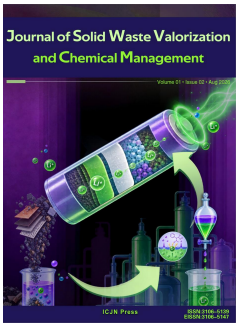
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REVIEW

Microwave Pyrolysis of Spent Activated Carbon-Laden Sludge: A Critical Review of Regeneration, Cross-Phase Pollutant Transfer, and Environmental Reactivity

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Abstract

Spent activated carbon-laden sludge (SACLS) is a composite residue containing a potentially recoverable porous carbon matrix together with organic contaminants, mineral phases, and heavy metals, thereby creating simultaneous resource-recovery and environmental-risk challenges. This review critically evaluates microwave pyrolysis as a strategy for activated-carbon regeneration and SACLS valorization, with particular emphasis on particulate formation, cross-phase pollutant transfer, heavy-metal redistribution, and environmentally persistent free radicals (EPFRs). Peer-reviewed evidence from spent activated-carbon regeneration, sewage-sludge microwave pyrolysis, particulate formation, metal speciation, and EPFR chemistry was critically synthesized into a unified process-level framework. The analysis indicates that selective microwave absorption by carbonaceous domains can accelerate adsorbate desorption, cracking, and pore redevelopment; however, heterogeneous energy deposition may also generate interfacial hot spots that promote tar conversion, mineral transformation, particle nucleation, metal volatilization and condensation, carbon loss, and radical stabilization. Fine particles should therefore be regarded as mobile carriers of metals, aromatic radical precursors, and redox-active mineral phases rather than merely as secondary dust. Existing studies commonly evaluate only the solid char, whereas particles, condensates, reactor deposits, and time-dependent EPFR evolution are rarely included in complete mass balances and integrated risk assessments. Safe SACLS valorization consequently requires a regeneration-risk-constrained operating window that jointly considers adsorption recovery, carbon preservation, energy demand, particle-size-resolved metal fate, organic contaminant redistribution, and EPFR/reactive oxygen species (ROS) reactivity. Standardized feedstock characterization, spatially resolved thermal diagnostics, and phase- and time-resolved analyses are essential for scalable application.

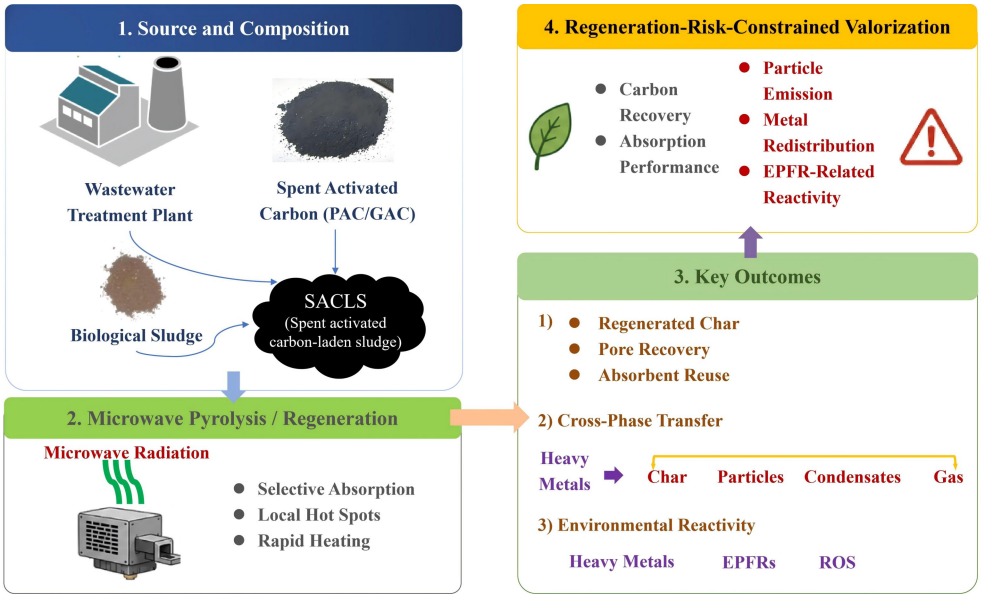
Keywords

Spent activated carbon-laden sludge; Microwave pyrolysis; Activated carbon regeneration; Heavy-metal redistribution; Environmentally persistent free radicals

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Graphical Abstract



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Highlights

- SACLS is defined as a carbon-organic-mineral composite from wastewater treatment.
- Microwave heating induces selective hotspots and heterogeneous regeneration pathways.
- Particulate formation governs cross-phase redistribution of metals and organics.
- EPFR-metal-ROS interactions determine environmental reactivity after pyrolysis.

1. Introduction

Sewage sludge is continuously generated during municipal and industrial wastewater treatment and is characterized by high moisture content, a heterogeneous organic matrix, mineral matter, nutrients, and accumulated contaminants. Its dual role as both a potential resource reservoir and a sink for environmental pollutants makes the selection of appropriate treatment and disposal routes a persistent challenge for circular-economy development and environmental-risk management[1-8]. Thermal conversion can substantially reduce sludge volume, destroy many organic contaminants, and retain part of the carbon and mineral nutrients in a solid product; however, its overall environmental performance depends on the fate of contaminants across all product streams rather than on char yield alone[9,10]. The increasing application of activated carbon-based adsorption processes in wastewater treatment has generated a growing stream of carbon-containing sludge residues. During wastewater treatment, powdered activated carbon (PAC) is frequently introduced into biological or advanced treatment systems to remove refractory organic contaminants, pharmaceuticals, and other trace pollutants. After adsorption saturation, PAC particles are commonly retained with biological solids and subsequently transferred into sludge thickening and dewatering processes, resulting in a composite residue containing spent carbon, organic matter, and mineral phases rather than an isolated spent adsorbent[11]. Full-scale studies have demonstrated that PAC addition can alter sludge properties and increase the amount of carbon-containing solids entering downstream sludge management processes[12]. However, the generation amount of spent activated carbon-laden sludge (SACLS) has not yet been systematically quantified because it is not currently classified as an independent waste category and depends strongly on carbon dosage, wastewater characteristics, treatment configuration, and sludge production rate[13,14]. Therefore, establishing appropriate management and valorization strategies for SACLS is becoming increasingly important. Powdered activated carbon is commonly co-separated with biological solids, while granular activated-carbon fines, backwash residues, and slurry-dosed carbonaceous particles may also enter the sludge line. In this review, SACLS specifically refers to carbon-containing sludge generated from wastewater treatment processes where spent activated carbon is intentionally introduced or accumulated within a sludge matrix. It mainly includes biological sludge produced from activated-sludge processes receiving PAC and, to a lesser extent, physically separated sludge residues containing spent granular activated carbon (GAC) fines or carbonaceous adsorption materials[11,12]. Therefore, SACLS is not considered a simple mixture of sludge and spent carbon, but a heterogeneous carbon-organic-mineral composite whose properties depend strongly on sludge origin, carbon type, carbon loading, and wastewater treatment configuration[15]. These components jointly affect dielectric properties, heat and mass transfer, pore accessibility, and contaminant partitioning, indicating that SACLS should be regarded as a coupled carbon-organic-mineral matrix rather than a simple physical mixture.

Conventional management routes do not fully resolve the combined resource and environmental challenges associated with SACLS. Landfilling sacrifices the residual value of the

carbonaceous fraction and leaves the long-term release of adsorbed contaminants unresolved, whereas incineration achieves volume reduction and contaminant destruction but may increase carbon loss and transfer volatile metals and fine particles to flue-gas-control residues. Pyrolysis offers an intermediate pathway that can preserve part of the carbon framework while transforming sludge organic matter and mineral phases. Microwave heating is particularly attractive because carbonaceous domains can efficiently absorb electromagnetic energy, enabling rapid internal heating and localized energy deposition[16]. Previous studies have demonstrated that microwave treatment can restore the adsorption performance of spent activated carbon[17], while pyrolysis of spent powdered activated carbon recovered from wastewater treatment systems can regenerate surface area and phosphorus adsorption capacity[18]. Nevertheless, the same selective absorption that promotes rapid regeneration may also produce non-uniform temperature fields and localized hot spots that are not adequately represented by a single bulk reactor temperature. These microenvironments may accelerate carbon burn-off, tar cracking, mineral decomposition, particle nucleation, and metal volatilization. Sludge pyrolysis can generate fine particulate matter whose composition shifts from predominantly condensed organic material at lower temperatures toward a greater inorganic contribution at higher temperatures[19]. Meanwhile, metals may be retained, transformed, volatilized, or enriched in particulate matter depending on their initial speciation and the surrounding carbon-mineral matrix[20-22]. Thermochemical treatment may also generate environmentally persistent free radicals (EPFRs), which can be stabilized on aromatic carbon structures or metal-oxide surfaces and subsequently promote the formation of reactive oxygen species (ROS)[23-26].

Despite these interconnected processes, the existing literature remains fragmented. Studies of activated-carbon regeneration generally emphasize pore recovery and adsorption capacity, microwave sludge pyrolysis research often focuses on product yields and energy recovery, investigations of heavy metals predominantly examine the bulk char, and EPFR studies rarely include particulate matter, condensates, or reactor deposits. Consequently, it remains unclear whether an apparently successful regeneration condition genuinely reduces environmental risk or merely transfers contaminants and reactive species from the regenerated solid to secondary product or emission streams. To address this gap, this review develops a process-level framework linking microwave energy deposition, interfacial thermal reactions, particulate formation, cross-phase metal redistribution, EPFR evolution, and final material performance. Specifically, the objectives are to: (i) define SACLS as a distinct composite residue and establish an appropriate analytical boundary; (ii) critically assess the advantages and limitations of microwave-assisted regeneration and pyrolysis; (iii) clarify the formation, distribution, and interactions of particulate matter, heavy metals, and EPFRs across different product phases; and (iv) propose an integrated basis for identifying an operating window that balances adsorption-function recovery, process efficiency, and environmental-risk control.

Before discussing the thermal transformation and environmental consequences of SACLS, its operational definition, formation pathways, and intrinsic physicochemical characteristics must be clarified because these factors determine microwave response, pollutant partitioning, and regeneration behavior. As illustrated in **Figure. 1**, SACLS originates from the interaction between spent activated carbon and sludge matrices during wastewater treatment, forming a heterogeneous carbon-organic-mineral composite with both resource value and environmental risks.

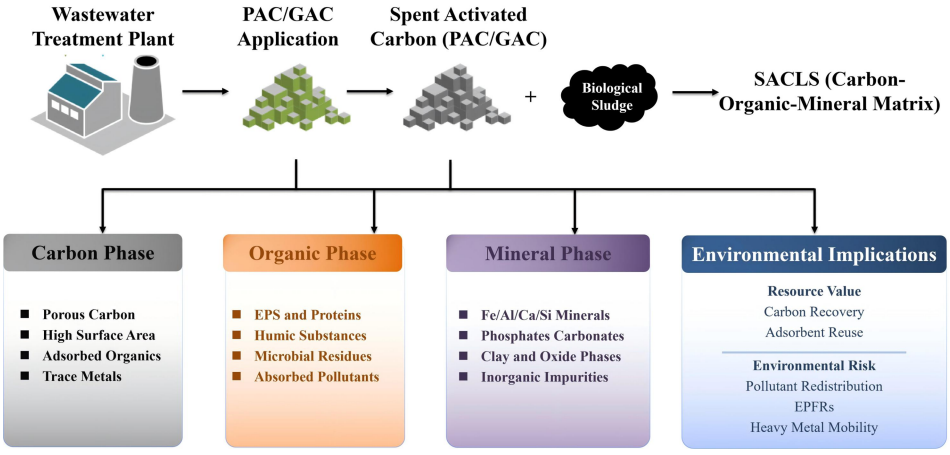


Figure. 1 Formation pathways, composition characteristics, and environmental implications of SACLS. **NOTE:** PAC: powdered activated carbon; GAC: granular activated carbon; EPFRs: environmentally persistent free radicals; EPS: extracellular polymeric substances; SACLS: spent activated carbon-laden sludge. Copyright: The figure was originally created by the authors using Microsoft PowerPoint and Adobe Photoshop. No copyrighted materials from other sources were used.

2. Definition, Formation, and Characteristics of SACLS

2.1 Formation Pathways and Operational Definition of SACLS

SACLS is defined here as a carbonaceous composite sludge residue generated after the incorporation, retention, and co-separation of spent activated carbon within wastewater treatment systems. Unlike conventional physical sludge or biological sludge, SACLS possesses a coupled structure consisting of carbon particles, extracellular polymeric substances (EPS), microbial-derived organic matter, mineral phases, and adsorbed contaminants. Depending on the sludge source, SACLS can exhibit substantially different physicochemical characteristics. For example, biological SACLS derived from activated sludge systems is dominated by microbial flocs, EPS, and biogenic minerals, whereas physically generated carbon-containing sludge may contain fewer biological components but higher proportions of mineral particles and carbon fragments[27]. These differences directly influence dielectric properties, heat

transfer behavior, pollutant partitioning, and regeneration performance during thermal treatment. It is commonly formed when powdered activated carbon added to biological or advanced wastewater treatment is co-separated with waste sludge. Other sources include fines from granular activated-carbon systems, carbonaceous adsorbents used in sludge conditioning, and adsorption media blended with sludge before thermal treatment[28]. Isolated spent activated carbon that can be physically separated and regenerated independently is excluded, because the surrounding sludge matrix is central to the thermal behavior considered in this review. SACLS composition varies with activated-carbon type, dose, particle size, pore structure, contaminant loading, moisture, ash, coagulant-derived minerals, and chloride, sulfur, calcium, phosphorus, iron, and aluminum contents. These differences strongly affect microwave absorption, devolatilization, pore redevelopment, and pollutant release. SACLS characterization should therefore report the carbonaceous fraction, particle-size distribution, proximate and ultimate analyses, ash and mineral composition, moisture basis, and major adsorbed contaminants.

2.2 Composition and Physicochemical Characteristics of SACLS

Unlike engineered carbon-sludge composites, SACLS does not possess a fixed activated carbon-to-sludge ratio because its composition is determined by the wastewater treatment configuration and operational conditions. In PAC-based wastewater treatment, the carbon fraction is controlled by the applied PAC dosage, sludge retention time, and sludge production rate[29]. Recent full-scale and pilot-scale studies have reported PAC dosages ranging from several mg L^{-1} to tens of mg L^{-1} for micropollutant removal, indicating that the final carbon content in sludge can vary substantially among treatment systems[11]. In GAC-based systems, the carbon fraction is additionally affected by carbon attrition, backwashing losses, and particle carryover. Therefore, SACLS should be considered a compositionally variable carbon-organic-mineral matrix rather than a material with a universal carbon/sludge ratio[30].

Typical physicochemical characteristics of SACLS include a porous carbon phase originating from spent activated carbon, microbial-derived organic matter and extracellular polymeric substances from biological sludge, mineral ash components, and concentrated adsorbed contaminants. Compared with conventional biological sludge, SACLS generally exhibits higher carbon content, stronger hydrophobicity, enhanced adsorption potential, and altered dielectric properties due to the presence of activated carbon[31]. However, these properties are highly dependent on carbon loading, sludge origin, and wastewater treatment process. A summary of reported characteristics of carbon-containing sludge systems is provided in **Table 1**.

Table 1. Typical characteristics of SACLS compared with conventional sludge and spent activated carbon

Feature	Conventional Biological Sludge	Spent Activated Carbon	SACLS	References
Origin	Produced from biological wastewater treatment; dominated by microbial flocs and EPS	Generated after activated carbon adsorption saturation during water treatment	Formed when PAC/GAC particles are retained or discharged with sludge during carbon-assisted wastewater treatment	[11,12,32]
Main Matrix	Microbial biomass, EPS, extracellular polymers, inorganic minerals	Porous carbon skeleton with adsorbed organic/inorganic contaminants	Carbon-organic-mineral composite containing activated carbon particles, sludge-derived organics, minerals and adsorbates	[11,33]
Carbon Source	Biomass-derived carbon from microorganisms and extracellular organic matter	Commercial activated carbon carbon framework	Dual carbon sources from spent activated carbon and sludge organic carbon	[32,33]
Activated Carbon Fraction	Generally absent	Dominant component (> carbon matrix)	Variable depending on PAC dosage, carbon retention, sludge production and treatment configuration	[11,12,32]
Organic Matter	Protein, polysaccharides, EPS and microbial residues dominate	Mainly adsorbed pollutants and surface oxygen groups	Combination of sludge-derived organic matter, EPS, humic substances and adsorbed contaminants	[11,33]
Mineral Phase	Fe/Al/Ca/Si/P-containing minerals from wastewater and coagulants	Usually ash/mineral impurities from precursor materials	More heterogeneous mineral phases from sludge ash and activated carbon impurities	[32,33]
BET Surface Area	Usually low because of compact biological flocs and mineral dilution	High due to developed micro/mesoporous carbon structure	Lower than isolated activated carbon due to pore blockage by sludge organics/minerals	[32-34]
Pore Structure	Limited intrinsic porosity; dominated by sludge floc structure	Well-developed micropore and mesopore network	Intermediate pore structure controlled by carbon loading and sludge matrix coverage	[32-34]
Moisture Content	High water content before drying/dewatering	Usually low after regeneration/drying	High because sludge water matrix remains associated with spent carbon	[11]
Heavy Metal Association	Associated with EPS, sulfides, phosphates and mineral surfaces	Adsorbed on carbon surface or trapped in mineral impurities	Distributed among carbon surface, sludge minerals, EPS and adsorbed contaminants	[33,35]
Microwave Response	Mainly controlled by moisture, ions and mineral components	Strong dielectric loss from carbon framework	Heterogeneous microwave absorption due to carbon-organic-mineral interfaces	[11,36,37]
Regeneration Objective	Stabilization/resource recovery	Adsorbate removal and pore restoration	Simultaneous recovery of carbon adsorption function and control of pollutant redistribution	[11,32,37]

2.3 Environmental Value and Risks of SACLS

The treatment objective is not simply to maximize char yield. Regeneration should restore accessible porosity, suitable surface chemistry, mechanical integrity, adsorption capacity, and application-specific selectivity while avoiding unacceptable contaminant release or environmental reactivity. Although the embedded carbonaceous fraction retains substantial reuse potential, the surrounding sludge matrix also concentrates organic pollutants, salts, mineral phases, and heavy metals, making SACLS fundamentally different from both conventional sewage sludge and isolated spent activated carbon. Environmental performance therefore cannot be judged from contaminant concentrations in the regenerated char alone. Organic-matter loss may increase the apparent concentration of non-volatile metals without increasing their absolute mass, whereas lower char concentrations may reflect transfer to particles, condensates, deposits, or downstream traps rather than actual destruction. Regeneration performance and environmental safety should consequently be evaluated on a common feed-mass basis and within a system boundary that includes all recoverable and releasable product phases. The distinctive characteristics, treatment objectives, and analytical requirements of SACLS relative to conventional sewage sludge and isolated spent activated carbon are summarized in **Table 2**.

Table 2. Distinctive features of SACLS relative to conventional sewage sludge and isolated spent activated carbon

Feature	Conventional Sewage Sludge	Isolated Spent Activated Carbon	SACLS
Dominant Matrix	Biomass-derived organics, water, and ash-forming minerals	Porous carbon with adsorbates and residual mineral matter	Interpenetrating carbon-organic-mineral matrix with treatment-derived additives
Microwave Response	Often limited by moisture loss and variable ash/mineral response	Generally strong carbon-mediated absorption	Strong but spatially heterogeneous absorption; carbon particles may create localized hot spots
Primary Treatment Objective	Volume reduction, stabilization, and energy/material recovery	Adsorbate removal and restoration of pore accessibility	Simultaneous sludge conversion and recovery of adsorbent function
Principal Risk Blind Spot	Product-focused evaluation may overlook aerosols and condensates	Carbon loss and incomplete destruction of concentrated adsorbates	Cross-phase transfer of particles, metals, organic products, and EPFRs
Minimum Analytical Requirement	Product yields and bulk contaminant fate	Pore structure, adsorption capacity, and carbon yield	Full product mass balance plus regeneration, particle-resolved emissions, metal speciation, and radical reactivity

NOTE: SACLS: spent activated carbon-laden sludge; EPFRs: environmentally persistent free radicals.

2.4 Regeneration Mechanisms of SACLS-Derived Activated Carbon

Spent activated carbon progressively loses adsorption performance through pore blockage, competitive adsorption, deposition of inorganic matter, accumulation of strongly retained contaminants, and modification of surface functional groups. Thermal regeneration aims to reverse these effects by removing or transforming retained species and restoring access to the internal pore network. During heating, weakly bound compounds may first be desorbed, whereas more strongly retained organic adsorbates undergo cracking, devolatilization, carbonization, or partial gasification. These reactions can reopen blocked pores, remove deposited organic matter, and reconstruct the surface chemistry of the carbonaceous matrix. At the same time, secondary reactions may form additional carbonaceous deposits, alter micropore dimensions, remove oxygen-containing functional groups, or promote mineral deposition within the pore structure. Regeneration therefore involves competing processes of pore recovery, surface reconstruction, secondary deposition, and carbon loss. The most effective regeneration condition is consequently not necessarily the condition with the highest treatment temperature or the greatest apparent contaminant removal. Rather, it is the condition that sufficiently removes or transforms adsorbates while preserving the carbon framework, restoring application-relevant pore accessibility, and limiting the generation or transfer of secondary pollutants.

2.5 Microwave-Assisted Regeneration and Matrix Effects

Conventional thermal regeneration relies on heat transfer from the reactor wall to the particle surface and interior. Although technically established, it often requires long residence times and may treat wet, aggregated, or heterogeneous materials non-uniformly. Excessive oxidation or gasification can also cause carbon loss, reduce mechanical strength, and alter pore-size distribution, particularly when activated carbon is embedded in a moisture- and mineral-rich sludge matrix. Microwave heating instead deposits electromagnetic energy directly within microwave-absorbing domains. Because activated carbon is an effective microwave absorber, this mode of heating can accelerate adsorbate desorption, cracking, and pore redevelopment. Microwave regeneration should not, however, be regarded simply as faster conventional heating. Ania *et al.*[38] showed that microwave treatment rapidly regenerated phenol-loaded activated carbon and produced a pore structure different from that obtained by conventional heating, indicating that spatial and temporal energy deposition affects desorption, vapor transport, and carbon restructuring. Microwave regeneration has also been demonstrated for activated carbons loaded with persistent or strongly retained contaminants. Its performance depends on activated-carbon properties, microwave power and irradiation time, pollutant characteristics, and carbon loss[32]. Adsorption-microwave treatment restored granular activated carbon used for ester-containing wastewater[17], while pyrolysis regenerated spent powdered activated carbon and recovered substantial surface area and phosphorus adsorption capacity[18]. These studies confirm technical feasibility, but regeneration must be assessed together with carbon yield, pore structure, energy use, residual contaminants, and releases to gaseous, particulate, and condensable streams. Selective microwave absorption may improve regeneration while also causing local overheating, carbon burn-off, and contaminant volatilization.

In isolated spent activated carbon, the carbon particle is both the principal microwave absorber and the regeneration target. In SACLS, it is surrounded by water, sludge-derived organic matter, microbial residues, minerals, coagulant-derived phases, and treatment chemicals. This heterogeneous matrix modifies dielectric behavior, heat and mass transfer, vapor-solid interactions, and contaminant fate. During initial heating, moisture may dominate microwave absorption and consume energy through evaporation. As

drying and carbonization proceed, carbon-rich domains can heat more rapidly than adjacent mineral-rich regions, producing spatial temperature gradients and localized carbon-organic or carbon-mineral hot spots. Meanwhile, sludge-derived vapors may be readsorbed, cracked on carbon surfaces, or converted into secondary char that blocks pores. Mineral phases may protect the carbon framework, catalyze gasification, alter surface reactions, or deposit within the pore network. These interactions explain why results obtained for isolated spent activated carbon cannot be transferred directly to SACLS. Strong microwave absorption may enhance adsorbate removal and pore recovery, but it may also accelerate carbon loss, pore widening or collapse, mineral volatilization, and fine-particle formation. Regeneration should therefore be evaluated using carbon yield, pore-size distribution, surface chemistry, adsorption capacity and kinetics, mechanical stability, repeated-use performance, leaching, residual organics, and radical-mediated reactivity[39]. The conceptual mechanism of microwave-induced thermal heterogeneity and interfacial reactions in SACLS is summarized in **Figure. 2**. The figure highlights selective microwave absorption by carbonaceous domains and the resulting formation of local hot spots, which may simultaneously enhance regeneration and promote secondary pollutant transformation.

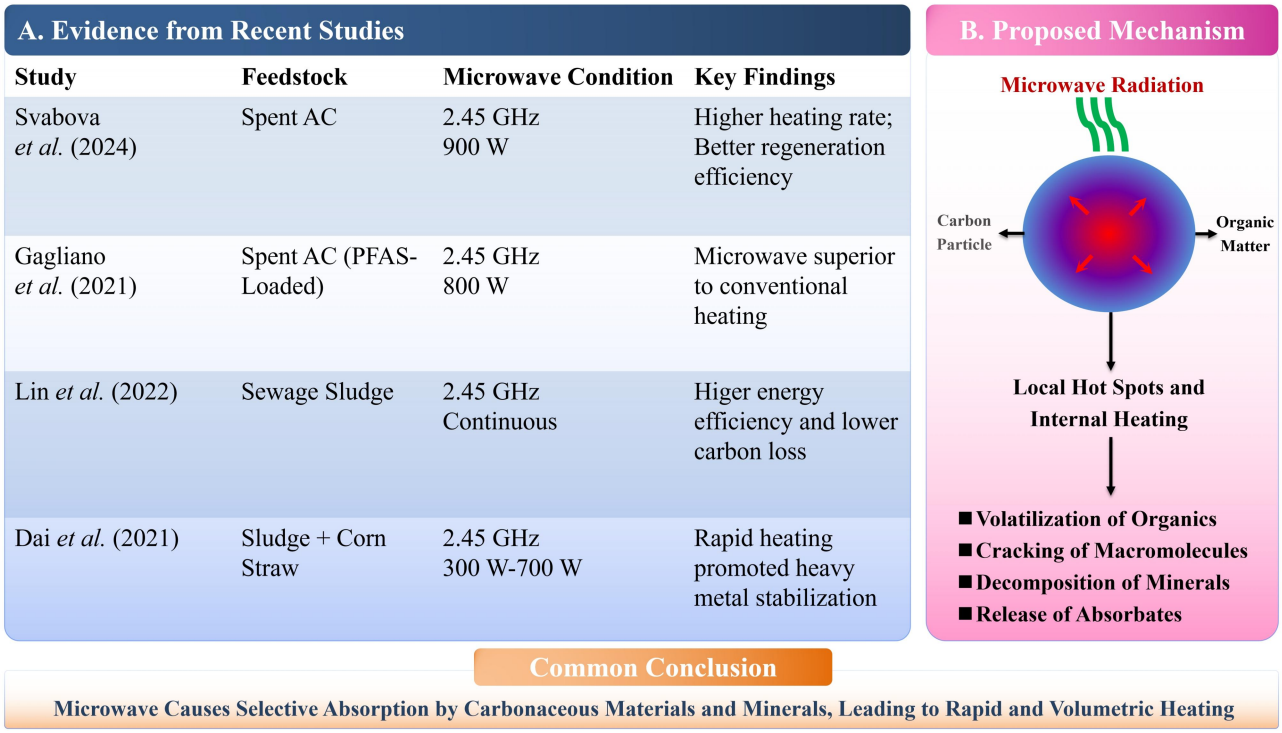


Figure. 2 Microwave-induced thermal heterogeneity and interfacial reactions in SACLS. **NOTE:** AC: Activated Carbon; PFAS: Perfluoroalkyl and Polyfluoroalkyl Substances. Copyright: The figure was originally created by the authors using Microsoft PowerPoint and Adobe Photoshop. No copyrighted materials from other sources were used.

3. Microwave Pyrolysis Processes and Particulate Formation Mechanisms

3.1 Composition-Dependent Microwave Absorption and Heating

Microwave heating of SACLS depends strongly on feedstock composition and cannot be represented by applied power alone. Early studies of sewage-sludge microwave pyrolysis showed that wet sludge may not reach effective pyrolysis temperatures without an additional microwave absorber. Although moisture initially promotes microwave coupling, much of the supplied energy is consumed by evaporation, after which the remaining organic and mineral fractions may absorb microwaves weakly or unevenly. Domínguez *et al.*[40,41] further showed that microwave and conventional heating can produce different liquid, gas, and solid yields even at comparable apparent temperatures. These findings support a central feature of SACLS: the embedded carbonaceous fraction acts simultaneously as the regeneration target, a microwave susceptor, and a reactive surface for vapor conversion.

The microwave response of SACLS reflects the combined effects of moisture, sludge-derived organic matter, activated carbon, ash-forming minerals, and treatment-derived additives. Antunes *et al.*[42] showed that moisture content, ash composition, and added susceptors substantially affect the dielectric behavior of sewage biosolids and the properties of the resulting biochar. In SACLS, activated-carbon particles generally absorb microwaves more strongly than surrounding organic- or mineral-rich regions, although the extent of this contrast depends on carbon loading, particle size, pore structure, mineral coverage, contaminant loading, and spatial distribution[43].

Feedstock composition also governs subsequent heat and mass transfer. Moisture delays pyrolysis through evaporation, carbon-rich domains promote local heating and devolatilization, and mineral phases may catalyze tar cracking, alter gas composition, or retain released inorganic species. Consequently, identical nominal microwave powers can produce markedly different thermal histories, product distributions, and pollutant-release profiles among SACLS feedstocks.

Representative experimental evidence for these feedstock- and heating-mode-dependent effects is compiled in **Figure. 3**. Oh *et al.*[37] demonstrated distinct char, liquid, and gas distributions

among raw and digested organic wastes during microwave-assisted pyrolysis and further identified correlations between feedstock composition and pyrolysis-product distribution. Li *et al.*[18] further demonstrated that pyrolysis temperature and residence time strongly influenced spent powdered activated-carbon regeneration, with subsequent recovery of adsorption performance. Collectively, these results illustrate that both feedstock characteristics and regeneration conditions govern the effectiveness of carbonaceous-residue valorization (**Figure. 3**).

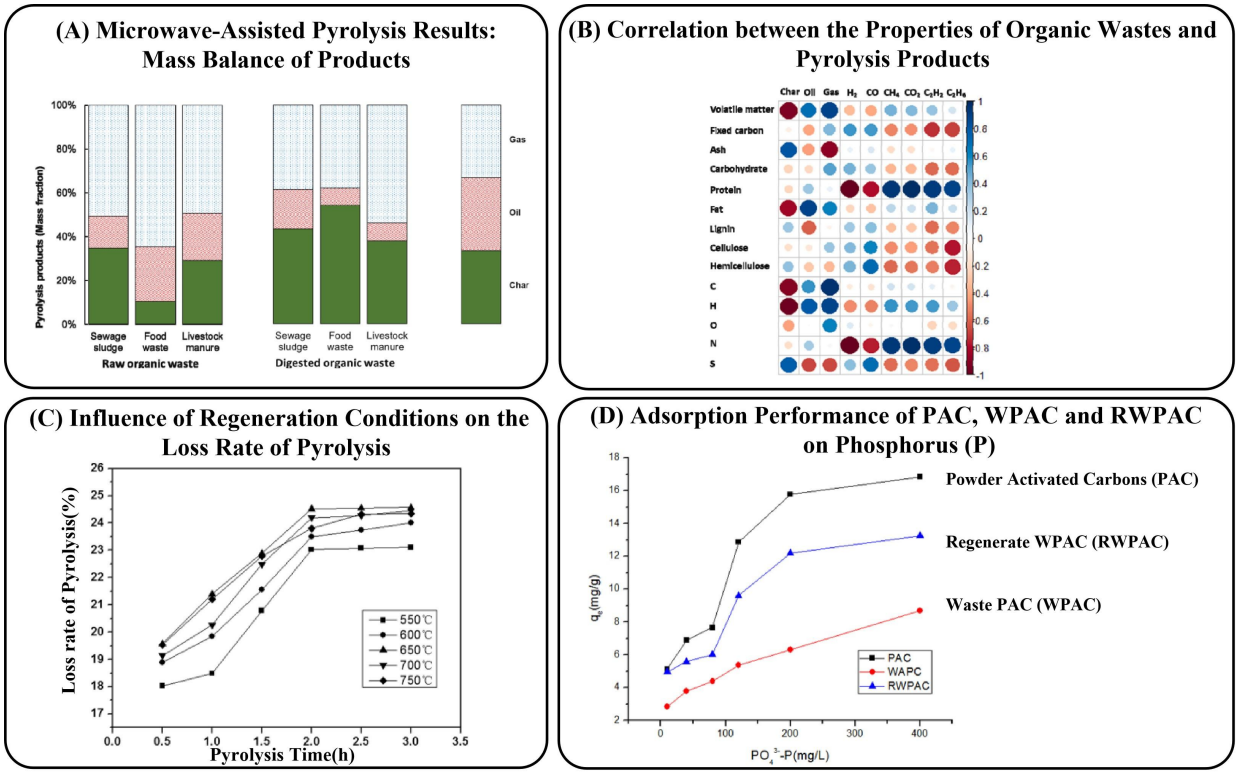


Figure. 3 Representative experimental evidence for microwave-assisted pyrolysis and activated-carbon regeneration. (A) Mass balance of products generated from microwave-assisted pyrolysis of raw and digested organic wastes and (B) correlations between the properties of organic wastes and pyrolysis products, reproduced from Oh *et al.*[37]; (C) Influence of regeneration conditions on the loss rate of pyrolysis and (D) Adsorption performance of PAC, WPAC and RWPAC on phosphorus (P), reproduced from Li *et al.*[18]. Copyright: Panels (A) and (B) are reproduced from Oh *et al.*[37] under the Creative Commons Attribution 4.0 International License (CC BY 4.0). Panels (C) and (D) are reproduced from Li *et al.*[18] under the Creative Commons Attribution 4.0 International License (CC BY 4.0).

3.2 Microwave Energy Deposition and Local Hot Spots

Unlike conventional heating, microwave energy is deposited directly within absorbing domains, allowing rapid internal heating but also creating spatially heterogeneous temperature fields. In SACLS, carbon-rich regions may heat more intensely than adjacent organic- or mineral-rich domains, generating local temperature gradients at carbon-organic and carbon-mineral interfaces. This energy distribution changes continuously during treatment. As water evaporates, organic matter decomposes, and the residual carbon becomes more aromatic, the dielectric properties and microwave penetration behavior of the material also evolve[44]. Applied power therefore does not correspond to a constant heating rate or a uniform temperature field, and carbon-rich regions may become increasingly dominant absorbers during drying and carbonization.

Interfacial hot spots can simultaneously accelerate adsorbate desorption, devolatilization, tar cracking, aromatization, carbon gasification, and mineral decomposition. They may also promote salt and metal volatilization followed by downstream nucleation or condensation, while increasing carbon burn-off, altering micropore structure, and generating defects that stabilize environmentally persistent free radicals. Reviews of microwave-assisted sewage-sludge pyrolysis identify hot-spot measurement, energy-efficiency assessment, reactor scale-up, and product safety as persistent uncertainties[45-50]. These issues are particularly important for SACLS because its strongly absorbing carbonaceous phase is heterogeneously distributed.

3.3 Limitations of Apparent Temperature as a Process Descriptor

Microwave sludge-pyrolysis studies commonly report applied power, final reactor temperature, residence time, and carrier-gas flow. Although useful for comparison, these parameters do not fully describe the thermal history of individual activated-carbon particles or carbon-organic and carbon-mineral interfaces. A single measured temperature may therefore conceal substantial spatial and temporal heterogeneity within the reactor bed.

Thermocouple readings depend on probe position, contact with surrounding solids, electromagnetic interference, and local gas flow. Measurements taken in colder regions may underestimate the temperature of nearby carbon-rich domains, whereas probes located close to strongly absorbing particles may overestimate the bulk temperature[51]. Infrared measurements avoid direct probe interference but generally represent only visible surfaces and may not capture internal gradients in opaque or heterogeneous beds. Because activated carbon absorbs microwaves strongly, individual particles may reach temperatures substantially higher than the measured bulk or surface value. These local differences can alter desorption, devolatilization, vapor-solid reactions, tar conversion,

mineral transformation, and particulate formation. Nominal reactor temperature should therefore be regarded as an incomplete indicator of reaction severity. Claims of a distinct "microwave effect" should also be interpreted cautiously. Differences between microwave and conventional pyrolysis may arise from heating rate, spatial temperature gradients, vapor residence time, vapor-solid contact, mineral catalysis, and interfacial temperatures rather than from a universal non-thermal mechanism. Meaningful comparisons therefore require equivalent and, where possible, spatially resolved thermal histories.

3.4 Major Pathways of Particulate Formation

Particulate matter generated during SACLS pyrolysis can be grouped into three overlapping categories: primary entrained particles, organic condensation particles, and inorganic nucleation particles. This mechanistic classification is more informative than total particulate mass because each pathway responds differently to feedstock composition, local temperature, gas flow, vapor residence time, and downstream cooling.

Primary particles arise from fragmentation, abrasion, mineral exfoliation, and entrainment of pre-existing solids. Sludge aggregates may disintegrate during drying and devolatilization, while activated-carbon particles, mineral coatings, ash, and secondary char may detach and enter the gas stream. Their abundance and size distribution are controlled mainly by feed preparation, particle size, gas velocity, mixing, and reactor configuration. Organic condensation particles form when volatile organic compounds and tar vapors cool, become supersaturated, and nucleate or condense onto existing surfaces. They may form in cooler reactor regions, transfer lines, dilution systems, or sampling devices rather than directly in the hot reaction zone. Dai *et al.*[52] showed that heating mode and temperature influence the distribution of polycyclic aromatic hydrocarbons among gaseous, liquid, and solid products, indicating that organic contaminants may be redistributed rather than destroyed. Ko *et al.*[53] further demonstrated that pyrolysis temperature and vapor residence time strongly affect particulate-bound priority polycyclic aromatic hydrocarbons. Inorganic nucleation particles form when salts, metal compounds, or other mineral-derived species volatilize at elevated local temperatures and subsequently nucleate or condense during cooling. These vapors may form ultrafine particles through homogeneous nucleation or condense heterogeneously onto entrained ash and carbonaceous particles, producing mixed organic-inorganic agglomerates.

Temperature-resolved experiments indicate that lower-temperature particles are often dominated by condensed carbonaceous material, whereas inorganic contributions become more important at approximately 500 °C–700 °C. Pb and Cd concentrations in collected particles have also been reported to increase at higher temperatures[19]. However, this transition is not universal because feed composition, local hot spots, vapor residence time, transfer-line temperature, and sampling conditions can shift the observed particle distribution.

The major particulate-formation pathways and their principal controlling factors are summarized in **Figure. 4**. These pathways include direct entrainment of carbon/mineral fragments, condensation of vaporized organics, nucleation of volatile inorganic or metal species, and subsequent coagulation and surface reactions.

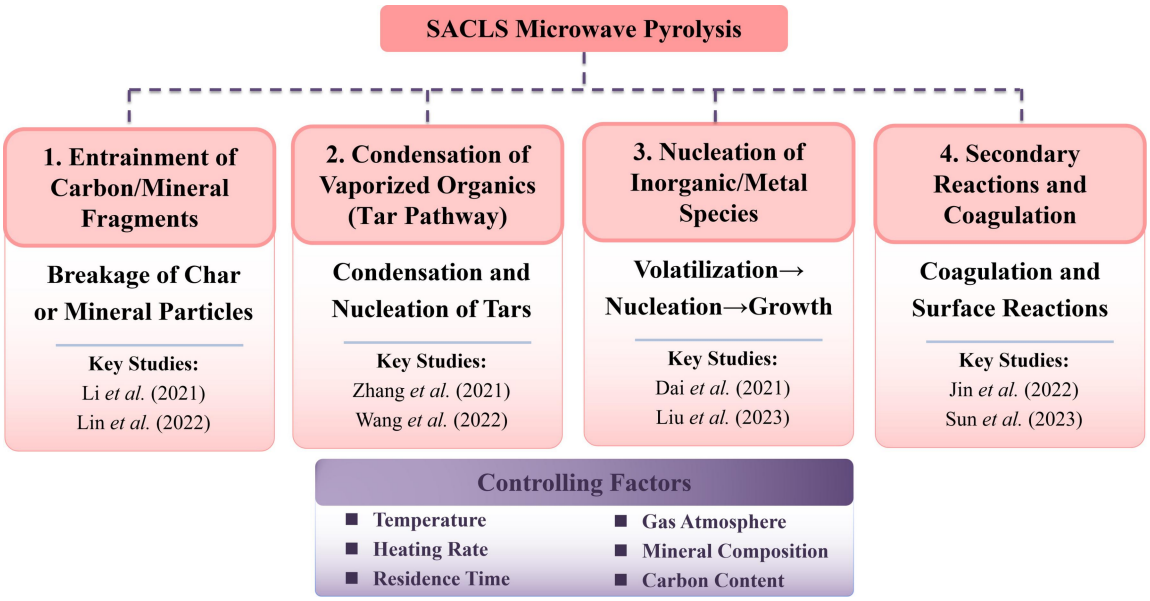


Figure. 4 Particulate formation pathways during SACLS microwave pyrolysis. Copyright: The figure was originally created by the authors using Microsoft PowerPoint and Adobe Photoshop. No copyrighted materials from other sources were used.

3.5 Dual Effects of Spent Activated Carbon on Particulate Formation

Spent activated carbon can either suppress or promote particulate formation during SACLS microwave pyrolysis. Its pore network and external surface can adsorb volatile and semi-volatile compounds, thereby delaying or reducing their immediate transfer into the particulate phase. Carbon surfaces may also catalyze cracking, deoxygenation, condensation, and aromatization reactions, converting condensable vapors into lighter gases or secondary carbonaceous deposits. These interactions can decrease the amount of condensable material leaving the hot reaction zone, but they may also promote secondary char formation on activated-carbon surfaces. When secondary carbon blocks micropores or accumulates on external surfaces, adsorption recovery may be reduced even if total char yield increases. The fate of adsorbed vapors therefore depends on local temperature, pore accessibility, mineral coverage, vapor composition, and vapor-solid contact time. Conversely, activated carbon may increase particulate emissions through several mechanisms. Selective microwave absorption can generate localized overheating and promote the volatilization of mineral- and metal-containing species. Thermal stress and mechanical mixing may fragment carbon particles or detach mineral coatings accumulated

during wastewater treatment. Adsorbed contaminants, inorganic salts, and coagulant-derived phases on spent carbon can also act as precursors for organic condensation particles or inorganic nucleation particles. In addition, carbon-rich primary particles can provide surfaces for the downstream condensation of tar vapors and volatilized metals.

Whether spent activated carbon suppresses or enhances particulate formation therefore depends on its loading history, particle size, pore structure, mineral coverage, contaminant inventory, heating rate, local temperature, gas velocity, and vapor-solid contact time. This dual role cannot be resolved by comparing total particulate mass alone. Particle number concentration, aerodynamic size, morphology, elemental composition, organic carbon and elemental carbon contents, mineral phases, surface functionality, and radical activity should also be determined. Size-resolved characterization is particularly important because submicrometer particles have high specific surface areas, long atmospheric residence times, and relatively high mobility. They may preferentially concentrate volatile metals, condensed aromatic compounds, carbon defects, and redox-active mineral sites. However, particulate collection and handling may also cause the loss of semi-volatile compounds or alter radical signals. Analytical procedures must therefore distinguish particles entrained directly from the hot zone from particles formed through downstream cooling and condensation.

4. Cross-Phase Migration and Transformation of Heavy Metals

Particulate formation provides a direct pathway for metal redistribution because volatilized species may nucleate, condense on mineral particles, or adsorb on carbonaceous aerosols. Metal fate must therefore be evaluated across char, particles, condensates, deposits, and terminal collection media rather than inferred from regenerated-char concentrations alone. The possible migration pathways and final distribution of heavy metals among char, particles, condensates, and deposits are illustrated in **Figure. 5**.

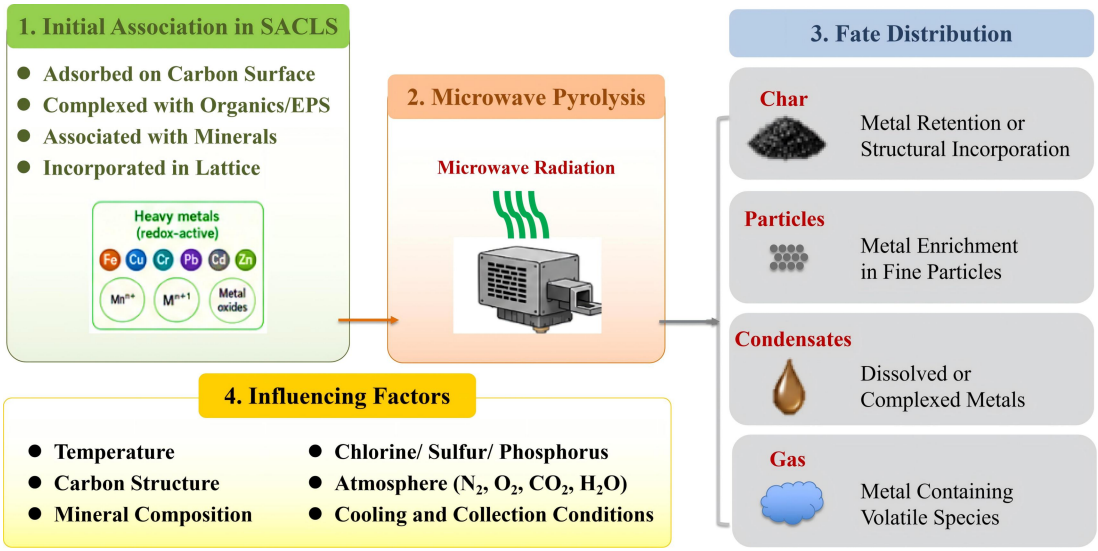


Figure. 5 Cross-phase migration pathways and fate distribution of heavy metals during SACLS microwave pyrolysis. Copyright: The figure was originally created by the authors using Microsoft PowerPoint and Adobe Photoshop. No copyrighted materials from other sources were used.

4.1 Retention, Enrichment, and Volatilization of Heavy Metals

During pyrolysis, heavy metals undergo competing retention, transformation, and release. Their concentrations in char may rise as organics and carbon are removed, while decomposition of organic complexes, redox changes, and reactions with sulfur-, chlorine-, phosphorus-, silicon-, aluminum-, iron-, and calcium-containing phases alter chemical form. Some metals remain in char or newly formed minerals; others volatilize and later condense in particles, liquids, or deposits[54].

Volatility alone cannot predict migration. Initial speciation, association with organics or minerals, local redox conditions, and available inorganic ligands determine whether a metal is immobilized, converted into a stable compound, or released as vapor or particulate matter[20-22]. Local microwave hot spots further weaken the value of nominal reactor temperature as a predictor. Increasing pyrolysis temperature can shift some metals from labile to residual fractions, but responses are element-specific[55,56]. Consequently, higher char concentrations may reflect mass loss rather than increased risk, whereas lower concentrations may indicate cross-phase transfer rather than detoxification[54]. Concentrations must therefore be combined with product yields and expressed as absolute recovery relative to the initial feed.

4.2 Distribution of Heavy Metals among Char, Particles, Condensates, and Deposits

Regenerated char is usually the dominant metal-containing product because many non-volatile elements remain associated with ash or enter transformed mineral phases. Metals with strong affinity for phosphates, silicates, aluminosilicates, sulfides, or oxides may be retained even as their concentrations increase through organic-matter loss. Such enrichment does not necessarily imply greater mobility, although a small leachable fraction may still control risk.

More volatile species can enter the gas phase and enrich fine particles. Pb and Cd enrichment at higher sludge-pyrolysis temperatures illustrates this pathway[19]. Metals may nucleate as ultrafine inorganic particles, condense on ash, or adsorb on carbonaceous aerosols. Although these fractions can contain a small share of total metal mass, their mobility, surface area, and inhalation relevance may be high. Their small aerodynamic diameter also increases residence time and reduces capture by conventional coarse-particle separators, so a minor mass fraction can still dominate

exposure-relevant risk.

Aqueous and organic condensates can contain soluble salts, metal-organic complexes, colloids, and entrained particles. Reactor walls, transfer lines, filters, sorbents, and impingers are also important sinks because vapors and particle-bound metals deposit as the stream cools. Excluding these products creates apparent mass deficits and can misclassify redistribution as gaseous loss. Final phase distributions therefore depend on element identity, initial speciation, matrix composition, atmosphere, vapor residence time, and downstream temperature history. Metal partitioning between aqueous and organic condensates may also change during phase separation or storage, making separate analysis of dissolved, colloidal, and suspended fractions preferable. Deposits are operationally important because they can be remobilized during cleaning and maintenance, creating a secondary waste stream that is absent from routine product-yield calculations.

4.3 Whole-Process Mass Balance of Heavy Metals

A whole-process mass balance is essential for distinguishing stabilization from redistribution. For each target metal, the recovered mass in char, size-resolved particles, aqueous and organic condensates, reactor and transfer-line deposits, and terminal traps should be calculated from product concentration and recovered mass or volume. Results should be reported as absolute mass, percentage of the feed inventory, and overall recovery. Where size-resolved sampling is used, each stage should be weighed independently and corrected for substrate blanks and handling losses. The particle enrichment of Pb and Cd reported by Li *et al*.[19] would be missed by feed-and-char analysis. Poor recovery should likewise not be assigned automatically to unmeasured gaseous species because metals may reside in deposits, condensates, or downstream sorbents. The sampling boundary should therefore include reactor solids, loose ash, deposits, condensers, filters, impactor stages, impingers, and terminal traps wherever practicable. Analytical methods and blanks must be validated for carbon-rich solids, minerals, water, and tar-containing matrices. Mass-balance closure should be treated as a quality-control criterion; unresolved fractions should be reported rather than interpreted speculatively. Digestion recovery should be checked with matrix-matched reference materials or spike tests because refractory mineral phases and carbon-rich matrices can produce element-specific bias.

4.4 Particle-Size-Dependent Metal Enrichment

Particle size is a critical dimension of metal transfer. Volatilized compounds may nucleate homogeneously, condense on ash or carbonaceous aerosols, or adsorb after cooling. Ultrafine particles can be strongly enriched because of their high surface area, whereas coarse fractions generally originate from feed fragmentation, mineral exfoliation, carbon attrition, and mechanical entrainment. The resulting size distribution determines atmospheric persistence, respiratory deposition, surface reactivity, and the efficiency of downstream control devices. Metal concentration alone is insufficient for comparing size fractions. A small ultrafine fraction may have a high concentration but contain little absolute mass, while a lower concentration in a large coarse fraction may represent a larger inventory. Enrichment factors should therefore be reported with particle mass distributions and the percentage of feed metal in each size class.

Size-resolved information is also required for emission control. Cyclones mainly remove coarse particles, whereas metal-rich submicrometer aerosols require high-efficiency filtration or electrostatic capture. Because coagulation, condensation, and deposition can change particle size during sampling, transfer-line temperature, dilution, residence time, and collection configuration must be documented. These data distinguish mechanically entrained mineral particles from secondary metal-rich aerosols and identify the fractions most relevant to mobility and exposure. Leaching or bioaccessibility should be measured by size class where possible because surface-enriched condensates can behave differently from metals incorporated into coarse mineral particles.

4.5 Controls Imposed by the Carbon-Mineral Matrix

The carbon-mineral matrix controls metal retention through adsorption, oxygen-containing functional groups, mineral coatings, pore confinement, and association with adsorbed organics. Pyrolysis removes some functional groups, increases aromaticity, and creates reducing microenvironments that can alter metal valence and coordination. Mineral phases may immobilize metals by adsorption, encapsulation, or formation of phosphates, silicates, aluminosilicates, sulfides, and oxides; thermal treatment can also convert amorphous associations into more crystalline and less soluble structures[57].

Chlorine can enhance volatility through metal-chloride formation, whereas sulfur and phosphorus may favor less volatile sulfides or phosphates. The net outcome depends on temperature, atmosphere, competing ions, mineral accessibility, and reaction sequence, with local hot spots creating transient high-temperature conditions. Activated carbon can adsorb released metals and support heterogeneous condensation, but it can also promote reduction, volatilization, or transfer through particle fragmentation. The multiple Pb(II) sorption mechanisms reported for sludge-derived biochar[22] illustrate why metal retention cannot be attributed to carbon alone: the same multiphase matrix can immobilize metals in char or provide surfaces for metal-rich particle formation.

4.6 Metal Speciation, Leaching, and Environmental Risks

Total metal concentration is only a partial risk indicator. Environmental relevance depends on speciation, mineral association, oxidation state, particle size, leachability, bioaccessibility, and exposure pathway. Pyrolysis may increase metal concentration in char through mass loss while shifting metals into less mobile fractions; conversely, a small mass transferred to fine particles or condensates may be more available. Temperature-dependent stabilization has been reported for several metals, but the response is element- and feedstock-specific[55,56]. Leaching tests should accompany concentration and mass-balance measurements under pH, ionic strength, redox, and dissolved-organic-matter conditions representative of intended use. Repeated adsorption-regeneration cycles are also important because mineral coatings and previously inaccessible phases can change. Fine particles require separate leaching or bioaccessibility tests because surface-enriched or amorphous metals may dissolve more readily, and coexisting organics or EPFRs may alter redox state and dissolution[58]. Condensates and periodically removed deposits should be assessed directly because they can contain mobile dissolved, colloidal, or particle-bound metals. For water-treatment reuse, tests should also consider whether target adsorption mobilizes metals through ion exchange, complexation, or pH change. For disposal or incorporation into materials, weathering and abrasion may be more relevant than short-term aqueous extraction.

Risk interpretation should distinguish total inventory, mobility, and exposure. Stable metal-rich char may constrain reuse without presenting high immediate mobility, whereas a low-mass ultrafine

fraction or aqueous condensate may require stringent control[59]. A defensible assessment therefore combines absolute recovery, phase and size distribution, oxidation state, speciation, leaching, bioaccessibility, and exposure-relevant endpoints, avoiding the assumption that apparent char stabilization represents whole-process risk reduction. Regulatory comparison should therefore be linked to the intended product use and exposure pathway rather than applied as a single generic threshold.

5. EPFRs and Their Coupled Evolution with Heavy Metals

Heavy-metal redistribution intersects with EPFR formation because aromatic carbon, condensed organics, mineral surfaces, and redox-active metals coexist in char, particles, condensates, and deposits. These interfaces can support radical formation, stabilization, aging, and ROS generation. Evidence is strongest for metal-assisted EPFR formation; the reverse influence of EPFRs on metal speciation and migration remains plausible but insufficiently demonstrated. Experimental evidence indicates that EPFR evolution should be interpreted in the context of the preceding thermal-conversion history. As summarized in **Figure. 6**, Li *et al.*[19] demonstrated that pyrolysis temperature markedly influences particulate formation, particle morphology, and the associated redistribution of heavy metals during sewage-sludge pyrolysis. Wang *et al.*[60] further showed that the abundance and characteristics of biochar-bound EPFRs depend strongly on feedstock type and pyrolysis temperature, and that the radical population can continue to evolve during subsequent storage. Collectively, these observations indicate that particulate formation, metal redistribution, and EPFR evolution are closely linked to thermal-conversion conditions and post-pyrolysis aging, highlighting the need to evaluate these processes as coupled rather than isolated endpoints (**Figure. 6**).

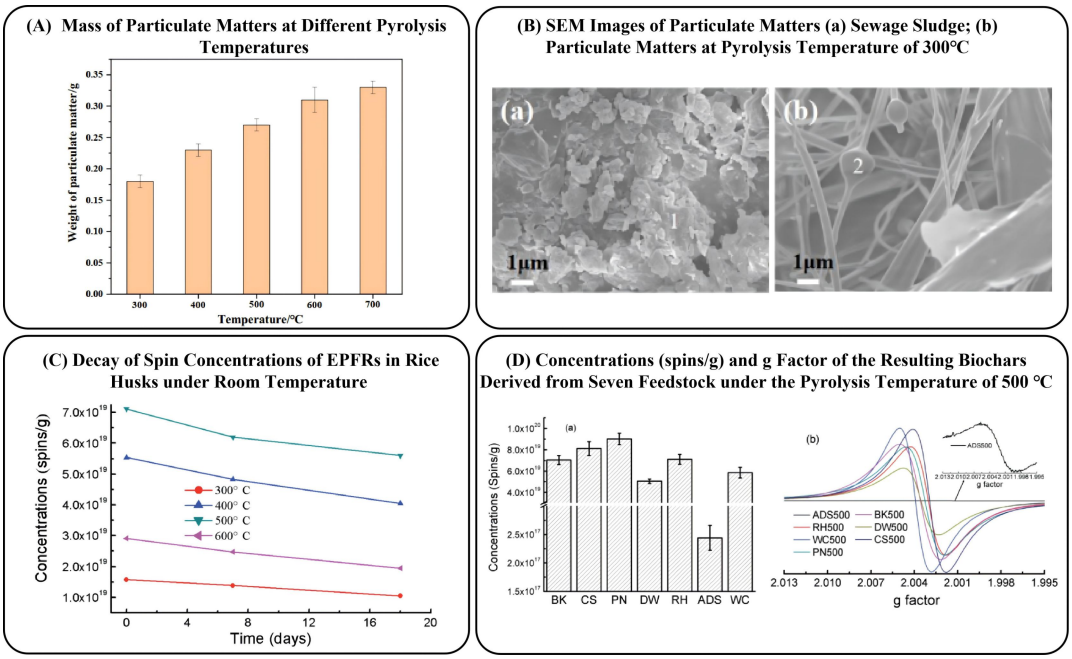


Figure. 6 Representative experimental evidence for particulate formation, heavy-metal redistribution, and EPFR evolution during pyrolysis. (A) Mass of particulate matters at different pyrolysis temperatures and (B) SEM images of particulate matters (a) Sewage sludge, (b) particulate matters at pyrolysis temperature of 300 °C, reproduced from Li *et al.*[19]; (C) Decay of spin concentrations of EPFRs in rice husks under room temperature and (D) Concentrations (spins/g) and g factor of the resulting biochars derived from seven feedstock under the pyrolysis temperature of 500 °C, reproduced from Wang *et al.*[60]. Copyright: Panels (A) and (B) are reproduced from Li *et al.*[19] under the Creative Commons Attribution 4.0 International License (CC BY 4.0). Panels (C) and (D) are reproduced from Wang *et al.*[60] under the Creative Commons Attribution 3.0 Unported Licence (CC BY 3.0).

5.1 Formation and Stabilization Mechanisms of EPFRs

EPFRs are paramagnetic species that persist far longer than transient aqueous or gas-phase radicals because unpaired electrons are stabilized on conjugated aromatic structures, defects, oxygen-containing groups, and mineral or metal-oxide surfaces. Their occurrence in combustion-derived PM2.5 demonstrates persistence after high-temperature formation[25]. During SACLS pyrolysis, decomposition and aromatization of sludge organics create conjugated structures and defects, while cleavage of functional groups, incomplete condensation, and secondary carbonization can preserve carbon- or oxygen-centered radical sites. Treatment severity can therefore produce non-monotonic trends: moderate carbonization may maximize defect-associated radicals, whereas extensive graphitization or radical recombination can reduce the measurable population.

Metal oxides provide an additional pathway. Organic precursors can chemisorb on Fe(III) oxide, transfer an electron to the surface, and form stabilized radicals[26]. Radical formation therefore depends not only on temperature but also on metal identity, oxidation state, coordination, and accessibility. EPFRs have been quantified in municipal and industrial sludge chars[23], and iron and natural organic matter jointly controlled radical generation in Fenton-conditioned sludge[24]. Sludge-derived biochars contain carbon-centered, oxygen-centered, and oxygen-adjacent carbon-centered radicals whose distributions vary with temperature, sludge composition, and biomass addition[61]. Different signatures in incineration ash and pyrolysis biochar further demonstrate the importance of thermal route and the mineral-carbon matrix[62,63]. EPFR evolution should thus be understood as coupled carbonization, defect generation, mineral transformation, and interfacial electron

transfer rather than as a single temperature-controlled reaction. The observed Electron Paramagnetic Resonance (EPR) signal consequently reflects both the number of radical sites and their stabilization environment, and comparisons across studies require attention to feed composition, thermal history, and measurement conditions.

5.2 Phase Distribution of EPFRs

Most studies measure EPFRs only in cooled bulk char, although radical-active material or precursors may also occur in particles, condensates, and reactor or transfer-line deposits. Char stabilizes radicals through aromatic structures, pore surfaces, defects, functional groups, and embedded minerals. Moderate thermal severity may preserve heterogeneous radical sites, whereas extensive carbon ordering can reduce some defect-associated populations. Bulk analysis can therefore mask redistribution from a relatively immobile char matrix to a smaller but more accessible particle fraction.

Fine particles may be particularly important because high surface area, condensed aromatic compounds, carbon defects, minerals, and redox-active metals are co-located. Primary carbonaceous particles may carry radicals formed in the hot zone, while condensation and nucleation particles can acquire aromatic precursors and metal sites during cooling. Condensates and deposits may contain radical precursors or stabilized surface radicals, but their contribution is poorly constrained because oxygen exposure, solvent handling, phase separation, and sampling alter detectability. Phase-specific EPR analysis should therefore distinguish char, size-resolved particles, deposits, and selected condensate fractions; a high radical concentration in a small particle fraction can have different implications from the same concentration in stable bulk char. Reactor-wall and transfer-line deposits deserve attention because repeated condensation, thermal cycling, and contact with metal-containing surfaces may promote secondary aromatization and radical stabilization. They may also become an occupational exposure source during maintenance[64].

5.3 Effects of Sampling, Storage, and Aging on EPFR Characterization

EPFR measurements are sensitive to collection, moisture, oxygen exposure, storage temperature, and measurement delay. Water can quench or transform surface radicals and affect EPR response; oxygen may either consume radicals or generate new oxygen-associated species while changing metal oxidation state. Continued reactions during storage mean that an EPR spectrum records the population present at analysis, not necessarily that formed during pyrolysis. Storage-induced changes may be phase-specific because condensed organic coatings, mineral surfaces, and pore-confined radicals have different access to water and oxygen[65].

Reports should therefore provide calibrated spin concentration, g-factor, linewidth, dry-mass basis, moisture, storage atmosphere and temperature, and elapsed time from collection to measurement. Time-resolved analyses under inert, air, humid, and aqueous conditions are needed to determine decay, transformation, or secondary formation[66]. Collection and preparation should minimize phase alteration because fine particles can lose semi-volatile precursors, aggressive drying can change surface chemistry, and extraction or filtration can redistribute condensate-associated species. Calibration standards, microwave power used during EPR measurement, sample packing, and replicate variability should also be reported where they affect quantitative comparison.

5.4 Functional reactivity, ROS Generation, and Toxicological Implications

EPFR-associated electron transfer can be functionally useful by activating oxygen, hydrogen peroxide, persulfate, or other oxidants and promoting contaminant degradation. The same reactivity can generate superoxide-related species, hydrogen peroxide, hydroxyl-radical-related oxidants, and oxidative stress when materials contact oxygen and water, particularly in the presence of redox-active metals. This dual functionality is important when regenerated material is proposed as an adsorbent-catalyst or catalyst support, because apparent treatment performance may partly arise from oxidative transformation rather than adsorption alone.

Hazard cannot be inferred from spin concentration alone. It depends on radical type, persistence, surface accessibility, moisture, oxygen, coexisting metals, particle size, aging, and reuse scenario. Fine particles may be especially reactive because they combine high surface area with accessible radical and metal sites, whereas radicals buried in stable char may be less available until leaching, abrasion, or repeated use exposes them. Evaluation should combine EPR, decay kinetics, ROS assays, metal leaching, and exposure-relevant biological or chemical endpoints. Reviews of biochar EPFRs accordingly emphasize context-dependent beneficial and adverse effects[65]. Application-specific tests are therefore essential: catalytic reuse may tolerate controlled radical activity, whereas water-contact or inhalation-relevant applications may require much lower persistent ROS-generating capacity.

5.5 Evidence for Metal-Assisted EPFR Formation

The most direct evidence for metal-EPFR coupling concerns metal-assisted radical formation. Multivalent transition metals can accept or donate electrons while changing oxidation state or coordination, and iron-containing phases are common in sludge as natural minerals, coagulant precipitates, and Fenton-conditioning products. Aromatic or phenolic precursors can chemisorb on metal oxides and transfer an electron to a metal center, producing a resonance-stabilized organic radical; Fe(III) oxide model systems directly support this mechanism[26]. The interfacial mechanism is favored when organic precursors and accessible metal sites are co-located, but can be inhibited by mineral encapsulation or loss of suitable functional groups.

Fenton-conditioned sludge further shows that iron and natural organic matter jointly govern EPFR formation[24]. Other transition-metal oxides may promote stabilization, recombination, or quenching depending on identity, loading, dispersion, mineral coating, and accessibility. Heterogeneous metals also regulate persistent radicals that act as redox-active sites in iron-containing biochar during persulfate activation[63]. These observations support metal-assisted EPFR formation, but correlations between total metal content and EPR intensity do not identify the active phase or prove electron transfer. Oxidation state, local coordination, spatial co-localization, and surface accessibility must also be established. Controlled comparison of metal-free, metal-depleted, and metal-reconstituted matrices would provide stronger causal evidence than correlations among bulk composition, temperature, and radical abundance.

5.6 Possible Effects of EPFRs on Metal Speciation and Migration

The reverse effect of EPFRs on metal behavior is less certain. Radical-mediated electron transfer could change the valence, coordination, surface affinity, or solubility of redox-sensitive metals,

while ROS generated during air or water exposure could oxidize sulfides, alter organic ligands and surface charge, or modify carbonaceous coatings around metal-bearing particles. These processes might either increase or decrease dissolution depending on metal identity, mineral phase, pH, oxygen, and radical chemistry. Radical reactions could also alter organic ligands that complex metals or expose previously shielded mineral surfaces, thereby changing bioaccessibility during aging.

Evidence from reactive biochars shows that persistent radicals and metals can participate in coupled redox processes[63], but it does not demonstrate that EPFRs control metal volatilization, condensation, or particle partitioning during SACLS pyrolysis. These pathways should therefore remain testable hypotheses. Causal evidence requires experiments that vary radical abundance independently of temperature, carbon structure, and mineral content while monitoring metal oxidation state, leaching, and phase distribution. Experiments should include radical quenchers or controlled oxygen exposure and verify that changes are not caused simply by altered pH, mineral dissolution, or carbon oxidation.

5.7 A Testable Three-Stage Metal-EPFR-ROS Coupling Model

A testable metal-EPFR-ROS model comprises three stages. First, co-localization occurs when aromatic precursors, carbon defects, and redox-active metals accumulate on char or particle surfaces during pyrolysis and cooling; activated-carbon pores, mineral coatings, tar deposits, and fine-particle agglomerates can bring them into close contact. Second, interfacial electron transfer produces or stabilizes radicals while changing metal valence or coordination, a pathway most strongly supported for iron-containing systems[24-26]. Third, exposure to oxygen, humidity, or water converts stored electronic reactivity into ROS generation, metal transformation, dissolution, contaminant conversion, or biological stress. The first and second stages may occur in the hot reactor or during downstream cooling, whereas the third is especially relevant during storage, reuse, or environmental release.

Each stage requires distinct evidence. Microscopy and elemental mapping should establish co-localization; synchronized EPR and oxidation-state or coordination measurements should test electron transfer; and controlled aging, ROS, leaching, and biological assays should evaluate environmental activation. Fine particles may amplify coupling through co-enrichment of metals, aromatic precursors, and defects, but statistical association does not establish causality and some metals or mineral coatings may quench radicals. Time ordering is also important: metal volatilization may precede radical stabilization, while subsequent aging can change both metal accessibility and ROS production. The model should therefore be tested with phase-resolved samples collected at defined positions and aging times. On the basis of the literature evidence discussed above, the proposed coupling among precursor transformation, EPFR formation, metal-mediated electron transfer, ROS generation, and environmental reactivity is synthesized in **Figure. 7**. Importantly, the arrows in this framework represent testable mechanistic links rather than universally established causal relationships.

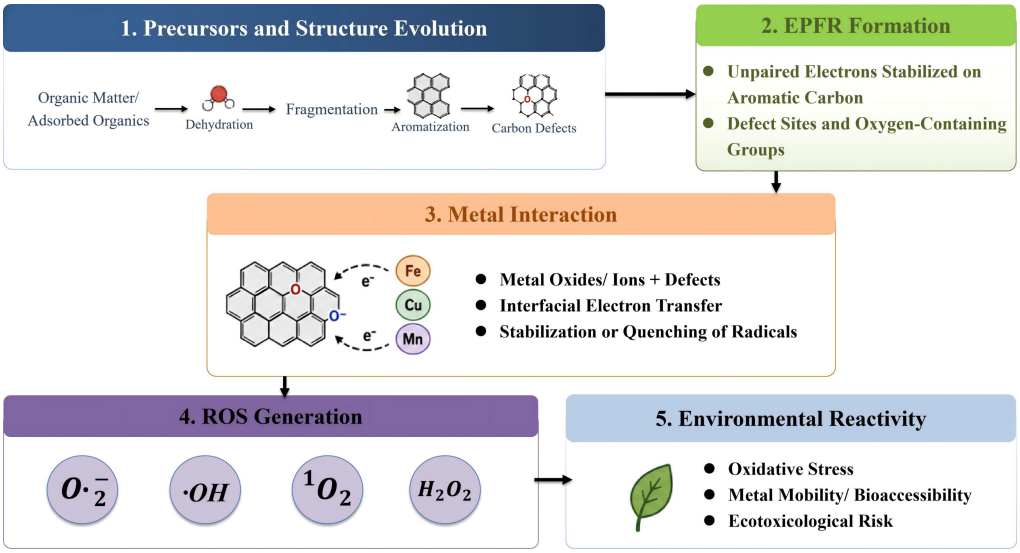


Figure. 7 Coupled evolution of EPFRs, heavy metals and ROS during SACLS thermal conversion. Copyright: The figure was originally created by the authors using Microsoft PowerPoint and Adobe Photoshop. No copyrighted materials from other sources were used.

6. Integrated Assessment of Regeneration Performance and Environmental risks

Microwave pyrolysis should be assessed as a whole process rather than by regenerated-char performance alone. Adsorbent recovery, carbon preservation, energy use, particulate emissions, contaminant redistribution, and exposure-relevant reactivity should be normalized to the initial feed so that improvement in one phase is not achieved by transferring risk to another.

6.1 Limitations of Single-Endpoint Optimization

Optimizing only BET surface area, pore volume, or adsorption capacity can favor severe conditions that improve pore accessibility while increasing carbon loss, energy demand, particles, metal volatilization, or oxidative reactivity. Mild treatment can preserve yield but leave strongly retained adsorbates, condensable organics, unstable precursors, and leachable contaminants. Temperature and heating mode also redistribute polycyclic aromatic hydrocarbons (PAHs) among gas, liquid, particles, and char[52,53], and temperature-dependent PAH leaching has been observed in sludge biochar[55]. Reuse tests must therefore distinguish adsorption of a new target from release of residual adsorbates, dissolved organic carbon, PAHs, and thermogenic products. The optimum should be defined as a constrained operating window, not a single maximum. This is especially important for SACLS because improved char properties can coincide with increased pollutant loading in a much smaller

particulate or liquid stream.

6.2 Indicators of Regeneration Performance

Regeneration performance requires complementary structural, functional, and durability indicators. Char yield and carbon loss should be reported together with pore-size distribution and surface chemistry because increased brunauer-emmett-teller theory (BET) area may reflect pore widening, collapse, or inaccessible secondary deposits rather than restoration of target-selective porosity. Adsorption capacity should be accompanied by kinetics, selectivity, and tests under relevant pH, ionic strength, competing solutes, and dissolved organic matter. Repeated adsorption-regeneration cycles should track mechanical stability, carbon loss, mineral accumulation, contaminant release, and declining selectivity[67]. Comparisons with fresh activated carbon should use identical target concentrations, contact times, and water chemistry so that apparent recovery is not inflated by different test conditions.

6.3 Indicators of Particulate, Metal, and Organic Chemical Risks

Cross-phase risk assessment should combine particle mass and number, aerodynamic size, morphology, carbon fractions, minerals, metals, and associated organics. Deposits and sampling-line condensation must be included so that primary entrainment is distinguished from secondary particle formation. Metal evaluation requires absolute recovery, phase and size distribution, speciation, leaching, and bioaccessibility rather than char concentration alone. Organic assessment should cover residual adsorbates, PAHs, thermogenic aromatics, leachable organic carbon, tar, and aqueous condensate, identifying whether contaminants were destroyed, transformed, or transferred. Phase inventories should be normalized to initial dry feed and, where relevant, to the initial activated-carbon fraction so that enrichment caused by mass loss is separated from true transfer.

6.4 EPFR and ROS Reactivity Assessment

EPFR assessment should report calibrated spin concentration, g-factor, linewidth, moisture basis, storage conditions, and measurement delay. Because radical populations evolve during storage and exposure, decay and transformation should be measured under inert, air, humid, and aqueous conditions. ROS assays should be linked with metal leaching and normalized to material mass, surface area, or particle number. EPFR concentration alone is not a hazard metric; persistence, accessibility, aging, ROS production, and exposure-relevant endpoints are required. The core indicator set is summarized in **Table 3**. Measurements should be conducted for regenerated char and the most exposure-relevant particle or deposit fractions, because equal spin concentrations do not imply equal accessible reactivity.

Table 3. Core indicators for evaluating regeneration, cross-phase pollutant transfer, and environmental reactivity during SACLS microwave pyrolysis

Assessment Dimension	Core Indicators	Relevant Product Phase(s)	Critical Interpretation	References
Regeneration and Process Performance	Char yield; carbon loss; BET specific surface area and pore-size distribution; surface chemistry; adsorption capacity, kinetics, and selectivity; mechanical and cycle stability; specific energy input	Regenerated char and whole process	High surface area or adsorption capacity does not guarantee carbon preservation, selectivity, mechanical stability, or process efficiency	[32,36,68,69]
Cross-Phase Particulate Transfer	Particle mass and number concentrations; aerodynamic or mobility size distribution; morphology; organic and elemental carbon; mineral composition; deposition losses	Size-resolved particles; reactor and transfer-line deposits	Filter mass may include condensable material formed during downstream cooling or within the sampling line	[19,70,71]
Cross-Phase Chemical Transfer	Absolute metal and organic-contaminant mass recovery; phase distribution; particle-size enrichment; residual adsorbates; PAHs and other thermogenic products; condensate composition	Char, particles, aqueous and organic condensates, deposits, and terminal traps	A declining concentration in char may indicate redistribution rather than destruction or stabilization	[70-73]
Environmental Reactivity	Metal oxidation state and speciation; leaching and bioaccessibility; EPFR spin concentration, g-factor, linewidth, and decay kinetics; ROS generation; air and water aging	Char, size-resolved particles, deposits, and selected condensates	Total concentration or initial radical abundance alone does not represent exposure-relevant mobility or reactivity	[65,71,74,75]
Decision Criteria	Whole-product mass-balance closure; non-compensable safety thresholds; multi-objective or Pareto comparison; reuse-specific performance and risk criteria	Integrated system	Regulatory or safety exceedances should not be offset by improvements in regeneration performance	[35,68,73]

NOTE: BET: Brunauer-Emmett-Teller theory; PAHs: Polycyclic Aromatic Hydrocarbons; EPFR: environmental persistent free radical; ROS: Reactive Oxygen Species.

6.5 Non-Compensable Environmental Safety Thresholds

Some outcomes should be treated as non-compensable constraints. Improved adsorption cannot justify metal leaching above application-specific criteria, uncontrolled submicrometer or metal-rich particle emissions, hazardous residual or newly formed organics, or persistent EPFR/ROS activity under realistic exposure conditions. Excessive carbon loss, mechanical failure, poor mass-balance closure, arcing, or disproportionate energy demand may provide additional exclusion criteria. Thresholds should reflect the intended reuse, applicable regulation, and feasible emission control rather than being converted into penalties that high adsorption performance can offset. These criteria should be specified before optimization to prevent post hoc weighting from masking unacceptable outcomes.

6.6 Definition of a Regeneration-Risk-Constrained Operating Window

A regeneration-risk-constrained operating window should first exclude conditions that fail these safety thresholds and then compare the remainder using adsorption recovery, carbon yield, pore characteristics, energy use, particle generation, residual chemical reactivity, and cycle stability. The trade-off is non-linear: low severity may leave adsorbates and unstable organics; intermediate severity can restore pores while preserving carbon and retaining many metals; high

severity may cause burn-off, pore damage, inorganic particles, metal volatilization, altered EPFRs, and greater energy demand. The intermediate region should not be assumed automatically safe; it must be demonstrated by complete product recovery and exposure-relevant testing.

The boundaries are feedstock-specific because moisture, activated-carbon loading, ash, coagulant minerals, chlorine, sulfur, phosphorus, and initial contaminants govern microwave coupling and pollutant fate. No universal optimum temperature or power should be proposed without composition- and phase-resolved evidence. After exclusionary constraints are met, transparent multi-objective or Pareto analysis can compare acceptable conditions for a defined reuse scenario. Sensitivity analysis should be used to show how conclusions change with uncertain weighting, incomplete balances, or alternative reuse scenarios.

7. Future Perspectives

The recent research evolution and emerging topics related to SACLS microwave pyrolysis are summarized in **Figure. 8**, indicating increasing attention toward regeneration, pollutant migration, and environmental reactivity.

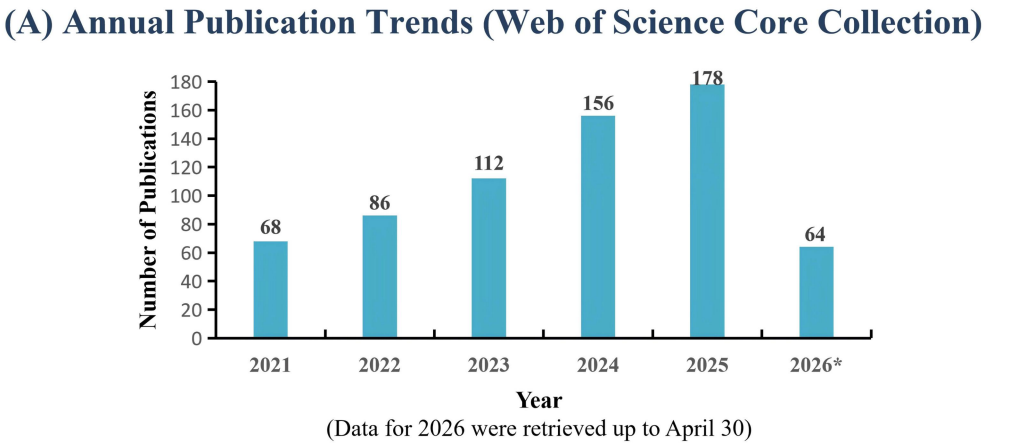


Figure. 8 Research evolution and knowledge clusters in SACLS microwave pyrolysis (2021–2026). Copyright: The figure was originally created by the authors using Microsoft PowerPoint and Adobe Photoshop. No copyrighted materials from other sources were used.

Future work should prioritize six needs: standardized SACLS definitions and reporting of carbon origin, dose, form, and sludge association; dielectric measurements and spatially resolved thermal diagnostics coupled with electromagnetic-thermal modeling; particle-resolved whole-process balances for mass, carbon, metals, and selected organics; phase- and time-resolved EPFR protocols controlling moisture, oxygen, storage, and measurement delay; causal tests of metal-EPFR coupling using metal removal and re-addition, model oxides, quenchers, chelators, synchronized EPR and oxidation-state analyses, and size-resolved particles; and integrated scale-up, emission control, energy, life-cycle, and economic assessment. SACLS microwave pyrolysis is circular only when recovered adsorption function and avoided virgin-carbon production outweigh energy use, carbon loss, and secondary-residue management without transferring contaminants into smaller, more mobile, or more reactive streams.

8. Conclusion

SACLS is a distinct carbon-organic-mineral residue whose microwave behavior cannot be inferred from sewage sludge or isolated spent carbon alone. Selective absorption can accelerate adsorbate removal and pore redevelopment, but heterogeneous hot spots also reshape tar conversion, particle formation, metal migration, and radical stabilization. Fine particles, condensates, deposits, and terminal traps must therefore be included with char in whole-process balances. Metal stabilization should be judged by absolute recovery, speciation, and leaching, while EPFR risk requires phase- and time-resolved EPR, ROS testing, and aging analysis. Current evidence supports metal-assisted radical formation, whereas EPFR-driven metal migration remains a hypothesis. Safe valorization should be based on a feedstock-specific operating window that meets non-compensable environmental thresholds

before regeneration, energy, and reuse performance are optimized. This framework shifts evaluation from single-product recovery to integrated resource value and cross-phase chemical-risk control.

Author Contributions

Conceptualization, Yongxiao Liu and Jun Zhang; methodology, Yongxiao Liu; investigation, Yongxiao Liu, Lu Liu and Hao Zheng; formal analysis, Yongxiao Liu; literature analysis, Yongxiao Liu and Lu Liu; writing — original draft preparation, Yongxiao Liu; writing — review and editing, Yongxiao Liu, Viacheslav A. Arlyapov, Yu Tian and Jun Zhang; supervision, Jun Zhang; project administration, Jun Zhang. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request

Informed Consent Statement

Ethics approval and informed consent were not applicable to this study because this manuscript is a review article and does not involve human participants, human samples, or personal data.

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Conflicts of Interest

The authors declare no competing financial interests.

References

[1] Liu Y, Ren JZ. Developing a sustainability-oriented multi-criteria game theoretical decision analysis framework: A case study of sludge management. *Journal of Cleaner Production*. 2022, 354. [Google Scholar] [CrossRef]

[2] Apollo S. A review of sludge production in South Africa municipal wastewater treatment plants, analysis of handling cost and potential minimization methods. *Physical Sciences Reviews*. 2022, 8 (11). [Google Scholar] [CrossRef]

[3] Zan FX, Liang MX, Guo G, *et al*. Long-term effects of sulfite pretreatment on the continuous anaerobic sludge digester for improving methane production and volatile solid reduction: Towards sustainable sludge treatment. *Chemical Engineering Journal*. 2023, 454. [Google Scholar] [CrossRef]

[4] Hua Y, Chen SX, Tong T, *et al*. Elucidating the Molecular Mechanisms and Comprehensive Effects of Sludge-Derived Plant Biostimulants on Crop Growth: Insights from Metabolomic Analysis. *Advanced Science*. 2025, 12 (2): 1-17. [Google Scholar] [CrossRef]

[5] Yue W, Yu W, Cao ZW, *et al*. Current status and trends of municipal sludge treatment and disposal in China. *Global Nest Journal*. 2024, 26 (9). [Google Scholar] [CrossRef]

[6] Jiao YM, Chen HB. Polydimethyldiallylammonium chloride induces oxidative stress in anaerobic digestion of waste activated sludge. *Bioresource Technology*. 2022, 356. [Google Scholar] [CrossRef]

[7] Chen HB, Wu Y, Zou ZM, *et al*. Thermal hydrolysis alleviates polyethylene microplastic-induced stress in anaerobic digestion of waste activated sludge. *Journal of Hazardous Materials*. 2024, 470. [Google Scholar] [CrossRef]

[8] Wang DB, Zheng YY, Deng Q, *et al*. Water-Soluble Synthetic Polymers: Their Environmental Emission Relevant Usage, Transport and Transformation, Persistence, and Toxicity. *Environmental Science & Technology*. 2023, 57 (16) :6387-6402. [Google Scholar] [CrossRef]

[9] Gupta VK, Suhas. Application of low-cost adsorbents for dye removal — A review. *Journal of Environmental Management*. 2009, 90 (8): 2313-2342. [Google Scholar] [CrossRef]

[10] Fytili D, Zabaniotou A. Utilization of sewage sludge in EU application of old and new methods — A review. *Renewable & Sustainable Energy Reviews*. 2008, 12 (1): 116-140. [Google Scholar] [CrossRef]

[11] Campinas M, Viegas RMC, Almeida CMM, *et al*. Powdered activated carbon full-scale addition to the activated sludge reactor of a municipal wastewater treatment plant: Pharmaceutical compounds control and overall impact on the process. *Journal of Water Process Engineering*. 2022, 49. [Google Scholar] [CrossRef]

[12] Qian J, Riede P, Abbt-Braun G, *et al*. Removal of organic micropollutants from municipal wastewater by powdered activated carbon-activated sludge treatment. *Journal of Water Process Engineering*. 2022, 50. [Google Scholar] [CrossRef]

[13] Woermann M, Kontchou JA, Sures B. Micropollutant-loaded powdered activated carbon released from waste water treatment plants: a risk for sediment-dwelling organisms? *Environmental Sciences Europe*. 2021, 33 (1): 1-9. [Google Scholar] [CrossRef]

[14] Gottardo M, Tuci GA, Parmar AC, *et al*. A combined treatment of aerobic activated sludge and powdered activated carbon: Pilot-scale study of per/polyfluoroalkyls (PFASs), organic matters, chromium, and color removal from tannery wastewaters. *Journal of Water Process Engineering*. 2023, 55. [Google Scholar] [CrossRef]

[15] Buss W. Pyrolysis Solves the Issue of Organic Contaminants in Sewage Sludge while Retaining Carbon-Making the Case for Sewage Sludge Treatment via Pyrolysis. *ACS Sustainable Chemistry & Engineering*. 2021, 9 (30): 10048-10053. [Google Scholar] [CrossRef]

[16] Yu Y, Yu JQ, Sun B, *et al*. Influence of catalyst types on the microwave-induced pyrolysis of sewage sludge. *Journal of Analytical and Applied Pyrolysis*. 2014, 106: 86-91. [Google Scholar] [CrossRef]

[17] Zheng TL, Wang QH, Shi ZN, *et al*. Microwave regeneration of spent activated carbon for the treatment of ester-containing wastewater. *RSC Advances*. 2016, 6 (65): 60815-60825. [Google Scholar] [CrossRef]

[18] Li Y, Jin HL, Liu WB, *et al*. Study on regeneration of waste powder activated carbon through pyrolysis and its adsorption capacity of phosphorus. *Scientific Reports*. 2018, 8: 1-7. [Google Scholar] [CrossRef]

[19] Li BB, Fan HH, Ding SX, *et al*. Influence of Temperature on Characteristics of Particulate Matter and Ecological Risk Assessment of Heavy Metals during Sewage Sludge Pyrolysis. *Materials*. 2021, 14 (19): 1-10. [Google Scholar] [CrossRef]

[20] Fonts I, Gea G, Azuara M, *et al*. Sewage sludge pyrolysis for liquid production: A review. *Renewable & Sustainable Energy Reviews*. 2012, 16 (5): 2781-2805. [Google Scholar] [CrossRef]

[21] Hossain MK, Strezov V, Chan KY, *et al*. Influence of pyrolysis temperature on production and nutrient properties of wastewater sludge biochar. *Journal of Environmental Management*. 2011, 92 (1):

223-228. [Google Scholar] [CrossRef]
[22] Lu HL, Zhang WH, Yang YX, *et al.* Relative distribution of Pb^{2+} sorption mechanisms by sludge-derived biochar. *Water Research*. 2012, 46 (3): 854-862. [Google Scholar] [CrossRef]
[23] Yang GH, Hu YJ, Chen DB, *et al.* Quantification of the formed environmentally persistent free radicals (EPFRs) in the pyrolyzed sewage sludges from municipal and industrial wastewater treatment. *Journal of Analytical and Applied Pyrolysis*. 2024, 177. [Google Scholar] [CrossRef]
[24] Li Z, Chen SJ, Liu L, Qian DK, *et al*. Formation mechanism of persistent free radicals during pyrolysis of Fenton-conditioned sewage sludge: Influence of NOM and iron. *Water Research*. 2024, 254. [Google Scholar] [CrossRef]
[25] Gehling W, Dellinger B. Environmentally Persistent Free Radicals and Their Lifetimes in PM2.5. *Environmental Science & Technology*. 2013, 47 (15): 8172-8178. [Google Scholar] [CrossRef]
[26] Vejerano E, Lomnicki S, Dellinger B. Formation and Stabilization of Combustion-Generated Environmentally Persistent Free Radicals on an Fe(III)2O3/Silica Surface. *Environmental Science & Technology*. 2011, 45 (2): 589-594. [Google Scholar] [CrossRef]
[27] Gutiérrez M, Grillini V, Pavlovic DM, *et al.* Activated carbon coupled with advanced biological wastewater treatment: A review of the enhancement in micropollutant removal. *Science of the Total Environment*. 2021, 790: 1-20. [Google Scholar] [CrossRef]
[28] Fernández LAG, Castillo NAM, Polo MS, *et al.* Algal-Based Carbonaceous Materials for Environmental Remediation: Advances in Wastewater Treatment, Carbon Sequestration, and Biofuel Applications. *Processes*. 2025, 13 (2): 1-27. [Google Scholar] [CrossRef]
[29] Ullah S, Shah SSA, Altaf M, *et al.* Activated carbon derived from biomass for wastewater treatment: Synthesis, application and future challenges. *Journal of Analytical and Applied Pyrolysis*. 2024, 179. [Google Scholar] [CrossRef]
[30] Kårelid V, Larsson G, Björlenius B. Pilot-scale removal of pharmaceuticals in municipal wastewater: Comparison of granular and powdered activated carbon treatment at three wastewater treatment plants. *Journal of Environmental Management*. 2017, 193: 491-502. [Google Scholar] [CrossRef]
[31] Mushtaq S, Jamil F, Hussain M, *et al.* Utilizing sludge-based activated carbon for targeted leachate mitigation in wastewater treatment. *Environmental Research*. 2024, 249. [Google Scholar] [CrossRef]
[32] Gagliano E, Falciglia PP, Zaker Y, *et al.* Microwave regeneration of granular activated carbon saturated with PFAS. *Water Research*. 2021, 198. [Google Scholar] [CrossRef]
[33] Liu YC, Zhou S, Liu R, *et al.* Utilization of waste sludge: Activation/modification methods and adsorption applications of sludge-based activated carbon. *Journal of Water Process Engineering*. 2022, 49. [Google Scholar] [CrossRef]
[34] Mian MM, Ao WY, Deng SB. Sludge-based biochar adsorbent: pore tuning mechanisms, challenges, and role in carbon sequestration. *Biochar*. 2023, 5 (1): 1-23. [Google Scholar] [CrossRef]
[35] Cui ZL, Li DH, Zhou K, *et al.* A critical review of sludge-based adsorbents: Application, recovery, regeneration, sustainable management, and feasibility assessment. *Process Safety and Environmental Protection*. 2026, 206. [Google Scholar] [CrossRef]
[36] Svábová M, Sváb M, Vorokhta M. Comparison of microwave and thermal reactivation of spent activated carbons: A pilot scale demonstration. *Journal of Water Process Engineering*. 2024, 67. [Google Scholar] [CrossRef]
[37] Oh DY, Kim D, Park KY. A comprehensive comparative study on microwave- assisted pyrolysis products derived from raw and digested organic waste, with emphasis on sewage sludge, food waste, and livestock manure. *Heliyon*. 2024, 10 (8): 1-10. [Google Scholar] [CrossRef]
[38] Ania CO, Menéndez JA, Parra JB, *et al.* Microwave-induced regeneration of activated carbons polluted with phenol. A comparison with conventional thermal regeneration. *Carbon*. 2004, 42 (7): 1383-1387. [Google Scholar] [CrossRef]
[39] Rasool A, Brozová K, Chromíková J, *et al.* Conventional and microwave-assisted pyrolysis biochars: comparative mechanistic insights, structural evolution, and environmental remediation applications. *Biochar*. 2026, 8 (1): 1-25. [Google Scholar] [CrossRef]
[40] Domínguez A, Menéndez JA, Inguanzo M, *et al.* Investigations into the characteristics of oils produced from microwave pyrolysis of sewage sludge. *Fuel Processing Technology*. 2005, 86 (9): 1007-1020. [Google Scholar] [CrossRef]
[41] Domínguez A, Menéndez JA, Inguanzo M, *et al.* Production of bio-fuels by high temperature pyrolysis of sewage sludge using conventional and microwave heating. *Bioresource Technology*. 2006, 97 (10): 1185-1193. [Google Scholar] [CrossRef]
[42] Antunes E, Jacob MV, Brodie G, *et al*. Microwave pyrolysis of sewage biosolids: Dielectric properties, microwave susceptor role and its impact on biochar properties. *Journal of Analytical and Applied Pyrolysis*. 2018, 129: 93-100. [Google Scholar] [CrossRef]
[43] Fan DK, Xiao R, Nasarul W, *et al.* Microwave-assisted pyrolysis of dyeing sludge: Reaction kinetics, elemental transformation, and heavy metal migration. *Chemical Engineering Journal*. 2026, 530. [Google Scholar] [CrossRef]
[44] Yang Z, Li ZY, Ye SX, *et al*. Molecular characterization of organic aerosol particles from biomass pyrolysis. *Journal of Analytical and Applied Pyrolysis*. 2024, 178. [Google Scholar] [CrossRef]
[45] Zaker A, Chen Z, Wang XL, *et al.* Microwave-assisted pyrolysis of sewage sludge: A review. *Fuel Processing Technology*. 2019, 187: 84-104. [Google Scholar] [CrossRef]
[46] Zhang J, Tian Y, Zhu J, *et al.* Characterization of nitrogen transformation during microwave-induced pyrolysis of sewage sludge. *Journal of Analytical and Applied Pyrolysis*. 2014, 105: 335-341. [Google Scholar] [CrossRef]
[47] Zhang J, Zuo W, Tian Y, *et al.* Sulfur Transformation during Microwave and Conventional Pyrolysis of Sewage Sludge. *Environmental Science & Technology*. 2017, 51 (1): 709-717. [Google Scholar] [CrossRef]
[48] Zhou JW, Liu SY, Zhou N, *et al.* Development and application of a continuous fast microwave pyrolysis system for sewage sludge utilization. *Bioresource Technology*. 2018, 256: 295-301. [Google Scholar] [CrossRef]
[49] Ma R, Sun SC, Geng HH, *et al.* Study on the characteristics of microwave pyrolysis of high-ash sludge, including the products, yields, and energy recovery efficiencies. *Energy*. 2018, 144: 515-525. [Google Scholar] [CrossRef]
[50] Li SB, Li CX, Shao ZG. Microwave pyrolysis of sludge: a review. *Sustainable Environment Research*. 2022, 32 (1): 1-14. [Google Scholar] [CrossRef]
[51] Yu SL, Tao RZ, Tan HZ, *et al.* Migration characteristics and ecological risk assessment of heavy metals in ash from sewage sludge co-combustion in coal-fired power plants. *Fuel*. 2023, 333. [Google Scholar] [CrossRef]
[52] Dai QJ, Jiang XG, Jiang YF, *et al.* Temperature Influence and Distribution in Three Phases of PAHs in Wet Sewage Sludge

Pyrolysis Using Conventional and Microwave Heating. *Energy & Fuels*. 2014, 28 (5): 3317-3325. [Google Scholar] [CrossRef]

[53] Ko JH, Wang JC, Xu QY. Impact of pyrolysis conditions on polycyclic aromatic hydrocarbons (PAHs) formation in particulate matter (PM) during sewage sludge pyrolysis. *Chemosphere*. 2018, 208:108-116. [Google Scholar] [CrossRef]

[54] Li DN, Shan R, Jiang LX, *et al.* A review on the migration and transformation of heavy metals in the process of sludge pyrolysis. *Resources Conservation and Recycling*. 2022, 185. [Google Scholar] [CrossRef]

[55] Jin JW, Li YN, Zhang JY, *et al*. Influence of pyrolysis temperature on properties and environmental safety of heavy metals in biochars derived from municipal sewage sludge. *Journal of Hazardous Materials*. 2016, 320: 417-426. [Google Scholar] [CrossRef]

[56] Souza CD, Bomfim MR, de Almeida MD, *et al*. Induced changes of pyrolysis temperature on the physicochemical traits of sewage sludge and on the potential ecological risks. *Scientific Reports*. 2021, 11 (1): 1-13. [Google Scholar] [CrossRef]

[57] Cui ZL, Xu GR, Ormeci B, *et al*. Transformation and stabilization of heavy metals during pyrolysis of organic and inorganic-dominated sewage sludges and their mechanisms. *Waste Management*. 2022, 150: 57-65. [Google Scholar] [CrossRef]

[58] Alipour M, Asadi H, Chen CR, *et al*. Bioavailability and eco-toxicity of heavy metals in chars produced from municipal sewage sludge decreased during pyrolysis and hydrothermal carbonization. *Ecological Engineering*. 2021, 162. [Google Scholar] [CrossRef]

[59] Li BB, Ding SX, Fan HH, *et al*. Experimental Investigation into the Effect of Pyrolysis on Chemical Forms of Heavy Metals in Sewage Sludge Biochar (SSB), with Brief Ecological Risk Assessment. *Materials*. 2021, 14 (2): 1-13. [Google Scholar] [CrossRef]

[60] Wang Y, Gu X, Huang Y, *et al*. Insight into biomass feedstock on formation of biochar-bound environmentally persistent free radicals under different pyrolysis temperatures. *RSC Advances*. 2022, 12: 19318–19326. [Google Scholar] [CrossRef]

[61] Hu YJ, Tong K, Guo QQ, *et al*. Effect of controlled temperature and biomass addition on the formed environmental persistent free radicals (EPFRs) in sewage sludge-based biochar from pyrolysis treatment. *Journal of Analytical and Applied Pyrolysis*. 2022, 162. [Google Scholar] [CrossRef]

[62] Jiang SF, Hao HC, Chen S, *et al*. Mechanistic elucidation and tuning pathway of environmentally persistent free radicals during sewage sludge pyrolysis. *Journal of Analytical and Applied Pyrolysis*. 2024, 179. [Google Scholar] [CrossRef]

[63] Hu YJ, Zhang BN, Guo QQ, *et al*. Characterization into environmentally persistent free radicals formed in incineration fly ash and pyrolysis biochar of sewage sludge and biomass. *Journal of Cleaner Production*. 2022, 373. [Google Scholar] [CrossRef]

[64] Yang X, Yang F, Pang Y, *et al.* A critical review of secondary environmentally persistent free radicals: formation, properties, environmental and health impacts. *Journal of Hazardous Materials*. 2025, 498 (c). [Google Scholar] [CrossRef]

[65] Chen X, Alvarez PJJ, Masiello CAJES, Technology. Environmentally Persistent Free Radicals in Biochar: Environmental Context and Future Research Needs. *Environmental Science & Technology*. 2025, 59 (23): 11440-11454. [Google Scholar] [CrossRef]

[66] Chalvatzaki E, Kopanakis I, Lazaridis M. Size distribution and metal composition of airborne particles in a waste management facility. *Journal of Material Cycles and Waste Management*. 2018, 20 (1): 323-335. [Google Scholar] [CrossRef]

[67] Liu ZW, Zhao Y, Cheng MQ, *et al.* Upcycling sewage sludge into pyrolytic biochar for sustainable energy and environmental applications: A critical review. *Journal of Analytical and Applied Pyrolysis*. 2026, 198. [Google Scholar] [CrossRef]

[68] Lin JH, Cui CW, Sun SC, *et al.* Synergistic optimization of syngas quality and heavy metal immobilization during continuous microwave pyrolysis of sludge: Competitive relationships, reaction mechanisms, and energy efficiency assessment. *Journal of Hazardous Materials*. 2022, 438. [Google Scholar] [CrossRef]

[69] Vali N, Zabihi S, Shamim S, *et al*. Slow-pyrolysis of municipal sewage sludge: biochar characteristics and advanced thermodynamics. *Biomass Conversion and Biorefinery*. 2025, 15 (14): 21045-21065. [Google Scholar] [CrossRef]

[70] Zhang YW, Zhou CB, Deng ZY, *et al.* Influence of corn straw on distribution and migration of nitrogen and heavy metals during microwave-assisted pyrolysis of municipal sewage sludge. *Science of the Total Environment*. 2022, 815. [Google Scholar] [CrossRef]

[71] Lv MY, Zhao TT, Chen JJ, *et al.* Distribution and transformation behavior of heavy metals and phosphorus during sewage sludge pyrolysis. *Environmental Technology & Innovation*. 2025, 37: 1-10. [Google Scholar] [CrossRef]

[72] Chen X, Ma R, Luo J, *et al.* Co-microwave pyrolysis of electroplating sludge and municipal sewage sludge to synergistically improve the immobilization of high-concentration heavy metals and an analysis of the mechanism. *Journal of Hazardous Materials*. 2021, 417. [Google Scholar] [CrossRef]

[73] Li JT, Yu HD, Lin FW, *et al.* Comparative study by microwave, fixed-bed and rotary kiln pyrolysis of oily sludge: Petroleum hydrocarbons, N-/S-/Cl-containing pollutants and heavy metals. *Journal of Environmental Chemical Engineering*. 2026, 14 (1). [Google Scholar] [CrossRef]

[74] Xie J, Latif J, Yang KJ, *et al.* A state-of-art review on the redox activity of persistent free radicals in biochar. *Water Research*. 2024, 255. [Google Scholar] [CrossRef]

[75] Yan X, Cao T, Chen H, *et al.* Formation and evolution of environmentally persistent free radicals in charcoal and soot generated from biomass materials. *Journal of Hazardous Materials*. 2025, 488. [Google Scholar] [CrossRef]