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Food-waste-derived sorbents for sample preparation: Recent trends, gaps and challenges

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Food-waste-derived sorbents have gained interest as low-cost and abundant materials. Compared to conventional sorbents, they offer advantages such as renewable origin, simple preparation, and alignment with circular economy principles. This review summarizes recent studies over the last two years (2024–2025) that report the use of food waste as sorbent materials for analytical sample preparation. Most of the reviewed works focus on two main groups of target compounds, namely contaminants and drugs or bioactive compounds. In terms of food sources, a prevalence of plant-based, lignocellulosic residues is observed with a strong contribution from Asian countries. The review discusses the main types of food waste employed, their role in green analytical chemistry, and the main challenges, limitations, and perspectives identified in the literature. This work provides an updated overview of this growing research area and supports the development of more sustainable sample preparation strategies within food systems.

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Introduction

Biowaste represents a major global challenge due to its environmental, health, and economic consequences. Food biowaste also reflects the loss of edible resources and inefficient use of raw materials that could otherwise support wider social needs [1]. Addressing this issue requires new recycling routes that allow biowaste to be converted into products with added value rather than treated as an unwanted residue [1,2]. In this context, the conversion of food waste into sorbent materials offers an attractive and yet not explored alternative, especially in larger scales for real applications. Food waste contains a complex mixture of components such as hemicelluloses, lignin, lipids, proteins, simple sugars, starch, hydrocarbons, and water. This chemical richness results in the presence of multiple functional groups that can interact with a wide range of pollutants, giving food waste a natural potential for sorption processes [3].

Growing interest has been directed toward sorbents produced from waste materials, commonly referred to as waste-derived sorbents (WDSs), as a response to sustainability demands in analytical chemistry and related fields [4]. These materials are usually obtained from agricultural, industrial, or municipal residues and are associated with lower cost, reduced environmental burden, and the possibility of surface modification when required [5]. Within this broad category, sorbents obtained specifically from food-related waste streams, referred to here as food-waste-derived sorbents (FWSs), have gained attention as extracting materials due to their availability and compatibility with green analytical principles. Several recent reviews have addressed WDSs from different angles, including broad overviews without a food-oriented focus [4], studies centred on pharmaceutical removal [6], endocrine-disrupting compounds [7], pesticide removal [8], or adsorption materials in general [3]. However, when FWSs are considered in the context of analytical sample preparation, different performance criteria become relevant, particularly regarding selectivity, reproducibility, and compatibility with analytical instrumentation. Despite this growing interest, a concise and up-to-date discussion specifically focused on the use of food waste as sorbent materials for sample preparation remains limited. To address this gap, the present work outlines recent trends and selected applications of FWSs in sample preparation, with emphasis on the most relevant studies published during the 2024–2025 period.

Food-waste-derived sorbents for sample preparation

Extensive effort has been carried out to the development of alternative sorbent materials that maintain analytical performance while limiting solvent consumption, waste generation, and secondary pollution [9]. Beyond the use of natural polymers, the conversion of biomass and waste biomass into multifunctional sorbents, such as biochar, has become a “hot topic” in recent research [10].

Within this context, FWSs have been studied in two main forms, namely as raw materials or after chemical or physical modification. In their natural form, food waste materials are typically washed, ground, and sieved to obtain a suitable particle size before being used in sorption or extraction experiments. In contrast, modified food solid waste is often treated with acidic reagents or with alkaline solutions. These treatments remove fats, waxes, and low-molecular-weight lignin fractions, while also increasing surface area and exposing functional groups that may favour analyte retention [3]. For example, Molina-Balmaceda et al. [11] described the preparation of biochar and activated carbon obtained from grapefruit peels and their application in rotating disk sorptive extraction (RDSE) for the determination of emerging contaminants in river water. The sorbent materials were obtained after carbonization at 400 °C, followed by chemical activation with $ZnCl_2$. After activation, the materials were treated with a 5 mol L^{-1} HCl solution to remove remaining activating agents and were then thoroughly washed with water until neutral pH was reached.

Among the different materials obtained from food waste, biochar and related carbonaceous sorbents have received attention. The synthesis of activated carbon, biochar, and charcoal from agricultural solid waste has grown in recent years [12]. Food biomass waste is often rich in carbon and therefore well suited for biochar production [13]. These residues are converted into activated carbons through processes such as pyrolysis or carbonization, followed by physical or chemical activation (see Figure 1). As a result, agroforestry and food-related residues are transformed into porous materials that can be used as sorbents while also mitigating issues linked to waste accumulation and uncontrolled degradation, which may otherwise lead to air and water pollution [6].

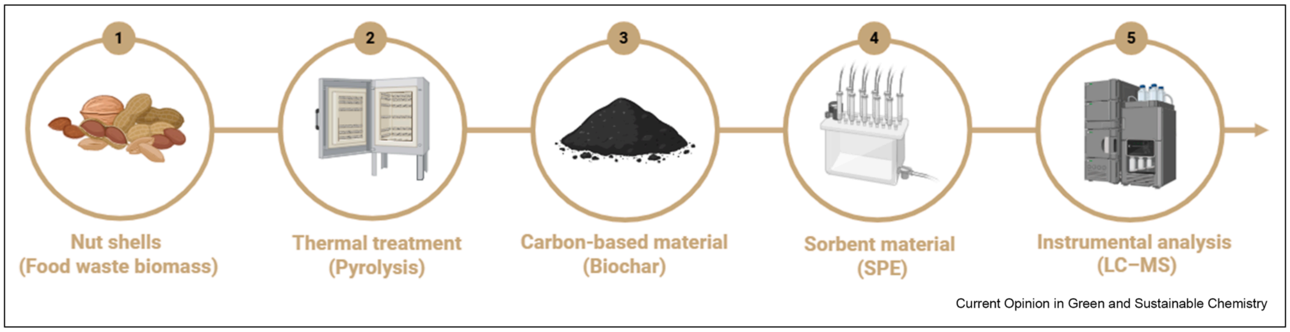
Compared to conventional synthetic sorbents, FWSs offer several advantages related to availability, cost, and sustainability, as summarized in Table 1. Their origin from abundant waste streams reduces dependence on fossil-based precursors and lowers production costs. Despite these benefits, FWSs also present limitations. The properties of sorbents derived from food waste can vary depending on the original biomass, processing conditions, and environmental factors, which may lead to inconsistent extraction behaviour [9]. In some cases, their adsorption capacity toward specific analytes remains lower than that of tailored synthetic sorbents, which can restrict their use in demanding analytical tasks. Even so, materials of natural origin continue to attract attention as sorbents for sample preparation, as their advantages in terms of sustainability, accessibility, and reduced environmental burden often outweigh these drawbacks [7].

Greenness of food-waste sorbent materials

Sorbent-based extraction has gained attention as an alternative to conventional extraction approaches that rely on large volumes of organic solvents and often fail to comply with green analytical chemistry (GAC) principles. The introduction of new sorbent-based extraction formats, together with the availability of alternative sorbent materials, has led to sample preparation strategies that reduce solvent use, lower costs, and improve selectivity while limiting environmental burden [14]. FWSs fit well with current efforts to reduce the footprint of analytical workflows without compromising the need for reliable clean-up and preconcentration.

The assessment of greenness in analytical procedures has received growing interest, supported by the introduction of metrics aimed at estimating and reducing the environmental impact of laboratory practices [15]. For sample preparation, tools such as the analytical greenness metric for sample preparation (AGREEprep) [16], complex modified green analytical procedure index (ComplexMoGAPI) [17], and the sample preparation metric of sustainability (SPMS) [18] have been used to evaluate the environmental performance of extraction procedures [19–21]. For

Figure 1



General workflow for the use of nut shells as food-waste-derived sorbent materials.

Table 1

Strengths and limitations of food-waste-derived sorbents compared with traditional sorbents for sample preparation.

Aspect	Food-waste-derived sorbents	Traditional sorbents
Main advantages	Renewable origin; low cost; valorization of food waste; natural functional groups enabling multiple interaction mechanisms	High selectivity; well-defined chemistry; high adsorption capacity; reproducible performance
Main limitations	Variability of raw materials; lower and less predictable adsorption capacity; limited standardization	Higher cost; dependence on non-renewable resources; higher environmental footprint in production
Chemical tunability	Can be modified or functionalized, but often with limited control	Highly tunable through controlled synthesis and surface chemistry
Reproducibility	Batch-to-batch variability may affect performance	Excellent batch-to-batch reproducibility
Stability and lifetime	Possible degradation over time, especially for organic matrices	High chemical and mechanical stability
Sustainability	Strong alignment with green analytical chemistry and circular economy principles	Sustainability depends on reusability and solvent consumption
Suitability for routine food analysis	Promising but still mostly at proof-of-concept level	Widely applied and accepted in routine laboratories
Scalability	Limited industrial-scale production at present	Established industrial production and supply chains

example, Mero et al. applied these metrics to sorbent-based methods and reported SPMS values between 5.16 and 10, along with AGREEprep scores ranging from 0.16 to 0.7 [22]. These results indicate that extraction strategies involving biochar-based sorbents already show favourable profiles, while also leaving room for further improvement. Factors that support lower environmental impact include the small amounts of biochar required, its reuse potential, and its frequent use in miniaturized extraction formats. Despite the acceptance that green metrics have received, their results should still be interpreted with caution. Many tools include subjective elements, such as how criteria are interpreted or how missing data are estimated, which can lead to variability between evaluators and reduce comparability across studies. The overall score is also highly dependent on the weighting of criteria, and when equal or default weights are applied without clear justification, different methods may appear more or less sustainable depending on these settings rather than on real performance differences. In addition, there is a balance between comprehensiveness and practicality. More detailed assessments can provide deeper insight, but they require extensive data collection and time, which may limit their routine use and increase inconsistencies when information is incomplete. The proliferation of partially overlapping tools further highlights the need for harmonization, as the absence of shared guidance on which metrics to apply and how to report them weakens cross-study comparison. Green metrics are still most often applied after a method has been fully developed, functioning more as a descriptive label than as a decision-making tool. Their true potential lies in being incorporated earlier in method development so that sustainability becomes an active design parameter rather than a final evaluation step.

Compared to conventional polymeric sorbents, materials obtained from food waste offer several advantages linked to biodegradability, reduced toxicity, low cost, and wide availability (see Table 1). Therefore, the use of FWSs meets several of the 12 principles of GAC [23], mainly: (i) the elimination of hazardous substances generated during the production of conventional sorbents (GAC principle number 11), (ii) reduced energy consumption during sorbent preparation and use (GAC principle number 9), (iii) the possibility of employing renewable raw materials as sorbent precursors (GAC principle number 10), and (iv) the use of biodegradable materials that contribute to reducing the overall amount of waste generated (GAC principle numbers 7 and 10).

From a broader perspective, the reuse of FWSs in circular economy strategies supports a transition away from linear waste management models toward systems that favour reuse and repurposing. Recycling food waste into sorbent materials through processes such as biochar production allows waste streams to be redirected into analytical applications, supporting closed material cycles [24]. In this sense, the production of biochar from biomass is consistent with the principles of circular analytical chemistry (CAC), as it links waste valorization with sample preparation needs while limiting resource consumption and waste generation [25]. Mukherjee et al. [26] evaluated the economic feasibility of producing activated carbon from nutshells and reported that processing 31.25 tons per day could yield 6.6 tons of activated carbon, with an estimated net present value of USD 2.8 billion and an internal rate of return of 21 %. Coffee waste represents another interesting case, as more than 500 billion cups of coffee are consumed globally, generating around 650 kg of spent coffee grounds per ton of coffee [27]. Silva et al. [28] showed that coffee grounds can be a cost-effective biosorbent for fluoxetine removal from water, with much lower costs per gram of removed compound (€0.16/g) compared to commercial adsorbents (up to €6.85/g). These examples indicate that waste materials can be economically viable sorbents at a large scale [28]. However, translating laboratory-scale success into industrial application remains challenging due to waste heterogeneity, supply chain logistics, pretreatment requirements, and limited operational cost data, which complicate realistic feasibility assessments [29].

Critical discussion

Trends

The present discussion is based on the analysis of representative studies (*n = 35*) published during the period 2024–2025, which are summarized in Table 2. At a general level, studies based on FWSs mainly focus on environmental contaminants and pharmaceuticals or bioactive compounds. Contaminants dominate the literature, including pesticides, heavy metals, polycyclic aromatic hydrocarbons, per- and polyfluoroalkyl substances, dyes, and endocrine-disrupting compounds. This predominance is linked to their widespread presence in environmental compartments and food systems because of industrial, agricultural, and urban activities, as well as to the health and food-safety risks associated with long-term exposure [3]. Similarly, some of these analytes have also attracted interest, as they have been classified as emerging contaminants [30].

Respect to the food source employed as sorbent material, a preference for plant-based, lignocellulosic waste is observed. Fruit peels, seeds, shells, husks, and other agricultural residues are selected due to their availability, low cost, and chemical composition rich in cellulose, hemicellulose, lignin, and diverse surface functional groups. For instance, avocado seeds is an important waste stream in countries with high avocado production, such as Ethiopia, and their conversion into biochar has been proposed as an effective route for recycling seed waste [31]. Similarly, nectarine cores have been identified as suitable precursors for biochar production because of their abundance, high carbon content, and favourable physicochemical properties, together with economic and environmental benefits [32]. Nut shells, including almond, walnut, hazelnut, pistachio, and neem tree seed shells, are also explored, partly because the neem tree (*Azadirachta indica*) is one of the most extensively studied plants worldwide and is native to regions such as India [19]. Other food-processing residues attract attention due to the large volumes generated at the industrial level. Orange peel is an example, with around 20 million tons produced annually by the food industry worldwide [33]. While a small fraction is used to extract valuable compounds such as limonene or pectin, most of this residue is still disposed of by landfilling, composting, or open-air burning [34]. Coconut clothing, the outer layer of the coconut, is another typical agricultural residue, with annual generation exceeding 50,000 tons in China [35]. Although traditionally used only for low-value applications such as organic fertilizers, its high carbon content, natural structure, and renewability make it a suitable raw material for biochar production [36]. In addition, spent coffee grounds, generated after coffee brewing, have been reported as promising sorbents due to their porous structure and surface chemistry [26].

In many cases, these food residues are applied after simple physical processing, while in others they are converted into porous carbonaceous structures such as biochar or activated carbon to increase surface area and sorption capacity. From a geographical point of view, sixteen countries are represented in the selected studies (see Fig. 2). Research activity is mainly concentrated in Asia, with China emerging as the most active contributor. This distribution is linked to high food-waste generation rates, strong investment in sustainable materials research, and national strategies focused on waste valorization.

Regarding sample preparation, sorbent-based extraction approaches are dominant, with miniaturized formats being commonly reported (see Table 2) [10]. These techniques are well suited to the physicochemical characteristics of FWSs and allow reductions in solvent consumption, extraction time, and handling steps. Magnetic configurations are a suitable option, as they enable rapid and efficient separation of the sorbent from the sample matrix using an external magnetic field, thereby simplifying sample preparation and minimizing the need for filtration or centrifugation steps [37].

Aqueous samples, including environmental waters, wastewater, and tap water, represent the most frequently studied matrices, followed by liquid food products such as juices, milk, beverages, and extracts. Solid food matrices and biological samples appear less often and are usually associated with more selective sorbents or additional clean-up steps. Detection is mainly based on liquid chromatography-based techniques (see Table 2). High-performance liquid chromatography (HPLC) and liquid chromatography-tandem mass spectrometry (LC–MS/MS) are the

Table 2

Representative works from the last two years (2024–2025) based on food-waste as sorbent materials.

#	Sample preparation	Food source (Country)	Target analytes	Matrix	Detection	Ref.
1	D–μ–SPE, DLLME	Avocado seeds (Ethiopia)	OCPs	Apple, mango, orange juice	GC–MS	[31]
2	US–MSPE	Nectarine core (Iran)	PAHs	Tomato paste	GC–MS	[32]
3	TFME	Nut shells (almond, pistachio, walnut, hazelnut and neem tree seed) (Iran)	Pesticides	Tap water	GC-ECD	[19]
4	–	Coffee grounds, ground walnut shells, compost (Poland)	Zn(II), Pb(II), Cd (II), Cu(II)	Aqueous solution	FAAS	[43]
5	–	Cabbage waste (Turkey)	Pb(II), Cd(II), Cu (II)	Aqueous solution	FAAS	[44]
6	Centrifugation, filtration	Food waste (China)	PFAS	Contaminated water	HPLC-MS/MS	[38]
7	d-SPE	Lemon and onion peels (Turkey)	Aflatoxin M1	Raw milk	HPLC-FLD	[45]
8	–	Food waste from a cafeteria (Pakistan)	Heavy metals	Wastewater	–	[13]
9	VWSE	Shells of walnut and peanut, bean pods, pumpkin peels (Italy)	Steroids	Water samples	HPLC-MS/MS	[21]
10	SPE	Corncob (Brazil)	Pesticides	Water	LC-MS	[46]
11	–	*Zizyphus jujuba* seed shells (China)	Triazine herbicides, PAHs	Tea beverages	HPLC-UV	[47]
12	In-vial SPE	Orange peel (Italy)	Sex steroids	Water	HPLC-MS/MS	[20]
13	SPE	Coconut-clothing (China)	Fungicides	Pear, apple, cucumber, cabbage	HPLC-UV	[48]
14	MSPE	Pumpkin peel (Turkey)	Naproxen	Lake water, urine, tablets	HPLC-UV	[49]
15	MSPE	Almond, walnut and peanut shells (Tunisia)	Naproxen	Human saliva	LC-MS	[50]
16	MSPE	*Zizyphus jujuba* seed shells (China)	Antiepileptic drugs	Plasma	HPLC-UV	[51]
17	MSPE	Coconut-clothing (China)	Neonicotinoids	Water samples	HPLC-MS/MS	[52]
18	SPE	Spent brewery grains (Portugal)	Pharmaceuticals	Surface waters	HPLC-UV/FLD	[53]
19	MD-μSPE, MDLLME	Waste mushroom sticks (China)	Herbicides	Water, tea, juice	HPLC-DAD	[54]
20	RDSE	Avocado seed (Chile)	Ibuprofen and 1-hydroxy ibuprofen	Water samples	GC–MS	[55]
21	DPX	Corncob (Brazil)	EDCs	Surface water	HPLC-DAD	[56]
22	MEPS	Herbal medicine (China)	Sulfonamides	Water samples	HPLC-MS/MS	[57]
23	SPE	Green walnut shells (Turkey)	Indigo carmine	Candies, textiles, hair dyes, fruit juices, water, edible cake decorations	UV–Vis	[58]

(*continued on next page*)

Table 2 (*continued*)

#	Sample preparation	Food source (Country)	Target analytes	Matrix	Detection	Ref.
24	MSPE	Cabbage leaves (Libya)	Pb(II), Cd(II), Cu (II)	Marine fish, water samples	GFAAS	[59]
25	SPME	Banana peel (China)	PAHs	Environmental water samples	GC–MS	[60]
26	MSPE	Rice husk (China)	Aflatoxin B1	Rice	TRFICA	[61]
27	SPE	Rice husk (China)	Zearalenone	Maize	HPLC-FLD	[62]
28	MSPE	Potato peel, pomegranate peel (Tunisia)	Ascorbic acid	Fruit juices	HPLC-UV	[63]
29	SPME	*Citrus reticulata* peel (China)	OCPs	Fruit, vegetable samples	GC-ECD	[64]
30	SPE	Rice husk (Spain)	Alkaloids	Gluten-free bread	HPLC-MS/MS	[65]
31	MD-µSPE	Aloe vera leaf (Malaysia)	Antidepressant drugs	Water	HPLC-DAD	[37]
32	–	Date palm leaves (Qatar)	Heavy metals	Wastewater	–	[66]
33	–	Leftover noodles (Malaysia)	Crystal violet dye	Wastewater	–	[67]
34	–	Spent coffee grounds (Serbia)	Pesticides	Tap water	–	[1]
35	RDSE	Grapefruit peel (Chile)	Emerging contaminants	River water	GC–MS	[11]

DLLME, dispersive liquid–liquid microextraction; **DPX**, dispersive pipette extraction; **d-SPE**, dispersive solid-phase extraction; **EDCs**, endocrine-disrupting compounds; **FAAS**, flame atomic absorption spectrometry; **GC-ECD**, gas chromatography with electron capture detector; **GC–MS**, gas chromatography-mass spectrometry; **GFAAS**, graphite furnace atomic absorption spectrometry; **HPLC-DAD**, high-performance liquid chromatography with diode array detector; **HPLC-FLD**, high-performance liquid chromatography with fluorescence detector; **HPLC-MS/MS**, high-performance liquid chromatography-tandem mass spectrometry; **HPLC-UV**, high-performance liquid chromatography with ultraviolet detector; **HPLC-UV/FLD**, high-performance liquid chromatography with ultraviolet or fluorescence detector; **LC-MS**, liquid chromatography-mass spectrometry; **MDLLME**, magnetic dispersive liquid–liquid microextraction; **MD-µSPE**, magnetic dispersive micro-solid-phase extraction; **MEPS**, microextraction in packed syringe; **MSPE**, magnetic solid-phase extraction; **OCPs**, organochlorine pesticides; **PAHs**, polycyclic aromatic hydrocarbons; **PFAS**, per- and polyfluoroalkyl substances; **RDSE**, rotating disk sorptive extraction; **SPE**, solid-phase extraction; **SPME**, solid-phase microextraction; **TFME**, thin-film microextraction; **TRFICA**, time-resolved fluorescence immunochromatography; **US-MSPE**, ultrasound-assisted magnetic solid-phase extraction; **UV–Vis**, ultraviolet–visible spectroscopy; **VWSE**, vial wall sorptive extraction.

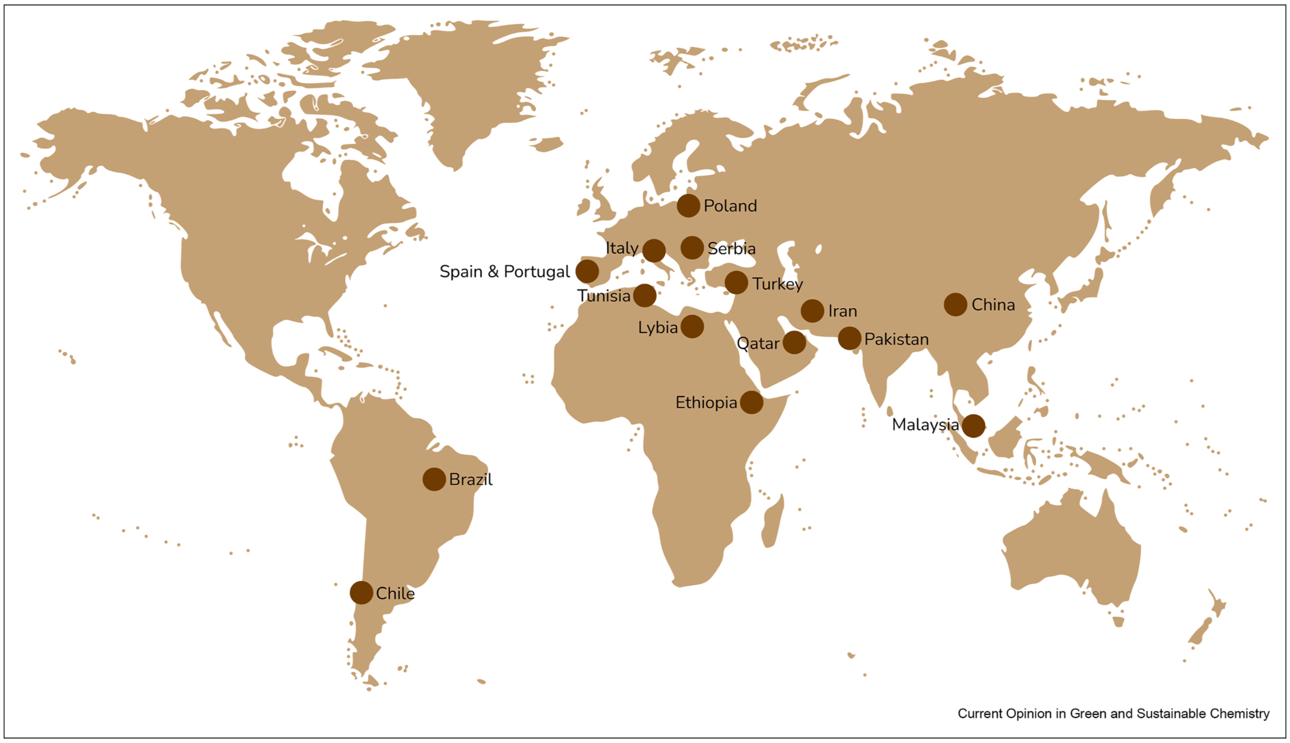
most used methods, given their suitability for polar and semi-polar analytes and their compatibility with multi-residue analysis. Gas chromatography-based techniques are mainly applied to volatile or semi-volatile compounds such as polycyclic aromatic compounds, organochlorine pesticides, and related contaminants.

Gaps

A gap that comes from the literature concerns the imbalance between material development and analytical and larger scale applicability. Most studies exploring FWSs devote substantial effort to the preparation, modification, and physicochemical characterization of new sorbent materials, often relying on an extensive set of techniques to describe surface area, porosity, morphology, and functional groups [12]. While such characterization is necessary to support the use of a newly proposed agricultural waste-derived adsorbent and to understand its behaviour in the intended process [3], many works tend to overemphasize this aspect. As a result, the actual performance of the sorbent within a realistic analytical workflow, particularly in food analysis and routine sample preparation, is often treated as a secondary element.

In line with that, a large proportion of the published studies primarily introduce and optimize new routes for converting food waste into biochar, focussing on their promising physicochemical features and potential adsorption capacity. The discussion highlights the expected advantages of the proposed materials and their prospective applications, sometimes without fully demonstrating their robustness under real analytical conditions [31,38]. For instance, Moureen et al. evaluated food waste collected from a cafeteria in Pakistan as a low-cost adsorbent for heavy metal removal from wastewater [13]. Although the results confirmed the technical feasibility of the approach, the study, as many others, concludes that further investigations are required to assess long-term stability, regeneration, and broader applicability. This

Figure 2



Global distribution of food-waste sources employed for the preparation of sorbent materials.

recurrent conclusion points to a gap related to scalability and real-world implementation, since most reports remain confined to laboratory-scale demonstrations.

Another important limitation is linked to the intrinsic variability of food waste [10]. Differences in origin, seasonality, processing conditions, and storage can lead to marked variations in chemical composition, which in turn affect adsorption performance and reproducibility [24]. This variability complicates direct comparison between studies and hampers the definition of standardized preparation or application protocols. In several cases, the food waste used as precursor is described only in general terms, without detailed information on its composition, or it is reported as a heterogeneous mixture of residues, as noted in studies dealing with mixed cafeteria or municipal food waste [13]. An understanding of the starting material is important, as the relative proportions of lignocellulosic components, proteins, lipids, and inorganic fractions influence sorption mechanisms and surface chemistry.

A further gap concerns the limited assessment of environmental compatibility beyond the sorbent preparation stage. Although increasing attention is given to the use of FWSs as extracting materials, complete evaluations of their overall environmental footprint are still scarce. Studies rarely include systematic environmental risk assessments, life cycle analysis, or comparisons with conventional sorbents in terms of resource use and waste generation. Moreover, truly industrial or semi-industrial applications remain uncommon in the reviewed literature. One of the few examples found involves the design of a biological treatment unit using agricultural residues such as rice husk, plum leaves, banana peels, and green bean peels for heavy metal removal from industrial wastewater in Egypt [39]. The scarcity of similar case studies highlights the need for future work that moves beyond proof-of-concept experiments and addresses performance, safety, and environmental impact under realistic operating conditions.

Challenges

One of the first challenges concerns the definition of what can be considered “food waste”. This distinction is not always straightforward and often depends on the context in which the material is generated and used. In some studies, materials that are still edible or traditionally consumed in certain regions are classified as food waste once they lose their primary commercial or culinary value. A representative example is the use of hairy basil seeds as a green biosorbent [40], where the classification as food waste depends largely on whether the seeds are considered surplus, by-products, or discarded fractions. This ambiguity complicates comparisons between studies and raises questions about the boundaries between food by-products, co-products, and true waste streams.

A second challenge relates to the characteristics of specific food biowaste streams that make difficult their handling and large-scale use. Among the different forms of food biowaste, some materials involve specific challenges due to their volume, heterogeneity, and treatment requirements [9]. Spent coffee grounds (SCG) are an example of this issue [1]. Coffee is among the most enjoyed beverages around the globe with major contributions from countries such as Brazil and Vietnam, which leads to the generation of vast quantities of SCG [41]. When these residues are not properly managed, they can generate serious environmental problems affecting air, water, and soil quality. During decomposition or inappropriate disposal, SCG release gases that contribute to smog formation, ozone formation, and climate-related impacts, reinforcing the urgency of developing suitable management and valorisation strategies. At the same time, the very scale and availability of SCG highlight their dual nature as both an environmental burden and a valuable resource. Their abundance makes them attractive as a feedstock for sorbent production, yet their high moisture content, organic load, and need for stabilization or pretreatment introduce additional processing steps that may offset some of the environmental benefits if not carefully optimized.

Key innovations

In earlier studies, many works mainly showed that food waste could be turned into biochar and used as a sorbent. Now, the focus is more practical and application-oriented. These materials are no longer only tested in simple adsorption experiments, but are integrated into analytical workflows, such as MSPE, TFME, cartridge SPE, UAE, and portable vial-based devices. Another important evolution is the use of surface modifications, like magnetic particles, boron doping, mixed-acid treatment, or controlled pyrolysis, to adjust surface chemistry and porosity. This allows the sorbents to extract different types of analytes at the same time, even when they have very different chemical properties. In addition, recent studies pay more attention to method performance, comparing biochar materials with commercial sorbents and reducing solvent and sorbent consumption. There is also a shift toward faster extraction times, miniaturized formats, and compatibility with advanced techniques such as GC–MS and LC–MS/MS, which increases sensitivity. Some works begin to include benchmarking strategies and structured comparisons under the same experimental conditions, helping to better understand which parameters really control performance. Although promising results have been reported, more routine validation and large-scale studies are still needed to confirm long-term robustness and real sustainability impact.

Perspectives

At present, the outlook for FWSs in sample preparation is still very much linked to analytical laboratory work scales [42]. Most published studies focus on demonstrating feasibility, testing new materials, and reporting analytical performance under controlled conditions. In fact, scalability of bio-based sorbents is a fundamental aspect that should be further considered, as well as metrics to determine their sustainable use, especially for real case applications. There is little evidence of industrial uptake or large-scale use in the investigated literature, which means that these approaches remain within an academic sphere. This situation reflects both technical limitations and the fact that many FWS-based strategies are at an early stage of development and need further validation before they can move beyond the lab.

A direction for future work is a closer connection between FWSs and biocircular economy concepts [2]. Using food waste as a source of sorbent materials fits well with the idea of zero-waste laboratories, where waste streams are reused rather than discarded. To make this link more meaningful, future studies should take a broader view of the full life cycle of the sorbents, from their preparation and use to regeneration and final disposal.

There is also growing interest in developing more advanced sorbent materials based on food waste. Hybrid systems that combine food-derived matrices with selective coatings, molecular imprinting, or magnetic components may offer better selectivity, stability, and reuse. At the same time, digital and data-driven tools, including artificial intelligence, could support the selection of suitable food-waste sources, the optimization of activation conditions, and the prediction of extraction performance.

In the coming years, research is expected to expand the range of food-related waste streams explored as sorbent sources. More attention will likely be given to underused residues from food production and processing, such as peels, shells, husks, seeds, and spent grains, with particular focus on their chemical composition and availability. Post-consumer food waste from households and catering services may also attract interest. In addition, bio-waste linked to newer food systems, including algal and marine biomass and residues from food-based biorefineries, is likely to gain relevance as alternative and sustainable sorbent sources for food analysis [7].

Moreover, questions related to efficiency, effectiveness and cost remain central and deserve further attention. Progress in these areas will likely require collaboration between material and computational scientists, environmental engineers, economists and related areas. Environmental impact studies and pilot-scale tests will be important to understand how these materials behave outside the laboratory and to identify practical limitations before wider application is considered [4].

Conclusions

The studies discussed in this review show that food-waste sorbents can be applied in a wide range of sample preparation strategies, mainly for the extraction of contaminants and drug-related compounds. Biochar technology has attracted increasing attention and has opened opportunities to meet the demand for low-cost sorbents derived from food waste. Their use allows discarded biomass to be redirected into analytical workflows, reducing reliance on conventional synthetic materials. In this context, the application of food-waste-based sorbents for the extraction of different analytes appears as a promising route toward lowering the environmental footprint of sample preparation while maintaining acceptable analytical performance. At the same time, the growing demand for more environmentally friendly analytical methods has driven the search for alternative sorbents and for affordable ways to implement them in routine analysis. While most current applications remain at the laboratory analytical scale, the overall picture shows that food-waste sorbents represent a realistic and sustainable option for future analytical and real case industrial workflows.

Author contributions

Adrián Fuente-Ballesteros, conceptualization, methodology, formal analysis, investigation, data curation, writing – original draft, writing – review & editing, visualization. **Vânia G. Zuin Zeidler,** conceptualization, supervision, writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

AGREEprep	analytical greenness metric for sample preparation
CAC	circular analytical chemistry
ComplexMoGAPI	complex modified green analytical procedure index
FWSs	food-waste-derived sorbents
GAC	green analytical chemistry
GSP	green sample preparation
HPLC	high-performance liquid chromatography
LC–MS/MS	liquid chromatography–tandem mass spectrometry
SCG	spent coffee grounds
SPMS	sample preparation metric of sustainability
WDSs	waste-derived sorbents

Data availability

Data will be made available on request.

References

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest
* * of outstanding interest

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