Nanoscale Materials for Instrumental Analysis of Mycotoxins

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With the continuous development of nanotechnology and materials science, a variety of nanoscale materials have been developed for purifying complex food matrices or providing response signals for accurate and rapid detection of various mycotoxins in foods. Mycotoxins are highly toxic, widely contaminated, and difficult to remove. They can enter and enrich the food chain through foodstuffs and animal-derived products such as meat, milk, and eggs and ultimately penetrate into organisms, causing reproductive abnormalities, immunosuppression, cancer, and other serious diseases, which pose a serious threat to human health.

mycotoxins nanoscale materials accurate and rapid detection food

1. Introduction

To date, food safety remains one of the major issues of widespread concern worldwide. The presence of toxic and hazardous substances in food is an important aspect that contributes to food safety problems [1][2]. Foods such as grains, oils, and fats are prone to contamination by fungi such as *Aspergillus*, *Penicillium*, and *Fusarium* at various stages, including production, processing, storage, and transportation [3][4][5]. Under conditions of high temperature and humidity, these microorganisms can produce and accumulate mycotoxins and secondary metabolites that serve as typical food contaminants. Mycotoxins are highly toxic, widely contaminated, and difficult to remove [6][7][8]. They can enter and enrich the food chain through foodstuffs and animal-derived products such as meat, milk, and eggs and ultimately penetrate into organisms, causing reproductive abnormalities, immunosuppression, cancer, and other serious diseases, which pose a serious threat to human health [9][10]. In addition, most fungi are capable of producing multiple toxins simultaneously, making the co-contamination of food with multiple toxins highly common. The cumulative or synergistic effects of these toxins can lead to more significant toxic effects than single toxins [11][12], further highlighting the importance of controlling and monitoring mycotoxins in food. Consequently, the World Health Organization (WHO), the European Food Safety Authority (EFSA), the Food and Agriculture Organization of the United Nations (FAO), and the Codex Alimentaria Commission (Codex Alimentaria) have jointly established limits and detection requirements for biotoxins, including mycotoxins [13][14] (**Table 1**). It is essential to strengthen the research on specific, sensitive, rapid, and reliable strategies for mycotoxins detection in food to safeguard human health effectively [15][16].

Table 1. Maximum permissible limits for mycotoxins in foods of different countries or organizations.

The United States	Total amount of AFB in food: <20 μg/kg; DON: <1000pg/kg, ZEN: <100 pg/kg; Milk and dairy products: AFM_1 ≤ 0.5 μg/kg.
European Union	Agricultural products: Total amount of AFs: <4 μg/kg, AFB_1: <2 μg/kg, OTA: <3 μg/kg, DON: <1000 μg/kg, ZEN: <50 μg/kg; Infant foods: Total amount of AFB: <2 μg/kg, AFB_1 <0.1 μg/kg, AFM_1: <0.025 μg/kg, OTA: <0.5 μg/kg, DON: <150 μg/kg, ZEN: <20 μg/kg
China	Corn, peanuts, and their products: AFB_1: < 20 μg/kg, OTA: <5 μg/kg, DON: <1000 μg/kg, ZEN < 60 μg/kg; Other grains, beans, and fermented foods: AFB_1: <5 μg/kg; Infant foods: AFB_1: 5 μg/kg, AFM_1: < 0.5μg/kg; Fresh milk and dairy products: AFM_1: < 0.5μg/kg; Rice and vegetable oils (except corn oil and peanut oil): AFB_1: <10 μg/kg.
Japan	Peanuts and their products: AFB_1: <10 μg/kg; Wheat: DON: <1100 μg/kg; Apple juice: Patulin: <50 μg/kg.

2. Nanoscale Materials for Instrumental Analysis of Mycotoxins

Currently, instrumental analysis techniques based on chromatographic separation, mass spectrometry, or spectroscopy remain the primary strategies for accurately detecting mycotoxins in food, widely accepted as standardized methods by international organizations [17][18][19]. Large-scale analytical instruments, typically equipped with sensitive detectors and data analysis modules, can successfully detect trace levels of toxin targets with advantages of accuracy, reproducibility, and reliability [20][21]. However, various mycotoxins may coexist at extremely low concentrations in food, and considering the complexity of food matrices, it is necessary to purify the food matrix during the detection process while achieving the enrichment of low-concentration mycotoxins to meet the requirements of instrument analysis [22]. In response to this challenge, novel purification materials with nanoscale features or exceptional structural characteristics have been continuously developed and used in combination with various large-scale analytical instruments, such as chromatography and mass spectrometry, achieving accurate and sensitive detection of mycotoxins in complex food matrices [23][24][25]. **Table 2** illustrates the application of various nanoscale materials in solid-phase extraction (SPE) and solid-phase microextraction (SPME) processes for the detection of mycotoxins in food.

Table 2. Application of various nanoscale materials in SPE and SPME processes for the detection of mycotoxin in food.

Materials/Methods	Mycotoxins	Substrates	Properties of Materials	Results	Ref.
SPE					
PDA-IL-NFsM SPE coupled with	AFB_1, AFB_2, AFG_1, AFG_2,	Corn, wheat	Various interception mechanisms with the target	Linear range: 1.0–	[26]

References

1. King, T.; Cole, M.; Farber, J.M.; Eisenbrand, G.; Zabaras, D.; Fox, E.M.; Hill, J.P. Food safety for food security: Relationship between global megatrends and developments in food safety. Trends Food Sci. Technol. 2017, 68, 160–175.
2. Fu, Y.H.; Yin, S.T.; Zhao, C.; Fan, L.H.; Hu, H.B. Combined toxicity of food-borne mycotoxins and heavy metals or pesticides. Toxicon 2022, 217, 148–154.
3. Medina, A.; Akbar, A.; Baazeem, A.; Rodriguez, A.; Magan, N. Climate change, food security and mycotoxins: Do we know enough? Fungal Biol. Rev. 2017, 31, 143–154.
4. Sharma, V.; Patial, V. Food mycotoxins: Dietary interventions implicated in the prevention of mycotoxicosis. ACS Food Sci. Technol. 2021, 1, 1719–1739.
5. Haque, A.; Wang, Y.H.; Shen, Z.Q.; Li, X.H.; Saleemi, M.K.; He, C. Mycotoxin contamination and control strategy in human, domestic animal and poultry: A review. Microb. Pathog. 2020, 142, 104095.
6. Ben Amara, A.; Menrez, A.; Ragoubi, C.; Romero-Gonzalez, R.; Frenich, A.G.; Landoulsi, A.; Maatouk, I. Fungal mycotoxins reduction by gamma irradiation in naturally contaminated sorghum. J. Food Process. Preserv. 2022, 46, e16345.

Materials/Methods	Mycotoxins	Substrates	Properties of Materials	Results	Ref.
UPLC-MS/MS	ST, FB_1, FB_2, OTA, ZEN, HT-2, T-2, DON, 3-AcDON, NIV, 15-AcDON		through hydrogen bonding, π-π interaction, and electrostatic or hydrophobic interaction; good simultaneous adsorption performance; significantly reducing the matrix effect	2000 μg/kg; LOD: 0.04–4.21 μg/kg; LOQ: 0.13–14.03 μg/kg; Recovery: 80.79–112.37 % (RSD: 2.91–14.82 %, *n* = 4)	
Fe_3O_4@COF Magnetic SPE coupled with UHPLC-MS/MS	AFB_1, OTA, ZEN, TEN, ALT, ALS, AME, AOH, TEA	Fruits	Abundant aromatic rings and carbonyl groups in Fe_3O_4@COF structure; through the strong π-π interaction and hydrogen bond between mycotoxin and Fe to realize effective enrichment of target mycotoxin	Linear range: 0.05–200 μg/kg; LOD: 0.01–0.50 μg/kg; LOQ: 0.10–1.00 μg/kg; Recovery: 74.25–111.75 % (RSD: 2.08–9.01 %, *n* = 5)	[27]
PDA@Fe_3O_4-MWCNTs Magnetic SPE coupled with HPLC-FLD	AFB_1, AFB_2, AFG_1, AFG_2, OTA, OTB	Edible vegetable oils	Good water solubility and dispersibility; largely eliminating the influence of matrix effect	Linear range: 1–100 μg/L; LOD: 0.2–0.5 μg/kg; LOQ: 0.6–1.5 μg/kg; Recovery: 70.15–89.25 % (RSD: ≤ 6.4 %, *n* = 6)	[28]
rGO/AuNPs SPE coupled with UHPLC-MS/MS	AFB_1, AFM_1, OTA, ZEA, α-ZOL, β-ZOL, ZAN, α-ZAL, β-ZAL	Milk	Good adsorbability; adding AuNPs increases the distance between graphene layers and minimizes agglomeration	Linear range: 0.02–200 ng/mL; LOD: 0.01–0.07 ng/mL; LOQ: 0.02–0.18 ng/mL; Recovery: 70.1–111.1 % (RSD: 2.0–	[29]

21. Fan, Y.Y.; Liu, F.J.; He, W.Z.; Qin, Q.M.; Hu, D.Q.; Wu, A.B.; Jiang, W.B.; Wang, C. Screening of multi-mycotoxins in fruits by ultra-performance liquid chromatography coupled to ion mobility quadrupole time-of-flight mass spectrometry. Food Chem. 2022, 368, 130858.

Materials/Methods	Mycotoxins	Substrates	Properties of Materials	Results	Ref.
				11.1 %, *n* = 5)	
MIL-101(Cr)@Fe_3O_4 Magnetic SPE coupled with UHPLC-MS/MS	AFB_1, AFB_2, AFG_1, AFG_2, OTA, OTB, T-2, HT-2, DAS	Maize, wheat, watermelon, and melon	Magnetic separation and adsorption capabilities involving polar or nonpolar forces, hydrogen bonding forces, and π-π conjugation with mycotoxin-rich functional groups	Linear range: 0.2–100 ng/mL LOD: 0.02–0.06 μg/kg; LOQ: 0.08–0.2 μg/kg Recovery: 83.5–108.5 % (RSD: 1.6–10.4 %, *n* = 5)	[30]
Fe_3O_4@SiO_2-NH_2 Magnetic SPE coupled with ELISA	AFB_1	Pixian douban	Rapid separation and enrichment under the external magnetic field; strong chemical stability, storage stability, and specificity combined with aptamer	Linear range: 0.5–2.0 ng/mL; LOD: 0.17 ng/mL; LOQ: 0.48 ng/mL; Recovery: 80.19–113.92 % (RSD: 2.30–7.28 %, *n* = 3)	[31]
HAS SPE coupled with HPLC-PHRED-FLD	AFB_1	Vegetable oils	Outstanding adsorption properties due to the large number of functional group hydrogen bonding, hydrophobicity, and π-π interactions; minimizing the pretreatment time and the amounts of organic solvents	Linear range: 0.10–50 μg/kg; LOD: 0.03–0.09 μg/kg; LOQ: 0.1–0.3 μg/kg; Recovery: 66.9–118.4 % (RSD: ≤ 7.2 %, n = 6)	[32]
UIO-66-NH_2@MIPs SPE coupled with HPLC	AFB_1, AFB_2, AFG_1, AFG_2	Wheat, rice, corn, soybean	Uniform and stable; the unique pore structure effectively improving the selective adsorption capacity; excellent affinity and selectivity	Linear range: 0.20–45 μg/kg; LOD: 0.06–0.13 μg/kg; LOQ: 0.24–0.45 μg/kg;	[33]

Determination of aflatoxin B1 in Pixian Douban based on aptamer magnetic solid-phase extraction. RSC Adv. 2022, 12, 19528–19536.

Materials/Methods	Mycotoxins	Substrates	Properties of Materials	Results	Ref.
				Recovery: 74.3–98.6 % (RSD: 1.0–5.9 %, n = 6)	
MWCNT-COOH + C_{18} SPE coupled with UPLC-MS/ MS	21 mycotoxins (AFs, OTA, OTB, ZEN, T-2, ZEN et al.)	Corn, wheat	Significantly reducing the matrix effect; high-throughput screening of various targets; greatly improving the detection efficiency	LOQ: 0.5–25 μg/L; Recovery: 75.6–110.3 % (RSD: 0.3–10.7 %, n = 5)	[34]
HNTs-HMIPs SPE coupled with HPLC-FD (**Figure 1**a)	ZEN	Rice corn, red beans, oats, wheat	Hollow imprinted polymer; excellent adsorption due to the loose and porous characteristics	LOD: 0.5 μg/kg; LOQ: 4.17 μg/kg (Oat), 1.8 μg/kg (Wheat); Recovery: 77.13–102.4 % (RSD: ≤ 5.59 %, n = 6)	[35]
SPME					
AuNPs SPME coupled with UHPLC-MS/MS	PAT	Apple juice, fresh apple, apple baby food, orange juice	Capillary monolithic column directly modified by AuNPs; high specificity and high affinity	Linear range: 8.11–8.11 × 10^3 pmol/L; LOD: 2.17 pmol/L; Recovery: 85.4–106 % (RSD: 4.1–7.3 %, n = 5)	[36]
MAA-co-DVB SPME coupled with HPLC	AFB_1, ZEN, STEH	Rice	High-strength micro/nanostructure containing a large number of acrylic groups forming hydrogen bonds with groups in the target structure; effectively overcoming the matrix effect	Linear range: 0.01–1.0 mg/kg; LOD: 0.689–2.030 μg/kg; LOQ: 5.36–14.4 μg/kg Recovery: 86.0–102.8 % (RSD: ≤ 4.8 %, n = 4)	[37]

41. Madikizela, L.M.; Ncube, S.; Chimuka, L. Recent developments in selective materials for solid phase extraction. Chromatographia 2019, 82, 1171–1189.

Materials/Methods	Mycotoxins	Substrates	Properties of Materials	Results	Ref.
Fe_3O_4@SiO_2@Cu/Ni-NH_2BDC Dispersive SPME coupled with HPLC-FLD	AFB_1, AFB_2, AFG_1, AFG_2	River water, well water, rice	Chemical bonds formed between three components making the adsorbent more stable and magnetic; rapid separation	Linear range: 0.11–79.2 ng/mL; LOD: 0.01–0.04 ng/mL; LOQ: 0.04–0.15 ng/mL; Recovery: 92.0–97.8 % (RSD: 4.1–7.6 %)	[38]
MOF+VB_3 Dispersive SPME coupled with HPLC-FLD	PAT, OTA, AFB_1, AFB_2, AFG_1, AFG_2	Fruit juices, milk	Green organic linker; high surface area, high adsorption capacity, and excellent porosity to form a new green adsorbent	Linear range: 42.8–1 × 10^6 ng/L; LOD: 11.3–48.2 ng/L; LOQ: 42.8–161.6 ng/L; Recovery: 64.0–87.0 % (RSD: ≤5 %, n = 3)	[32]

adsorbent has outstanding adsorption properties due to the large number of functional groups, hydrogen bonding, hydrophobicity, and π-π interactions, which minimize the pretreatment time and the amounts of organic solvents. It can efficiently and stably adsorb two targets from the lipid matrix and obtain accurate detection results (limits of quantification (LOQs), 0.05–0.30 μg kg^{-1}, limits of detection (LODs), 0.01–0.09 μg kg^{-1}). Compared with a single type of SPE material, the composite SPE material composed of multiple nanoscale materials can combine the advantages of various materials in a targeted manner. This not only helps to improve the purification efficiency but also significantly improves the selectivity of the target compound. Especially in high-throughput, multi-target mycotoxin detection, composite SPE materials have obvious advantages. Wang and his team compared the performance of composite SPE materials composed of different types and dosages of multi-walled carbon nanotubes (MWCNTs) and five different typical adsorbents (i.e., octadecylsilyl (C_{18}), hydrophilic–lipophilic balance (HLB), mixed-mode cationic exchange (MCX), silica gel, and amino-propyl (NH_2)) in purifying corn and wheat matrices extracted by the total of 21 mycotoxins [34]. The combination of MWCNTs (20 mg) and C_{18} (200 mg) was demonstrated to be the most effective, significantly reducing the matrix effect, enabling the high-throughput screening of various mycotoxins, and greatly improving the detection efficiency. The study of Han et al. combined carbon-based nanomaterial graphene (rGO) with stable chemical properties, a high specific surface area, and a strong adsorption capacity with gold nanoparticles (AuNPs), which effectively overcame its irreversible aggregation problem in solution [29]. Compared with commercial SPE materials, their novel nanoadsorbent rGO/AuNPs showed comparable or even better adsorption and purification effects at a lower cost. A satisfactory linear quantification range (0.02–0.18 ng mL^{-1}, R^2 ≥ 0.992) was obtained for nine mycotoxins in milk in combination with ultra-performance liquid chromatography–tandem mass spectrometry (UPLC-MS/MS) analysis, which laid the foundation for the further development of an effective method for high-throughput and rapid screening of multi-mycotoxins. Although such nanoscale composite SPE materials have largely enhanced the purification and detection rates, they are not specific enough to accurately purify or enrich for a single mycotoxin. Therefore, the

PDA-IL-NFsM, polydopamine and ionic liquid bifunctional nanofiber mat; HNTs-HMIPs, halloysite nanotubes hollow molecularly imprinted polymers; ST, sterigmatocystin; FB_1, fumonisin B_1; HT-2, HT-2 toxin; T-2, T-2 toxin; NIV, nivalenol; 3-AcDON, 3-acetylated deoxynivalenol; 15-AcDON, 15-acetylated deoxynivalenol; TEN, tentoxin; ALT, altenuene; ALS, altenusin; AME, alternariol monomethyl ether; AOH, alternariol; TEA, tenuazonic acid; ZEA, zearalenone; α-ZOL, α-zearalenol; β-ZOL, β-zearalenol; ZAN, zearalanone; α-ZAL, α-zearalanol; β-ZAL, β-zearalanol; OTB, ochratoxin B; [illegible]; STEM, sterigmatocystin; OTA, ochratoxin A.

based solid-phase extraction for effective pre-concentration of highly toxic metal ions from food and water samples. Appl. Organomet. Chem. 2018, 32, e4012.

48. Chao, Y.H.; [illegible] Graphene-like BN/SiO2 nanocomposites as efficient sorbents for solid-phase extraction of Rhodamine B and Rhodamine 6G from food samples. Food Chem. 2020, 320, 126666.

49. BelBruno, J.J. Molecularly imprinted polymers. Chem. Rev. 2018, 119, 94–119.

50. Dong, C.Y.; Shi, H.X.; Han, Y.R.; Yang, Y.Y.; Wang, R.X.; Men, J.Y. Molecularly imprinted polymers by the surface imprinting technique. Eur. Polym. J. 2021, 145, 110231.

51. Bui, B.T.S.; Auroy, T.; Haupt, K. Fighting antibiotic-resistant bacteria: Promising strategies orchestrated by molecularly imprinted polymers. Angew. Chem. Int. Ed. 2022, 61.

52. Ashley, J.; Shahbazi, M.A.; Kant, K.; Chidambara, V.A.; Wolff, A.; Bang, D.D.; Sun, Y. Molecularly imprinted polymers for sample preparation and biosensing in food analysis: Progress and perspectives. Biosens. Bioelectron. 2017, 91, 606–615.

53. Villa, C.C.; Sanchez, L.T.; Valencia, G.A.; Ahmed, S.; Gutierrez, T.J. Molecularly imprinted polymers for food applications: A review. Trends Food Sci. Technol. 2021, 111, 642–669.

54. Song, Z.H.; Li, J.H.; Lu, W.H.; Li, B.W.; Yang, G.Q.; Bi, Y.; Arabi, M.; Wang, X.Y.; Ma, J.P.; Chen, L.X. Molecularly imprinted polymers based materials and their applications in chromatographic and electrophoretic separations. TrAC Trends Anal. Chem. 2022, 146, 116504.

development of pretreatment materials that are both efficient and specifically recognized for the extraction of mycotoxins from food products is of great importance.

Molecularly imprinted polymers (MIPs) are a class of chemically synthesized materials with the specific recognition capability to target molecules, which are called “artificial antibodies (Abs)” [49][50][51]. Due to the remarkable stability and selectivity, MIPs have been widely used as sorbents for the extraction of various chemical substances [52][53][54]. Dalibor’s team compared the prepared MIPs with selective recognition and binding sites for zearalenone (ZEN) with the non-selective reversed-phase C_{18} extractant and evaluated the difference in the analytical characteristics of the two extractants during the extraction process [55]. Due to the use of online SPE, the two detection strategies based on the high-performance liquid chromatography (HPLC) of MIPs or C_{18} absorbents established in this study overcame the drawbacks of time-consuming and manual sample pretreatment in ZEN detection. Unfortunately, the two SPE detection strategies were similar in terms of linear range, sensitivity, reproducibility, and even no significant difference in specificity identification, which was inferred to be caused by the strong affinity of the esterophilic target ZEN on the C_{18} sorbent. Metal–organic frameworks (MOFs) are a class of crystalline materials formed by the coordination of metal ions or clusters with organic ligands [56][57]. They are characterized by a high specific surface area, large porosity, ease of synthesis, thermal stability, and tenability [58][59]. Liang’s team attached MIPs to the surface of MOF material UiO-66-NH_2 via the precipitation aggregation method as an adsorbent for SPE, which was used for the adsorption and quantification of aflatoxins (AFB_1, AFB_2, AFG_1, and AFG_2) in grains, and the adsorption capacity was compared with that of commercial SPE [33]. In this study, the surface of UIO-66-NH_2 was modified by grafting glycidyl methacrylate (GMA), which effectively preserved the interaction between the monomer and the virtual template and formed hydrogen bonding sites. The prepared novel surface-imprinted polymer materials were uniform and stable, and the unique pore structure could effectively improve the selective adsorption capacity of polymer materials. Secondly, due to the large specific surface area of MOFs and the high specificity of MIPs, it shows excellent affinity and selectivity for aflatoxins, and it is a rapid, cheap, efficient, and reusable method. Unfortunately, although the problem of high cost and high toxicity of the target as a template has been solved, it still fails to selectively adsorb a single target substance.

Magnetic SPE is a new SPE method that has attracted extensive attention in the field of separation science because of its convenient, rapid, and efficient adsorption separation in a magnetic field [60][61]. Magnetically functionalized nanomaterials, such as metal oxides, polymers, and organic frameworks are used in enrichment and separation processes for different targets [62][63][64]. Covalent organic frameworks (COFs) are a new type of crystalline material with the advantages of a large specific surface area, high porosity, abundant functional groups, and good thermal and chemical stability [65][66]. They can be combined with magnetic nanoparticles to increase pretreatment extraction materials’ porosity and specific surface area. In the study of Nie et al. [27], a magnetic COF nanomaterial Fe_3O_4@COF (TAPT-DHTA) was prepared via a simple template precipitation polymerization method, which was applied to simultaneously enrich nine mycotoxins in fruits. Combined with the analysis of ultrahigh-performance liquid chromatography in combination with tandem mass spectrometry (UHPLC-MS/MS), a wide linear range (0.05–200 μg kg^{-1}) and a low LOD (0.01–0.5 μg kg^{-1}) for nine targeted mycotoxins were achieved. Notably, the Fe_3O_4@COF adsorbent prepared in the study was rich in aromatic rings and carbonyl groups and, thus, can effectively enrich the target toxins through strong π-π interactions and hydrogen bonding. Zhang et al. [67]

55. Lhotská, I.; Gajdosová, B.; Solich, P.; Satinsky, D. Molecularly imprinted vs. reversed-phase extraction for the determination of zearalenone: A method development and critical comparison of sample clean-up efficiency achieved in an on-line coupled SPE chromatography system. Anal. Bioanal. Chem. 2018, 410, 3265–3273.
56. Razavi, S.A.A.; Morsali, A. Linker functionalized metal-organic frameworks. Coord. Chem. Rev. 2019, 399, 213023.
57. Hu, M.L.; Masoomi, M.Y.; Morsali, A. Template strategies with MOFs. Coord. Chem. Rev. 2019, 387, 415–435.
58. Hu, Y.L.; Dai, L.M.; Liu, D.H.; Du, W.; Wang, Y.J. Progress & prospect of metal-organic frameworks (MOFs) for enzyme immobilization (enzyme/MOFs). Renew. Sust. Energ. Rev. 2018, 91, 793–801.
59. Wang, D.G.; Liang, Z.B.; Gao, S.; Qu, C.; Zou, R.G. Metal-organic framework-based materials for hybrid supercapacitor application. Coord. Chem. Rev. 2020, 404, 213093.
60. Barreto, I.S.; Andrade, S.I.E.; Cunha, F.A.S.; Lima, M.B.; Araujo, M.C.U.; Almeida, L.F. A robotic magnetic nanoparticle solid phase extraction system coupled to flow-batch analyzer and GFAAS for determination of trace cadmium in edible oils without external pretreatment. Talanta 2018, 178, 384–391.
61. Hamidi, S. Recent advances in solid-phase extraction as a platform for sample preparation in biomarker assay. Crit. Rev. Anal. Chem. 2023, 53, 199–210.
62. Maya, F.; Cabello, C.P.; Frizzarin, R.M.; Estela, J.M.; Palomino, G.T.; Cerdà, V. Magnetic solid-phase extraction using metal-organic frameworks (MOFs) and their derived carbons. TrAC Trends Anal. Chem. 2017, 90, 142–152.
63. Soylak, M.; Ozalp, O.; Uzcan, F. Magnetic nanomaterials for the removal, separation and preconcentration of organic and inorganic pollutants at trace levels and their practical applications: A review. Trends Environ. Anal. Chem. 2021, 29, e00109.
64. Salve, S.; Bahiram, Y.; Jadhav, A.; Rathod, R.; Tekade, R.K. Nanoplatform-integrated miniaturized solid-phase extraction techniques: A critical review. Crit. Rev. Anal. Chem. 2023, 53, 46–68.
65. Lohse, M.S.; Bein, T. Covalent organic frameworks: Structures, synthesis, and applications. Adv. Funct. Mater. 2018, 28, 1705553.
66. Tran, Q.N.; Lee, H.J.; Tran, N. Covalent organic frameworks: From structures to applications. Polymers 2023, 15, 1279.
67. Li, J.; Xu, X.L.; Guo, W.; Zhang, Y.; Feng, X.S.; Zhang, F. Synthesis of a magnetic covalent organic framework as sorbents for solid-phase extraction of aflatoxins in food prior to quantification by liquid chromatography-mass spectrometry. Food Chem. 2022, 387, 132821.

designed an efficient magnetic COF sorbent using two monomers of 1,2,4,5-tetrakis-(4-formylphenyl) benzene (TFPB) and p-phenylenediamine (PPD) at room temperature. The adsorption capacities for AFs ranged from 69.5 to 92.5 mg/g under the optimized conditions, the SPE extraction efficiency was enhanced, saving both time (5 min) and organic reagent (2 mL), and satisfactory results for AF detection in food matrices (milk, edible oil, and rice) were obtained. The magnetic COF sorbent can be reused more than eight times. Wei et al. [68] developed a vortex-assisted magnetic SPE method, using a core–shell structured magnetic covalent organic skeleton (FeO/COF-TpBD) as the adsorbent for rapid and simultaneous extraction of ten mycotoxins commonly found in maize. The prepared magnetic adsorbent was demonstrated to have the advantages of strong magnetism and good stability, which also obtained high sensitivity (LOD: 0.02–1.67 μg kg^{-1}) and recovery (73.8–105.3%). Furthermore, the adsorbent dosage (5 mg) and required time (0.5 min each for adsorption and desorption) were greatly shortened compared with previous reports. Due to the complexity of the food matrices and the rapid consumption of food, magnetic SPE sorbents are required to have good chemical stability, strong dispersion ability, and a high affinity for mycotoxins. These attributes are crucial for ensuring the efficiency and reproducibility of magnetic SPE purification process. Therefore, magnetic SPE adsorbents used for food matrices' purification are typically designed as core–shell structures. That means functionalizing the surface of the magnetic core to form a specific recognition shell with high affinity for the targets. The preparation of such core–shell magnetic SPE adsorbents involved multiple complex steps, leading to significant batch-to-batch variations, which limited the widespread application of these materials to some extent. Additionally, the magnetic properties may decrease after multiple modifications on the surface of magnetic nanoparticle core, directly affecting the efficiency of adsorption and separation. Therefore, it is necessary to develop magnetic SPE materials that are easy to prepare, possess stable magnetic properties, and exhibit a high affinity for the target compounds.

3.2. Absorbent for SPME

In contrast to traditional SPE technology, SPME greatly simplifies the analytical operation procedure, reduces the extraction time, and enhances the extraction efficiency, and it has been emphasized in food detection [69][70][71]. Nanomaterial-based novel solid-phase adsorbent materials possess a larger specific surface area, suitable pore size, and surface structure, along with excellent adsorption and mechanical properties [72][73]. These features enable the highly selective adsorption of target analytes in complex matrices, showing great potential for application in SPME [74]. This provides crucial support for the rapid and highly sensitive detection of mycotoxins.

Gold nanoparticles (AuNPs) are composed of nanoscale gold atoms (1–100 nm), which not only have unique optical, electrical, and excellent surface enhancement properties but also have a high specific surface area. AuNPs can be used as the carrier of Abs, aptamers, and other specific recognition molecules, making them the most commonly used material in the field of food detection [75][76][77]. Wang et al. proposed an innovative approach for the facile and controllable preparation of an aptamer-functionalized capillary monolithic polymer hybrid, which achieved high specificity and high affinity for the determination of patulin in food samples [36]. AuNPs with patulin aptamers were directly modified via Au-S bonds on capillary monolithic columns. These aptamer-functionalized capillary monomer–polymer hybrid materials were applied as the SPME adsorbent combined UPLC-MS/MS to achieve very high sensitivity and selectivity for patulin, with an LOD of 2.17 pmol L^{-1} and linear range of 0.0081–

68. Wei, D.; Pan, A.; Zhang, C.; Guo, M.; Lou, C.Y.; Zhang, J.; Wu, H.Z.; Wang, X. Fast extraction of aflatoxins, ochratoxins and enniatins from maize with magnetic covalent organic framework prior to HPLC-MS/MS detection. Food Chem. 2023, 404, 134464.

69. Liu, S.Q.; Huang, Y.Q.; Qian, C.Y.; Xiang, Z.M.; Ouyang, G.F. Physical assistive technologies of solid-phase microextraction: Recent trends and future perspectives. TrAC Trends Anal. Chem. 2020, 128, 115916.

70. Delinska, K.; Rakowska, P.W.; Kloskowski, A. Porous material-based sorbent coatings in solid-phase microextraction technique: Recent trends and future perspectives. TrAC Trends Anal. Chem. 2021, 143, 116386.

71. Zambonin, C.; Aresta, A. Recent applications of solid phase microextraction coupled to liquid chromatography. Separations 2021, 8, 34.

72. Reinholds, I.; Jansons, M.; Pugajeva, I.; Bartkevics, V. Recent applications of carbonaceous nanosorbents in solid phase extraction for the determination of pesticides in food samples. Crit. Rev. Anal. Chem. 2019, 49, 439–458.

73. Dal Bosco, C.; De Cesaris, M.G.; Felli, N.; Lucci, E.; Fanali, S.; Gentili, A. Carbon nanomaterial-based membranes in solid-phase extraction. Microchim. Acta 2023, 190, 175.

74. Hou, F.Y.; Chang, Q.Y.; Wan, N.N.; Li, J.; Zang, X.H.; Zhang, S.H.; Wang, C.; Wang, Z. A novel porphyrin-based conjugated microporous nanomaterial for solid-phase microextraction of phthalate esters residues in children's food. Food Chem. 2022, 388, 133015.

75. Chen, M.; Zhou, X.; Zhao, G.H. Gold nanoparticles: From synthesis, properties to their potential application as colorimetric sensors in food safety screening. Trends Food Sci. Technol. 2018, 78, 83–94.

76. Hua, Z.; Yu, T.; Liu, D.H.; Xianyu, Y.L. Recent advances in gold nanoparticles-based biosensors for food safety detection. Biosens. Bioelectron. 2021, 179, 113076.

77. Hou, S.L.; Ma, J.J.; Cheng, Y.Q.; Wang, Z.F.; Yan, Y.X. Overview-gold nanoparticles-based sensitive nanosensors in mycotoxins detection. Crit. Rev. Food Sci. Nutr. 2022, 16, 2095973.

78. Wu, F.L.; Xu, C.S.; Jiang, N.; Wang, J.B.; Ding, C.F. Poly (methacrylic acid-co-diethenyl-benzene) monolithic microextraction column and its application to simultaneous enrichment and analysis of mycotoxins. Talanta 2018, 178, 1–8.

79. Justyna, P.-W.; Natalia, S.; de la Miguel, G.; Jacek, N. Miniaturized solid-phase extraction techniques. TrAC Trends Anal. Chem. 2015, 73, 19–38.

80. Ghorbani, M.; Aghamohammadhassan, M.; Chamsaz, M.; Akhlaghi, H.; Pedramrad, T. Dispersive solid phase microextraction. TrAC Trends Anal. Chem. 2019, 118, 793–808.

11 mmol L^{-1}. Based on the co-polymerization reaction of methacrylic acid and divinylbenzene, Wu et al. developed a poly (methacrylic acid-co-divinylbenzene) [poly (MAA-co-DVB)] monolithic column for in-tube SPME of three mycotoxins [78]. The high-strength micro/nanostructure formed by two polymer monomers contained a large number of acrylic acid groups capable of forming hydrogen bonds with the carbonyl, hydroxyl, and hydrophobic benzene groups in the structure of AFB_1, ZEN, and sterigmatocystin. Therefore, the developed monolithic column based on poly (MAA-co-DVB) had a high recognition ability for three target molecules, effectively overcame the matrix effect of rice food, and realized the highly sensitive determination of three target mycotoxins.

Dispersive solid-phase microextraction (DSPME) is a non-fiber extraction method, which operates by mixing the solid-phase sorbent directly with the sample medium through vortexing and sonication [79][80][81]. After target adsorption, the sorbent was separated and desorbed the target with a suitable solvent for further detection and analysis. This approach eliminates the need to coat the adsorbent onto a carrier surface, thereby increasing the contact area between the adsorbent and the sample solution, leading to improved extraction efficiency and reduced adsorption time. However, due to the mixing of the sorbent with the sample matrix, the separation process becomes challenging [82][83]. Therefore, magnetically separable magnetic adsorbent materials have attracted significant attention from researchers. The reverse-phase/phenylboronic-acid (RP/PBA) magnetic microsphere prepared by Xu et al. demonstrated rapid and efficient dispersive extraction of amatoxins and phallotoxins [84]. The phenyl and phenylboronic-acid groups on the surface allowed for selective adsorption of the target toxins through hydrophobic interaction, π-π, and boronic acid affinity, thereby significantly reducing matrix effects in UPLC-MS/MS analysis. The proposed method obtained satisfactory linearity ($r > 0.9930$), LOD (0.3 μg kg^{-1}), and recovery (97.6–114.2%) values. Javier and co-workers synthesized core–shell poly (dopamine) magnetic nanoparticles, which were used for the simultaneous extraction of six mycotoxins (zearalenone, α-zearalanol, β-zearalanol, α-zearalenol, β-zearalenol, and zearalanone) from milk products [85]. This DSPME method combined with magnetic separation provided a very promising scheme for the rapid extraction and high-throughput detection of mycotoxins in food substrates.

Carbon-based nanomaterials, MOFs, and MIPs are some of the commonly used materials in SPME[92,93,94]. They have unique nanostructures and excellent physical and chemical properties, which help to improve the analytical efficiency, selectivity, and sensitivity of complex matrix extraction processes, and are widely used in the detection of mycotoxins [86][87]. Graphene is a typical carbon-based nanomaterial with an abundance of oxygen-containing functional groups (-OH and -COOH) on the surface. These functional groups can form hydrogen bonds or electrostatic interactions with target molecules, thus facilitating the adsorption process [88][89]. In addition, the modification of the graphene surface can reduce the agglomeration phenomenon and enhance its adsorption capacity. The group of Wu et al. prepared reduced rGO and ZnO nanocomposites (rGO-ZnO) through a hydrothermal process for separation, purification, and enrichment of 12 mycotoxins [90]. The key parameters affecting DSPME, including the extraction solution, eluent, and dosage of adsorbent, were optimized in detail to obtain the ideal purification and extraction efficiency. In combination with UHPLC-MS/MS, the prepared rGO-ZnO material was applied for extraction and analysis of 12 mycotoxin targets, achieving high sensitivity (LOQ: 0.09–0.41 μg kg^{-1}) and satisfactory precision (RSD: 1.4–15.0%). MOF materials have extremely high porosity, excellent

81. Soares da Silva Burato, J.; Vargas Medina, D.A.; de Toffoli, A.L.; Vasconcelos Soares Maciel, E.; Mauro Lanças, F. Recent advances and trends in miniaturized sample preparation techniques. J. Sep. Sci. 2019, 43, 202–225.

82. Vállez-Gomis, V.; Grau, J.; Benedé, J.L.; Giokas, D.L.; Chisvert, A.; Salvador, A. Fundamentals and applications of stir bar sorptive dispersive microextraction: A tutorial review. Anal. Chim. Acta 2021, 1153, 338271.

83. Yu-Xin, G.; Tian-Ci, Y.; Zi-Xuan, Y.; Fang-Ming, L.; Jun, C.; Li-Hong, Y. Recent developments and applications in the microextraction and separation technology of harmful substances in a complex matrix. Microchem. J. 2022, 176, 107241.

84. Xu, F.; Gong, B.; Xu, Z.; Wang, J. Reverse-phase/phenylboronic-acid-type magnetic microspheres to eliminate the matrix effects in amatoxin and phallotoxin determination via ultrahigh-performance liquid chromatography-tandem mass spectrometry. Food Chem. 2020, 332, 127394.

85. Gonzalez-Salamo, J.; Socas-Rodriguez, B.; Hernandez-Borges, J.; Rodriguez-Delgado, M.A. Core-shell poly(dopamine) magnetic nanoparticles for the extraction of estrogenic mycotoxins from milk and yogurt prior to LC-MS analysis. Food Chem. 2017, 215, 362–368.

86. Atapattu, S.N.; Poole, C.F. Recent advances in analytical methods for the determination of citrinin in food matrices. J. Chromatogr. A 2020, 1627, 461399.

87. Rezaeefar, A.; Nemati, M.; Farajzadeh, M.A.; Mogaddam, M.R.A.; Lotfipour, F. Development of N and S doped carbon sorbent-based dispersive micro solid phase extraction method combined with dispersive liquid-liquid microextraction for selected mycotoxins from soymilk samples. Microchem. J. 2022, 173, 107039.

88. Hou, X.D.; Tang, S.; Wang, J. Recent advances and applications of graphene-based extraction materials in food safety. TrAC Trends Anal. Chem. 2019, 119, 115603.

89. Kori, A.H.; Jagirani, M.S.; Soylak, M. Graphene-based nanomaterials: A sustainable material for solid-phase microextraction (SPME) for environmental applications. Anal. Lett. 2023, 56, 2385–2400.

90. Tanveer, Z.I.; Huang, Q.W.; Liu, L.; Jiang, K.Q.; Nie, D.X.; Pan, H.Y.; Chen, Y.; Liu, X.S.; Luan, L.J.; Han, Z.; et al. Reduced graphene oxide-zinc oxide nanocomposite as dispersive solid-phase extraction sorbent for simultaneous enrichment and purification of multiple mycotoxins in Coptidis rhizoma (Huanglian) and analysis by liquid chromatography tandem mass spectrometry. J. Chromatogr. A 2020, 1630, 461515.

91. Wang, S.W.; Shao, R.; Li, W.W.; Li, X.; Sun, J.L.; Jiao, S.S.; Dai, S.J.; Dou, M.H.; Xu, R.M.; Li, Q.J.; et al. Three-dimensional ordered macroporous magnetic inverse photonic crystal

microsphere-based molecularly imprinted polymer for selective capture of aflatoxin B-1. ACS Appl. Mater. Interfaces 2022, 14, 18845–18853.

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thermal stability, and a large specific surface area. Their tunable pore size, porous channels, and nano-space make them ideal SPME adsorbent materials. Lotfipour and co-workers [39][40] prepared a vitamin-based MOF material using vitamin B_3 as a bio-linker and cobalt ions as a metallic center in water, and applied it as a sorbent in a DSPME of patulin and Ochratoxin A (OTA) from fruit juice samples and four aflatoxins (AFB_1, AFB_2, AFG_1, and AFG_2) from soy milk. High extraction efficiencies can be achieved by mixing the precipitated protein supernatant with the sorbent and simply vortexing and centrifuging. This MOF material exhibited an excellent adsorption capacity for the target mycotoxins and can be prepared on a large scale in an environmentally friendly manner. The developed strategy required only a small amount of sorbent and organic solvent during the extraction process, which was one of its significant advantages. Using the microfluidic self-assembly technology, Wang et al. successfully prepared magnetic inverse photonic microspheres with a regular three-dimensional ordered macroporous structure and further utilized the “virtual template” molecular imprinting method to fabricate an MIP with high selectivity [91]. This MIP material, with the advantages of an adjustable pore size, easy modification, and good thermal stability of photonic crystal microspheres, was used as a DSPME adsorbent in combination with HPLC to realize the rapid quantitative analysis of AFB_1.