methods by enabling effective pre-treatment of samples. In most cases,

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SPE is used alongside other preparatory steps, such as dilution or pH adjustment. [11,12] The method operates on principles similar to those of liquid–liquid extraction (LLE), as both rely on analyte partition across immiscible phases. However, unlike LLE, SPE does not involve the mixing of immiscible liquids. Instead, the analyte is distributed between the liquid sample and solid phase (that sorbent material). During the process, the liquid sample passes through the sorbent, where analytes are selectively retained due to their higher affinity for the solid phase. Those are then recovered via solvent-mediated elution (Fig. 2).

This approach simplifies analytical procedures by efficiently removing unwanted matrix components. Because of its simplicity, reduced solvent consumption, and time efficiency, SPE is now more commonly used for analyte preconcentration and matrix cleanup compared to LLE. In contrast, LLE is less effective for polar analytes, more labor-intensive, prone to emulsion formation, and requires the evaporation

and disposal involving considerable volumes of harmful solvents. As a result, S.P.E. has become the preferred sample preparation technique in multiple environmental and analytical uses and has served as integrated into standard analytical methods in recent years. Despite a few limitations, on-going innovations such as Methods including magnetic solid-phase extraction, solid-phase micro extraction, and kinetic adsorption extraction have addressed many of these challenges, further enhancing the performance and versatility of SPE technologies.[13]

The use of SPE in conjunction with chromatographic methods, particularly Liquid Chromatography and Gas C., further strengthens its role in analytical workflows. These developments have broadened its application across diverse fields, including pharmaceuticals, clinical and biological studies, natural product research, food and beverage analysis, pesticide monitoring, and environmental pollutant detection. Overall, SPE continues to evolve as a versatile and indispensable sample preparation technique, combining theoretical principles with practical advances for modern analytical science.[15]

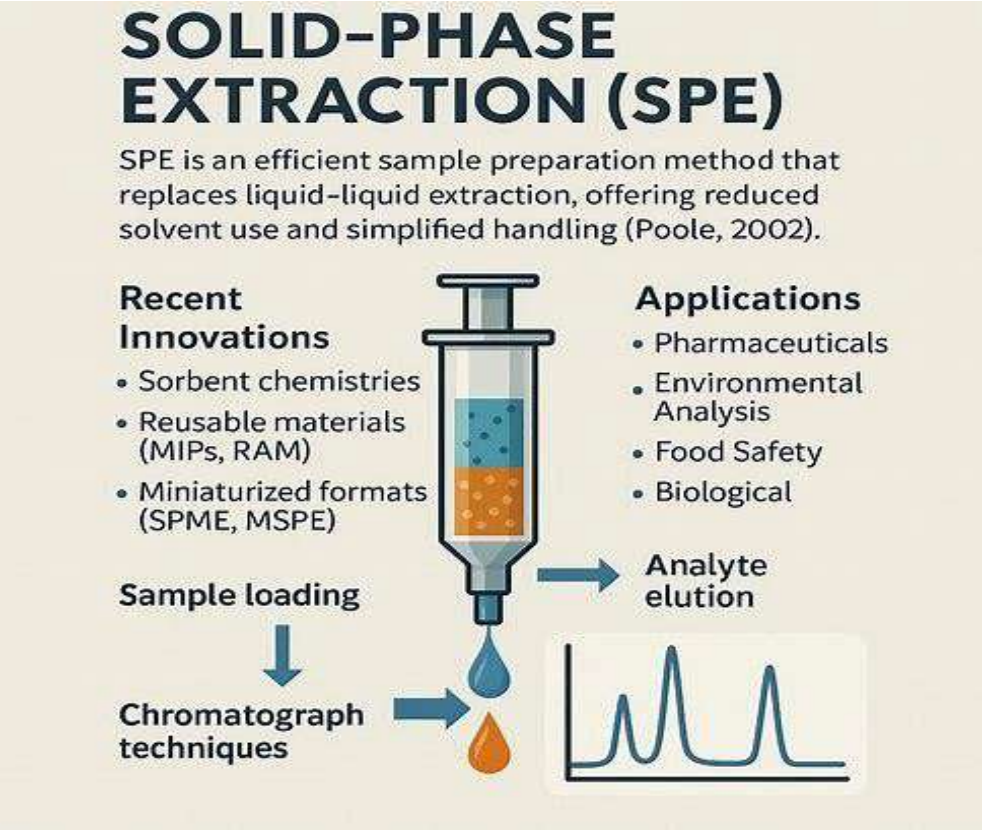

Fig.2 SPE Method

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TYPES OF SOLID PHASE EXTRACTION

Different mechanisms of analyte retention and the common procedural steps involved in solid-phase extraction (SPE) are outlined above.

Stationary phase Analytes Form	Sorbents Material	Functional group	Selected Analyte	Sovent conditioning	Wash	Solvent
Polar (Normal) Phase	Amine & Silica gel	Polar interaction &Absorption	Exhibits polar functiona-lities	Non-polar solvent (C6H14, CHCl3)	Nonpolar Solvent	Highly polar Solvent
Reverse Phase	Triacontyl & Octadecyl	Absorption	Slightly nonpolar	MeOH/ H2O	Polar Solvent	Strong nonpolar
Ion Exchange	Sulfonic	Absorption	Slightly nonpolar	Water/ Buffer	pH<pKa	Ionic buffer mobile phase

Table No.1 Mechanisms of analyte Retention

1. NORMAL-PHASE SPE (NPSPE)

Mechanism

Normal-phase solid phase extraction (NP S.P.E) was used for separate lower-molecular-weight charged compounds on the basis of type including position of their chemical moieties within uncharged sample substrates. This technique utilizes the highly hydrophilic phase, such as untreated silica, aluminum oxide, or magnesium silicate (Florisil), which acts as an adsorbent. Additionally, silica modified with hydrophilic groups like nitrile, dihydroxy, or amino functionalities can be used; these offer hydrophilic interactions with analytes through mechanisms like charge interactions, H+ bonding, π-π interactions, as well as dipole-dipole forces.NP S.P.E. are typically applied for isolating polar analytes from non-polar environments, where the smallest and most polar molecules tend to elute first. The extraction process based on both these polarity nature of the analytes as well as the existence of functional groups capable for interacting with the polar sorbent such as hydroxyl, amino, carbonyl, aromatic rings, double bonds, or heteroatom-containing groups (O, N, S, P).To ensure effective extraction, all components involved—sample matrix, conditioning solvent, equilibration solvent, and wash solvent—should be non-polar organic solvents. This prevents premature analyte loss during loading and rinsing steps. Finally, elution of target compounds is achieved using solvents with potent elution efficiency, e.g.,isopropanol (Ɛ° = 0.63) or methanol (Ɛ° = 0.73.[15]

Advantages:

Highly effective for polar compounds and useful for separating analytes from non-polar matrices.

Limitations:

Retention is sensitive to water, and non-polar analytes are poorly retained.

Applications:

Commonly applied for organic acids, amino acids, sugars, polar pharmaceuticals, and environmental analysis of polar pollutants.[2]

2. REVERSED-PHASE SPE (RPSPE)

Mechanism:

Reversed-phase solid-phase extraction (R.P-S.P.E.) used in hydrophobic sorbents to retain hydrophobic compounds from a polar matrix sample matrices using hydrophobic interactions including van der Waals interactions[14].The sorbents utilised in RP-SPE are typically silica-containing materials that were chemically treated with hydrophobic groups like C2, C4, C8, C18, C30, cyclohexyl, benzene, and cyano. Given the

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varying polarities of these sorbents, careful selection is essential. More polar sorbents like phenyl and cyano offer enhanced selectivity and require lower elution volumes, reducing the possibility of excessive drying. However, they may lead to premature elution while the wash step, necessitating application of a dilute washing solvent.In contrast, less polar sorbents provide broader analyte retention and allow stronger wash solvents to be used, but often require larger elution volumes and may not clean up the sample as efficiently. All hydrophobic sorbents must be conditioned with a polar organic solvent followed by aqueous solution or buffering agent. Extraction of non-polar analytes should be performed using non-polar solvents with adequate strength, while polar to semi-polar analytes are best eluted with a combination with an aqueous buffer and polar organic solvent that has the suitable elution strength (see Fig. 4).Recently, C30-bonded silica sorbents have emerged as advanced reversed-phase materials for both liquid chromatography and SPE. These sorbents are particularly effective for separating geometric isomers and enriching highly hydrophobic analytes from aqueous samples. Compared to C18, C30 sorbents offer longer alkyl chains for enhanced hydrophobicity, improved hydrolytic stability in aqueous environments, and larger particle sizes with ample surface area, resulting in higher adsorption capacity.[16]

Advantages:
Versatile, compatible with aqueous samples, and suitable for high-throughput workflows
Limitations:
Poor retention of highly polar or ionic analytes; derivatization may be required for very hydrophilic compounds.
Applications:
Extraction of hydrophobic compounds, including pesticides, steroids, lipids, and drugs from biological fluids.[2]

3. ION-EXCHANGE SPE (IEX-SPE)
Mechanism:

Charged polar solutes, such as acids and bases, may be effectively isolated from polar solvents such as water as well as moderately polar liquids via a technique referred to as ion exchange extraction (IX).[14,17] That method relies on strong interactions driven by charges between the analytes' functional groups and those present on the stationary phase material. Consequently, the selection of sorbent is determined by the electrical charge of the target compound (analyte).

Cationic-exchange (C.X.) columns are used to isolate basic compounds, such as 1^0,2^0& 3^0 amines . On the other hand, anion exchange (A.X.) columns are employed for extracting acidic compounds, including carboxyl acids, sulfonic acids, as well as phosphate groups. Based on the polar functional groups bound to their surfaces, both AX and CX materials are further divided into strong and weak ionic exchange materials.
Strong cation-exchange sorbents (SCXS) carry strongly low pH (acidic) groups like sulfonic acids, which remain ionized across the range of pH. Weak cation exchange sorbents (WCX) typically contain carboxylic acid Acidic groups that lose a proton at high pH but become uncharged (neutral) at low pH. Similarly, strong anion exchange sorbents (SAX) contain permanently charged groups such as quaternary ammonium, whereas weak anion exchange sorbents (WAXS) feature amine groups (1^0, 2^0, or 3^0) that are ionized lesser pH conditions and Non-ionized in alkaline conditions (see Tab.1).Proper sample preparation is essential for effective anion exchange solid phase extraction method (SPE). That sample may have a low ionic strength and a pH adjusted to favor the analyte's ionized form. For CX solid phase extraction, the pH may have lowered to about 2 units below this analyte's pKa using strong acid via a strong buffered solution while avoiding increased ionic strength. Conversely, for AX S.P.E., the pH must become raised two units higher than analyte's pKa with a base via appropriate buffering agent.

Before sample loading, the sorbent in SPE must first be conditioned and properly equilibrated to ensure it is in the correct ionized state to retain analytes. Conditioning istypically done with a mixture of a mixture of water with a water-miscible organic solvent, and then rinsed with water. Stabilization serves 2 main aims: (1) converting the associated ion on the sorbent into a form that can be easily readily replaced by the analyte, and (2) adjusting the pH to maintain the sorbent in its ionized state. This step can be performed with a saline (salt) solution or buffering agent.The efficiency of ion exchange depends on both the concentration and binding strength of the ions involved. In CX SPE, ions with higher charges and stronger affinities—such as Ba^{2+}, Pb^{2+}, Ag^{2+}, and Cu^{2+}—are preferred over monovalent or weakly binding ions.
The order of cation affinity typically follows:

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Ba^{2+}> Pb^{2+}> Ag^{2+}> Cu^{2+}> Fe^{2+}> Mg^{2+}> K^+ roughly equal to RNH_3^+> NH_4^+> Na^+>H^+.
H+(hydrogen) has their weakest binding tendency, which is why many sorbents are available in the H^+form. For AX SPE, ions with lower affinity include fluoride and hydroxide, while the order of anion affinity is as follows:
HSO_4^-> NO_3^-> HSO_3^-> NO_2^-> Br^-> Cl^-> HCO_3^-> HPO_4^-> $HCOO^-$> CH_3COO^-> F^-> OH^-.
It is also importantly to record that sample injection should be conducted slowly, as ion exchange SPE generally involves slower mass transfer kinetics compared to reverse-phase (RP) and normal-phase (NP) SPE techniques.[15]

Advantages:
Highly selective for ionic compounds and effective in cleaning complex matrices.
Limitations:
Requires precise pH control; salts or buffers in samples may interfere.
Applications:
Used for amino acids, peptides, nucleotides, ionic drugs, and metal ions in clinical and biochemical analyses.[2]

4.MIXED-MODE SPE (MM-SPE)

Mechanism:

Over the past decade, mixed-mode solid-phase extraction (SPE) has gained significant popularity due to its capability to incorporate hydrophobic and electrostatic interactions and ion-exchange a sorbent surface bearing ion exchange (IX) functionalities[3,18]. Hydrophobic groups can vary in chain length from short chains like C2, which offer high selectivity, to longer chains like C18, known for their strong retention. The ion-exchange sites can include cation-exchange (CX), anion-exchange (AX), or even a combination of both within the same sorbent. This technique is often favored because it allows consistent attachment of an individual chemical group onto the silica phase. Additionally, sorbents with various active groups can be blended in various ratios to fine-tune retention characteristics. Mixed-mode sorbents are especially useful for producing purified fractions from complex matrices. For effectively wash out the analytes bound through both hydrophobic and ion-exchange interactions, the elution solvent should contain non-polar components along with suitable buffers, acids, or bases[15].

Advantages:
Efficient for complex matrices and reduces cleanup steps.
Limitations:
Optimization is more complex due to solvent and pH requirements.
Applications:
Ideal for extracting Pharmacological substances and their metabolites of multiple Functional moieties in biological compounds samples and environmental monitoring of mixed-property analytes[2].

5.SOLID PHASE MICRO EXTRACTION (SPME)

Mechanism:

Solid phase micro extraction method (SPME), presented in 1990[20], is a solvent-free and environmentally friendly sample preparation method. It is sometimes mistaken for solid-phase extraction (SPE), but unlike SPE, SPME involves a non-exhaustive microextraction process where analytes reach Partition equilibrium of analytes between the fiber and sample. The technique uses Limited amount of sorbent, typically a Fused-silica fiber with a thin (7–100 μm) coating of a solid adsorbent otherwise immobilized polymer[19,21].SPME can be performed in three main modes:direct extraction, headspace SPME, and membrane-protected SPME techniques (see Figure 3).On both conventional extraction and vapor-phase modes, the sorbent fiber are coated with an adsorbent polymer. In the direct extraction mode, the fiber is immersed directly into that liquid the sample, enabling the analytes to be absorbed on these coating. In contrast, in headspace mode, the fiber was positioned over the sample to capture evaporating chemicals that help to minimize interference from large macromolecules. SPME using a protective membrane is currently the maximum used mode because the selective-access membrane shields that polymer coating from potential interference. SPME techniques can be carried out either manually or automatically and are often efficiently integrated with chromatographic analysis systems[15].

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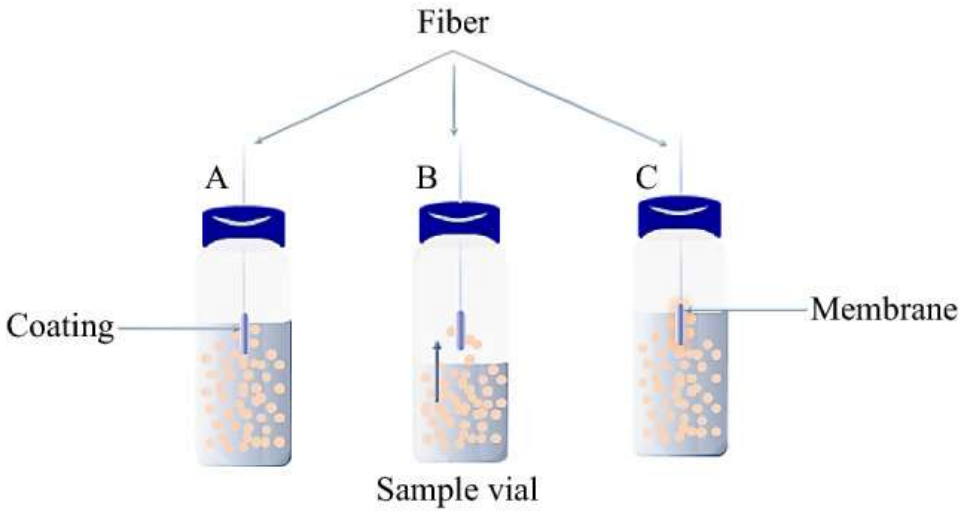

Fig.3 Different operational modes of SPME

Advantages:

Solvent-free, reduces chemical waste, minimal sample handling, and combines extraction with pre-concentration.

Limitations:

Limited capacity due to small fiber surface area; not ideal for high-concentration samples.

Applications:

Used for volatile and semi-volatile compounds in food, environmental, and forensic analysis.

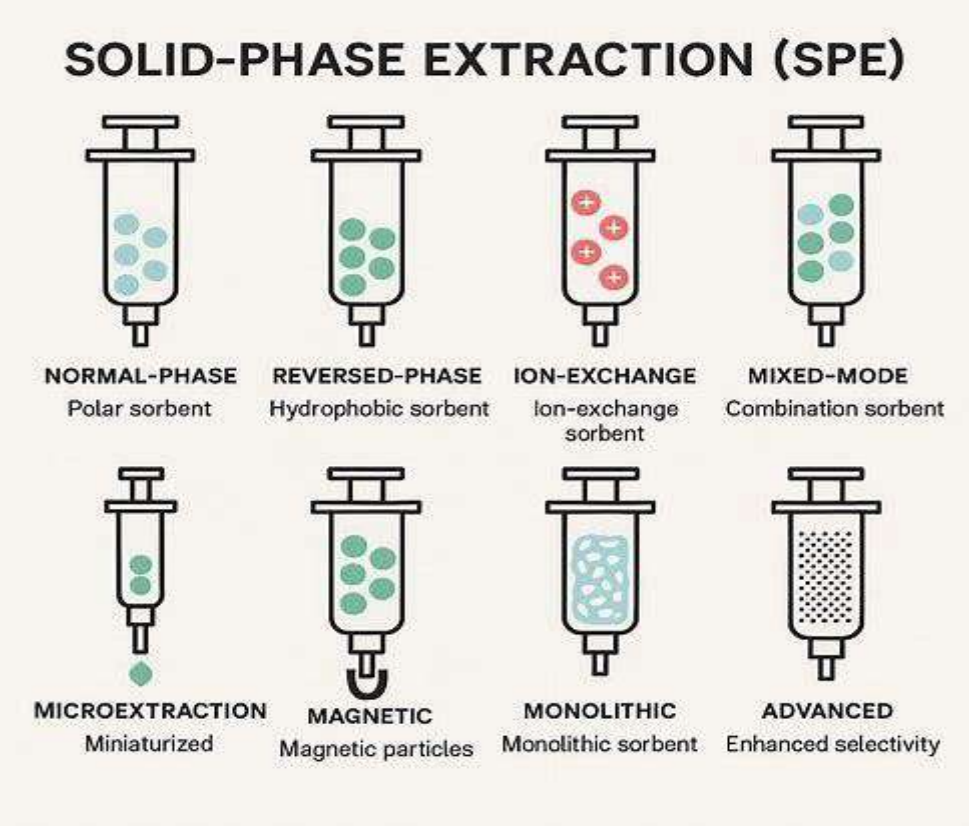

Fig.4 Types of SPE

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FORMAT AND MODES OF SPE

1. Cartridge

Typically, cartridges contain packing medium characterized by particle sizes of 40 to 60 µm. Conventional packed cartridges have some limitations, such as controlled flow rates as well as potential clogging regarding the uppermost frit when processing samples including suspended solids, like natural or treated water. For unfiltered samples, a common processed volume measures around 500 mL, though larger volumes can be handled if the sample is pre-filtered.Sizes of SPE cartridges vary from 1 mL to 50 mL, and choosing that optimal cartridge depends on factors such as analyte retention, sample volume, and the desired volume of purified eluate[22] . The sorbent is held between two frits made of cartridges made of glass or polypropylene, with components of either polyethylene or stainless steel which come in various column capacities. Cartridges have identified drawbacks applied to water examination, including small transverse areas that prolonged sample processing with minimal tolerance for particulate restriction, as well as channeling that can reduce analyte retention. Despite these issues, cartridges remain the most commonly used format due to the limited availability of sorbent disks[23].SPE cartridges are especially useful for pesticide residue analysis, as they often reduce the need for costly and environmentally sensitive solvents. In this application, pesticides are retained over the sorbent layer while matrix components flow through. These retained pesticides are washed out and subjected forfurther analytical estimation [2].

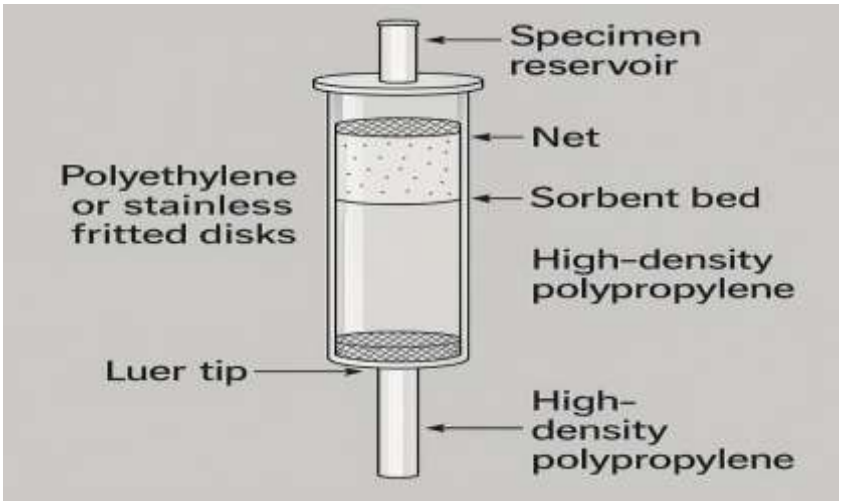

Fig. 5 Cartridge

2. DISCS

In recent years, disk-based designs have emerged as an alternative to traditional SPE cartridges. These disks consist of a thin membrane about 0.5 mm thick in which the sorbent is immobilized within a network of microfibrils. The sorbent material, whether silica or polymer-based, is embedded in a matrix of PTFE or glass fibers. Glass-fiber disks tend to be thicker and sturdier, which allows for higher flow rates compared to PTFE-based membranes. The particles contained within these disks are also much smaller than those in cartridges (approximately 8 µm instead of 40 µm)(see Fig. 6). Because of the shorter flow path and reduced particle size, disks can capture analytes efficiently even at comparatively high flow rates.

These membranes are especially useful for speeding up the processing of large volumes of aqueous environmental samples. The earliest commercial disk format was introduced by Empire. A notable drawback, however, is that disks exhibit lower breakthrough volumes, particularly for larger and more polar compounds. Therefore, they are most effective when the analyte exhibits strong retention on the sorbent phase. For context, a typical Empire disk has a plate height of about 0.1 mm, whereas a standard SPE cartridge usually has a bed height of around 1 cm.

A modified version of the extraction disk is the disk cartridge, available in diameters of 4 mm (1 mL), 7 mm (3 mL), and 11 mm (6 mL). In this format, the sorbent layer is housed inside a syringe-like plastic barrel and secured with

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retaining rings. The disk's high surface-area-to-mass ratio also makes it suitable for passive sampling applications, where the disk can be immersed directly into the sample rather than having the sample drawn through it like in a filtration setup. This passive sampling approach is advantageous for both field and laboratory use, although it has only been explored to a limited extent so far.[2]

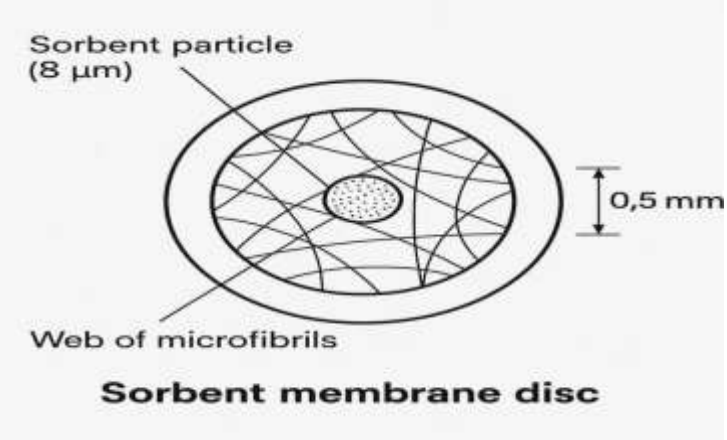

Fig.6 SPE Disc

3. MICRO-SPE TIPS

Atomizing solid phase extraction led to the development of latest forms including SPE pipette tips, which were first introduced in 1998.This technique offers a simple and rapid extraction method, where the sorbent is contained within a sampling tip and Retained by a mesh barrier. Unlike conventional SPE, no conditioning step is required since the stationary phase mixes directly with the sample. The sample flows to waste, sorbent is cleaned using a small volume of water or buffer,and analytes are extracted using only 0.1 to 0.3 mL in mobile phase, followed through vortex mixing and transfer to a GC or HPLC vial.The small elution volume eliminates the need for time-consuming concentration steps.[2]

Solid-phase extraction (SPE) pipette tips offer several advantages, including faster extraction times (1–2 minutes), the ability to use a single method for multiple analytes, cleaner extracts, reduced sample volume requirements (≈200 µL), lower solvent consumption (200–400 µL), and decreased chemical waste. Several companies have developed proprietary versions of these tips, such as Millipore's ZipTip and the DPX disposable pipette tips from EST Analytical. These products are designed for applications such as extracting abuse-related substances from limited urine or serum specimens. In these systems, the sorbent is lightly packed between two frits; the sample is drawn through and sent to waste, and the analytes are subsequently eluted with a small volume of solvent for downstream GC-MS analysis.[25]

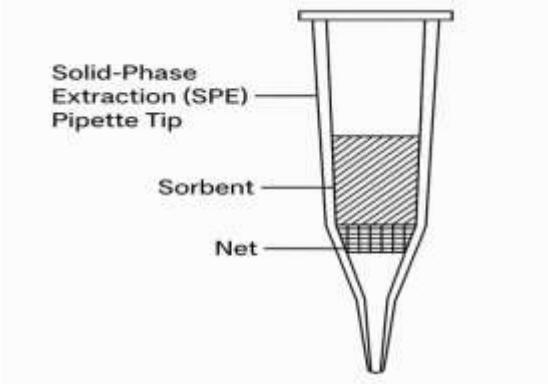

Fig. 7 SPE Pipette tips

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4. MULTI- WELL SPE PLATE

Microwell plates, usually referred to as Multi-well SPE plates are available in a variety of formats such as 96-cell (8×12), 384-well (16×24), and 1536-well (32×48) configurations. These plates are widely utilized for high-throughput sample processing in automated systems, often operated with vacuum manifolds. The introduction of the automated 96-well SPE workstation in 1996 marked a significant advancement in automating large-scale sample preparation[19]. Since then, robotic systems supporting 96, 384, & 1536-cell forms have become commercially available. Every individual cell contains a micro SPE cartridge (ranging from 0.65 to 2 mL), packed with a sorbent material (3–200 mg) secured between two frits. Multi-well SPE plates are categorized into fixed and flexible types. Fixed plates feature non-removable cartridges with set volumes and sorbent quantities, while flexible plates use detachable cartridges that snugly fit into a reusable plastic frame[12]. The widespread adoption of multi-well SPE formats has enhanced robotic sample and solvent handling, resulting in improved accuracy and consistency compared to manual techniques.[2]

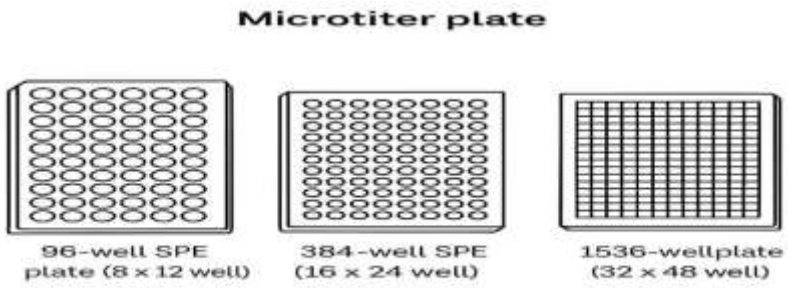

Fig .8 Multi-Well SPE Plate

STEPS IN SPE METHOD

This extraction method was developed around the late 1970s, although its initial experimental use dates back to the 1960s (Liška, 2000). The first cartridges appeared in 1978, followed by various Types of syringes used in 1979, & disposable SPE cartridges were launched around the-1980s (Anthemidis, Giakisikli, Xidia, & Miró, 2011). Up to that period, Liquid-Liquid extraction technique (LLE) continued to be The most frequently employed sample pretreatment method (Andrade-Eiroa, Canle, Leroy-Cancellieri, & Cerdà, 2016b).

Solid-phase extraction operates upon the principle about selectively retaining analytes on an An absorbing substrate (stationary phase) & then eluting them using a solvent with a stronger higher affinity for the analytes compared to the adsorbent (Frago-Ramos, 2016; Serrano de la Hoz, 2014).Fig. presents a typical diagram of the SPE process, which includes the below stages (Andrade-Eiroa et al., 2016b; Frago-Ramos, 2016).[24]

Fig.9 Steps in SPE method

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1. Conditioning along with equilibration of these cartridge

Previously introducing the sample, the cartridge is first treated with a strong solvent (such as methyl alcohol or acetyl nitrile) followed by an equal capacity of a weaker medium (such as H2O). That step minimizes interference and optimizes the active surface area of the cartridge for better analyte retention. [26]

2. Sample application

After conditioning, these samples are injected onto such SPE cartridges thereby the target analytes can be adsorbed onto the stationary phase. This process, along with elution, is considered one of the most crucial stages of the SPE procedure.[26]

3. Rinsing (Washing) step

After the analytes have been retained, the cartridge is rinsed with an aqueous wash to remove impurities or unwanted components that could interfere with the analysis.[26]

4. Elution of analytes

The retained analytes are then eluted from the cartridge using a highly non-polar solvent (e.g., pentane), dichloromethane, or acetic ester) which exhibits higher affinity toward the analytes compared to the stationary phase, ensuring their efficient recovery.[26]

NEW MATERIAL AND TREND IN SORBENTS

1. Surfactant-Modified Sorbents

When surfactant concentrations exceed the critical micellar concentration (CMC), the molecules self-assemble into micelle nanosized spherical structures in which the hydrophilic heads interact with the solvent and the hydrophobic chains orient inward. At levels slightly under the CMC, however, ionic surfactants are able to adsorb onto such surfaces of reactive solid supports such as aluminum oxide, silicon dioxide, titanium dioxide, and iron oxide compounds.[27]

2.Polymeric sorbents with combined retention mechanisms

Dual-phase, or integrated-form, sorbents represent a versatile category of extraction materials that can display either broad non-selectivity or high selectivity for target analytes,while maintaining strong adsorption efficiency within a single step.[28]Early designs were mainly based on silica containing ion-exchange functionalities, but current developments favor polymeric backbones. Depending on conditioning and operating conditions, these materials can function as ion exchangers by capturing charged species.[27]

3.Molecular Recognition Sorbents

Many biochemical interactions are governed by biomolecules with highly specific recognition abilities, capable of selectively binding to target compounds and initiating biological processes such as reactions or transport across membranes. Examples include antibodies (both monoclonal and polyclonal), as well as nucleic acids like DNA and RNA [29]. Such recognition systems, due to their intrinsic selectivity, can be reproduced in vitro for a variety of practical applications.[27]

Type of absorbent	Key features	Examples / Mechanism
Surfactant - modified Sorbents	Above CMC: form micelles Below CMC: surfactants adsorb on solid surfaces	Supports: alumina, silica, titania, iron oxides.
Mixed-mode polymeric sorbents	Dual-phase; can be non-selective or selective. High adsorption in one step.	**Early**: silica with ion-exchange. **Modern**: polymeric types; act as ion exchangers.
Molecular recognition sorbents	Highly specific binding; mimic biochemical recognition. Enable selective processes.	Antibodies (mono/polyclonal), DNA, RNA. Applied in vitro.

Table 2: New material and trends in sorbents

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II. APPLICATIONS

1. Food and beverage

Solid-phase extraction (SPE) has demonstrated strong performance techniques for isolating a broad range of volatile compounds from different food products through analytical testing.[30]Table 3 outlines several recent methods that utilize SPE to detect organic substances and heavy metals in food and beverages. Due to the complex nature of food matrices which may exist in solid, semi-solid, or liquid forms sample preparation plays a critical role in accurately identifying target compounds. SPE offers significant advantages for analyzing diverse food samples and supports advancements in analytical techniques. Its wide range of available sorbents makes it a highly suitable option for tailored preparation of food samples for analytical testing.[15]

2.Pesticides and environmental pollutants

Sample preparation is essential because contaminants are often present at very low concentrations within highly complex food matrices. These have superseded traditional liquid-liquid extraction methods due to its simplicity, ability to extract polar pesticides, shorter processing times, and reduced use of organic solvents. Pesticides and other agrochemicals are extensively used in both agricultural and non-agricultural settings. Various types of pesticides such as organochlorines (OCPs), organophosphates (OPPs), carbamates (CPs), phenyl ureas (PUPs), and pyrethroids (PPs) have been shown to be effective in controlling insects, fungi, and weeds.[15]

3. Pharmaceuticals drug along with other role

This extraction method (SPE) is commonly used alongside Chromatographic methods such as HPLC and GC for analyzing and ensuring the quality of these drugs throughout these manufacturing processes. Ensuring drug quality is a key objective for pharmaceutical companies. Quality verification about raw inputs, intermediates, as well as finished products involves such development of targeted tests as well as procedures. These also include conducting analyses, compiling data, and regularly reporting the findings to regulatory bodies. Throughout this process, the drug's identity, effectiveness, purification, and overall purity was consistently assessed as well as observed.[35]

Despite this, pharmaceuticals have increasingly been identified as developing environmental threats contaminants, detected within several ecosystems such as within wastewater, groundwater, soil matrices, and drinking water supplies typically in residue amounts ranging from nanograms to a few micrograms per liter.[36] These substances may enter the environment either in their original form or as metabolites, making it essential for monitoring efforts to track both primary compounds and their byproducts. Progress in analytical methods has greatly contributed to detecting Environmental occurrence of pharmaceuticals, their metabolic by-products, and transformation derivatives samples**.** Table 3 presents recent examples of SPE used for isolating and examining pharmaceutical substances across multiple environmental and biological matrices[15].

III. CONCLUSION

Sample preparation remains an indispensable component of analytical chemistry, ensuring accurate and reproducible measurements even when dealing with complex matrices. Among various extraction methods, SPE has established itself as the principal widely utilised & efficient method due to its adaptability, ease of automation, and reduced solvent consumption. The evolution of SPE from traditional normal and reversed-phase modes to ion-exchange, mixed-mode, and microextraction variants reflects ongoing innovation aimed at improving selectivity, speed, and environmental sustainability. Advances in sorbent materials, such as polymeric and nanostructured phases, have further expanded the applicability of SPE across diverse analytical domains. When properly optimized, SPE not only enhances analyte recovery and detection sensitivity but also reduces instrument maintenance and overall analytical cost. As analytical science continues to evolve, integrating SPE with advanced chromatographic and spectrometric systems will remain key to achieving rapid, precise, and green analytical workflows.

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