



Removal of polychlorinated biphenyls combining the synergy of bacteria and iron bionanoparticles prepared from agrowaste

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Abstract

This study presents an environmentally sustainable approach for synthesizing iron bionanoparticles using grape berries and grape pomace from two *Vitis vinifera* cultivars (Merlot and Blaufränkisch) highlighting the valorization of food industry waste within circular economy principles and the synergistic approach involving bacteria for environmental cleanup. The Merlot pomace-derived nanoparticles exhibited an amorphous structure, predominant Fe(III) species (Mössbauer spectroscopy), high specific surface area ($398 \text{ m}^2 \cdot \text{g}^{-1}$), and nanometric, porous morphology. Fe–O bond formation and polyphenol complexation was confirmed. Evolution of pH and redox potential values during synthesis revealed that slightly alkaline, near-physiological conditions favor nanoparticles formation and redox activity. All iron nanoparticle types were applied in removal experiments targeting polychlorinated biphenyls (from congener mixture Delor 103). The highest removal of the sum of PCBs congeners by nanoparticles alone reached 62% after 14 days using Merlot pomace-derived nanoparticles. When combined with the bacterium *Ochrobactrum anthropi* in a sequential synergistic approach, removal efficiency increased to 76%. Co-application with *Stenotrophomonas maltophilia* also resulted in high removal (70%). Ecotoxicological assessment revealed general non-toxicity of tested nanoparticles (derived from Merlot pomace) using *Sinapis alba* seed germination and *Ochrobactrum anthropi* auxanogram assays. However, higher concentrations ($10 \text{ g} \cdot \text{L}^{-1}$) induced 46% inhibition of plant growth, likely due to restricted translocation of nutrients to the upper plant tissues. The results demonstrate the dual benefit of transforming agrowaste into effective, low-toxicity nanomaterials for remediation, supporting sustainable nanotechnology for environmental applications.

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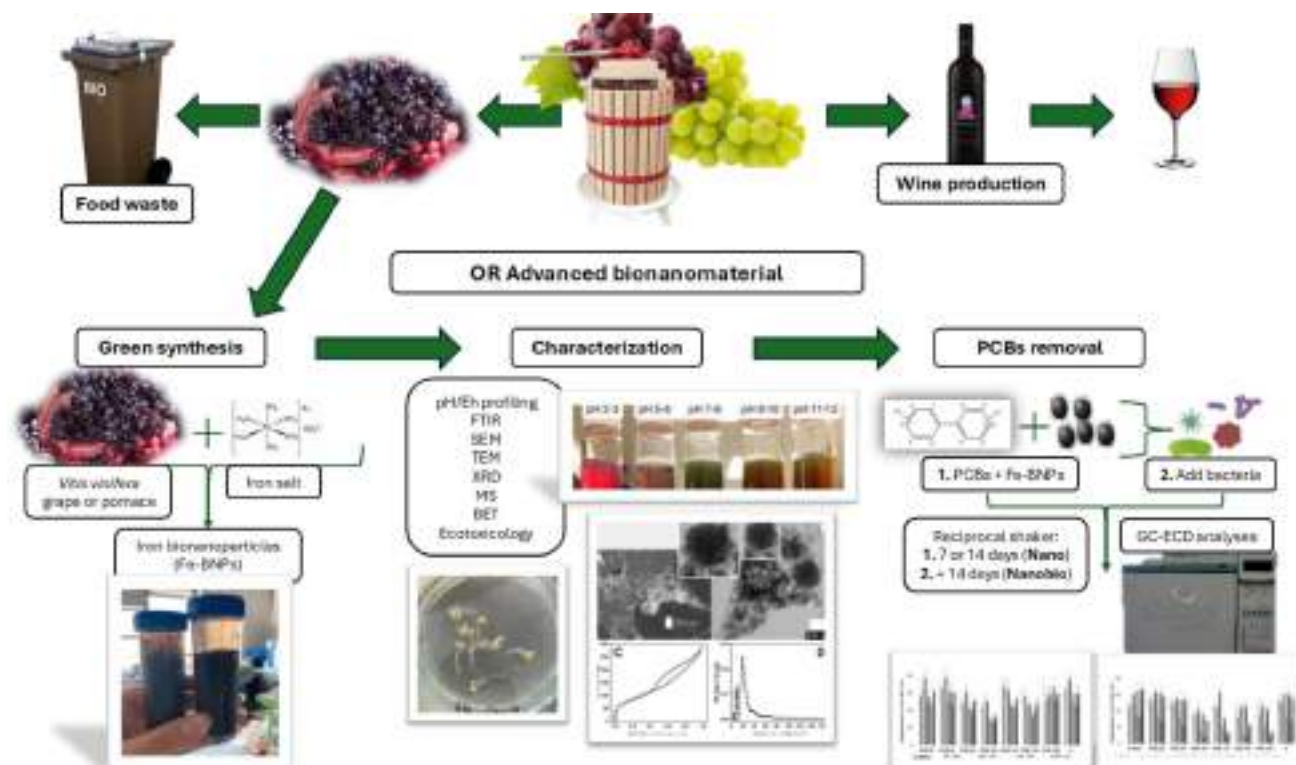
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Graphical abstract



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Introduction

Polychlorinated biphenyls (PCBs) are a group of synthetic organic compounds that were industrially produced from 1929 until production was banned in the late 1970s due to their proven toxic effects and environmental persistence (Štrédllová and Cajthaml 2022). Chemically, they are substituted derivatives of biphenyl, where hydrogen atoms are replaced by one to ten chlorine atoms. PCBs are characterized by their high chemical and thermal stability, non-conductivity, low volatility, and resistance to degradation. These properties led to their widespread use, especially in the electrical and chemical industries. They served as insulating fluids in transformers and capacitors, as additives in paints, varnishes, plastics, hydraulic fluids, and lubricants. Commercially, they were marketed under various trade names such as Aroclor and Pyranol (USA), Delor (former Czechoslovakia), or Clophen (Germany).

Despite the cessation of production, PCBs remain among the most hazardous environmental contaminants. Their lipophilicity and resistance to metabolism lead to bioaccumulation in fatty tissues and biomagnification along food chains,

resulting in elevated concentrations in fish, mammals, and humans (Prince et al. 2021). Chronic exposure has been associated with endocrine disruption, immune and reproductive system damage, and carcinogenic effects. PCBs have been detected in all environmental compartments, including remote regions where they were never used. Due to their persistence and toxicity, they were included in the “Dirty Dozen” persistent organic pollutants (POPs) regulated under the Stockholm Convention. Notorious examples of contamination include the Hudson River (USA) caused by historical discharges from General Electric (Melymuk et al. 2022) and the heavily polluted area near the Chemko Strážske plant in eastern Slovakia, where PCBs were produced between 1959 and 1984 (Hlisníková et al. 2024; Kočan et al. 2001). Similar environmental burdens have been confirmed in the Czech Republic near Nový Jičín and Uherské Hradiště (Lána et al. 2008). Despite global regulatory measures, PCBs persist in the environment, requiring sustainable remediation strategies (Melymuk et al. 2022).

Traditional methods for PCBs removal, such as incineration, chemical oxidation, or physical extraction, are energy-intensive, costly, and often produce toxic by-products.



To overcome these limitations, nanobiodegradation has emerged as a promising strategy that combines the reductive power of iron-based nanoparticles with the metabolic capacity of PCB-degrading microorganisms. This typically involves sequential application, where iron nanoparticles first initiate dechlorination, reducing the toxicity and persistence of PCB congeners, followed by microbial degradation of the resulting intermediates (Horváthová et al. 2022; Tlčíková et al. 2024).

A critical factor in this approach is the synthesis of iron nanoparticles. Conventional nanoparticle production often requires hazardous chemicals—strong reducing agents, raising environmental and health concerns. Green synthesis offers a sustainable alternative: iron bionanoparticles (Fe-BNPs) can be synthesized using plant extracts rich in polyphenols, flavonoids, or organic acids, eliminating the need for toxic reagents while enabling valorization of plant waste (Machado et al. 2013; Tlčíková et al. 2024). The valorization of agricultural and lignocellulosic residues into value-added materials is increasingly recognized as a key component of sustainable and circular-economy strategies. Hydrothermal and solvent-based pretreatment methods have demonstrated that agrowaste can yield recoverable fractions that serve as effective precursors for environmentally friendly material synthesis (Ma et al. 2022; Zhou et al. 2024). Although the current studies focus primarily on the removal of metals and pharmaceuticals, the potential of Fe-BNPs for pollutants remediation is substantial for our study. Their small size, high surface reactivity, and functional groups make them suitable for interaction with halogenated compounds. When combined with PCB-degrading bacteria such as *Pseudomonas*, *Bacillus*, *Dehalococcoides*, or *Achromobacter*, they form an efficient degradation system (Alabresm et al. 2018; Rizwan et al. 2019; Wu et al. 2021; Xie et al. 2011; Zhang et al. 2023).

Nevertheless, the use of nanoparticles in remediation raises concerns regarding their ecotoxicological impacts. Some studies report minimal toxicity (Giri 2014; Němeček et al. 2014), while others emphasize potential risks depending on nanoparticle concentration, size, and surface properties (Auffan et al. 2008; Chen et al. 2013). Comprehensive toxicological assessment is therefore necessary to ensure the safe implementation of bionanoparticle-based remediation strategies.

Many existing studies focus on nanoparticle-based remediation of toxic heavy metals or simpler linear chlorinated compounds. Microbial biodegradation studies on dyes and related pollutants, though performed with different bacterial strains, provide methodological principles that are important for evaluating synergistic interactions in combined remediation systems (Almamoori et al. 2024). This work opens new perspectives for the degradation of persistent, chlorinated aromatic residual PCBs in the environment. The results demonstrate the feasibility of utilizing food industry by-products, such as grape pomace, for the remediation of chlorinated

aromatic organic pollutants, thereby contributing to sustainable environmental technologies and advancing circular economy strategies with a new environmental green approach of nanobiodegradation using selective bacterial strains.

The objectives of this study were to (i) synthesize and characterize Fe-BNPs prepared from grape berries and pomace of *Vitis vinifera* cultivars (Merlot and Blaufränkisch) using a green synthesis, (ii) evaluate their structural, morphological properties, and surface, (iii) investigate their efficiency in PCBs removal from the Delor 103 mixture and assess the influence of synthesis conditions (pH, Eh), (iv) test the synergistic effect of sequential nanobioremediation by combining Fe-BNPs with selected PCB-degrading bacteria (*Ochrobactrum anthropi*, *Stenotrophomonas maltophilia*), and (v) conduct an ecotoxicological assessment to evaluate the environmental safety and potential risks of Fe-BNPs to selected plant indicators. The synthesis and removal experiments were conducted at the Slovak University of Technology in Bratislava, Faculty of Chemical and Food Technology, Institute of Biotechnology, and at Comenius University in Bratislava, Faculty of Natural Sciences, Department of Geochemistry, in December 2022. Material characterization was carried out at Palacký University Olomouc, Czech Advanced Technology and Research Institute (CATRIN), Regional Centre of Advanced Technologies and Materials, in April 2023.

Materials and methods

Green synthesis of Fe-BNPs

Fe-BNPs were synthesized via green synthesis using aqueous extracts and iron salts. Crushed and frozen grape berries (G) or grape pomace (P) from Merlot or Blaufränkisch varieties (MG–Merlot grape, MP–Merlot pomace, BG–Blaufränkisch grape, BP–Blaufränkisch pomace; grapes and pomace from both varieties were obtained by Víno Matyšák, Ltd.) were mixed with distilled water and incubated in a water bath for 2 h at a maximum temperature of 70 °C. The plant extract was prepared using a plant material-to-water ratio of 1:100 (w/v). This ratio was selected based on preliminary optimization experiments (data not shown) and is consistent with ratios reported in previous studies on plant-mediated synthesis of iron-based nanoparticles (Izadiyan et al. 2020; Vitta et al. 2020). The iron precursor $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (p.a., Centralchem, Slovakia) was then added to the extract (Solmošiová et al. 2016), and the pH was adjusted to 7–8 using 0.3 M NaOH (97%, Centralchem, Slovakia). The synthesis was carried out at 23 °C, for 48 h, on reciprocal shaker at 100 rpm (EB GmbH SM30, Germany). The resulting Fe-BNPs were centrifuged (9500 rpm, 15 min), rinsed with distilled water, and either used immediately for removal tests or stored in a freezer (−19.4 °C) for further characterization.



Before characterization, the Fe-BNPs were dried in the glove box filled with the N_2 inert atmosphere (Sylatech GmbH, Germany).

pH—dependent redox profiling

The oxidation–reduction potential (ORP) and pH values were monitored in the aqueous extract of Merlot grape pomace (MP) and in solution of Fe-BNPs synthesized from this extract using the iron salts $Fe_2(SO_4)_3$ (p.a. $\geq 76.0\%$, Fluka, Switzerland) and $Fe(NO_3)_3 \cdot 9H_2O$ ($\geq 98\%$, Sigma-Aldrich, USA). The pH was adjusted to 3, 6, 8, 10, and 12 using 3 M NaOH (97%, Centralchem, Slovakia). ORP was measured at each pH level and at different time intervals. For the Merlot pomace extract (MP), ORP was measured after 5, 30, 60, and 120 min; for the Fe-BNPs, measurements were taken after 1 min, 60 min, and 24 h post-synthesis. The pH and ORP values were monitored during experiments using a multimeter (Multi 3630 IDS, WTW, Germany) equipped with a pH electrode (SenTix® 940, WTW, Germany) and ORP electrode (SenTix® ORP-T 900, WTW, Germany). The measured ORP values were subsequently converted to the standardized redox potential (Eh) value relative to the standard hydrogen electrode (SHE).

Characterization of Fe-BNPs

The surface morphology of nanoparticles and their size and shape were studied with electron microscopes. The transmission electron microscope (TEM) JEM-2100 (JEOL Ltd., Japan) was used for the Fe-BNPs images obtained at an electron acceleration voltage of 200 kV. The surface of the samples was examined by scanning electron microscope (SEM) JSM-7900F (JEOL Ltd., Japan) with an accelerating voltage of 5.0 kV. Energy dispersive spectrometry (EDS) was performed to verify the composition of the samples using Jeol JED-2300 SDD detector, with an acquisition time of 60 s and under an accelerating voltage of 15.0 kV.

The specific surface area (SSA) of the material could significantly affect its reactivity. The SSA was determined via gas sorption analysis performed by means of N_2 adsorption/desorption measurements at 77 K on a volumetric gas adsorption analyzer (Autosorb iQ XR, Anton-Paar Quanta Tec, USA) up to 0.965 p/p₀. Prior to the analysis, the sample was prepared in the glove box and then degassed under high vacuum (10^{-7} Pa) at 130 °C for 24 h, while high purity N_2 (99.999%) and He ($\geq 99.9999\%$) gases were used for the measurements. The Brunauer-Emmet-Teller (BET) method was used to determine the SSA of prepared Fe-BNPs. Pore size distribution was obtained using DFT-based method.

The crystalline and amorphous phase in the samples was distinguished by X-ray powder diffraction (XRD). The

measurements were performed with the Aeris diffractometer (Malvern PANalytical, Ltd, USA) equipped with iron filtered Co K α radiation source and operating in Bragg–Brentano geometry from 5 to 105 °. Powder sample was prepared in the glove box and the sample was placed on a zero-background silicon sample holder and covered with a Kapton foil.

The ^{57}Fe zero-field Mössbauer spectra were recorded at laboratory temperature employing a Mössbauer spectrometer (MS96 3Gen, UPOL, Czech Republic) operating in a constant acceleration mode and equipped with a $^{57}Co(Rh)$ source. The values of the isomer shift are referred to α -Fe foil sample at laboratory temperature.

Fourier transform infrared (FT–IR) absorption spectra were measured on an FT–IR spectrometer Nicolet iS5 (Thermo electron, USA) employing attenuated total reflection (ATR) on a ZnSe crystal, using 64 scans with resolution of 2 cm^{-1} . The IR absorption spectra were recalculated from ATR to absorbance and baseline correction.

Removal of PCBs

For Fe-BNPs mediated PCBs removal (solely Fe-BNPs): 100 mL of minimal mineral medium (Dudášová et al. 2014), Delor 103 solution in DMSO (99.0%, Centralchem, Slovakia) (0.1 L^{-1}), and 3 mL of freshly synthesized Fe-BNPs derived from grape berries or pomace were added to reagent bottles. The pH of the solution was adjusted to a range of 6 to 7 with 3 M NaOH (97%, Centralchem, Slovakia). Experimental conditions were 120 rpm on reciprocal shaker (EB GmbH SM30, Germany), 25 °C, in the dark for 7 and 14 days. The reagent bottles were sealed with plastic stoppers to prevent oxygen interference, as the presence of oxygen inhibits the reductive activity of the Fe-BNPs. Delor 103 (Chemko a.s., Slovakia), a viscous commercial mixture of low-chlorinated PCBs, was dissolved in DMSO to prepare a stock solution at 54 $g \cdot L^{-1}$.

For synergistic removal of PCBs (Fe-BNPs + bacteria): 100 mL of minimal mineral medium (Dudášová et al. 2014), Delor 103 solution in DMSO (0.1 $g \cdot L^{-1}$), and 3 mL of freshly synthesized Fe-BNPs derived from grape berries or pomace were added to reagent bottles, adjusted pH 6–7 with 3 M NaOH (97%, Centralchem, Slovakia) and remove for 7 days without air oxygen at the same conditions as in the first set of experiments. Then the utilized adapted bacterial strains *Ochrobactrum anthropi*—OA and *Stenotrophomonas maltophilia*—SM (bacteria isolated from contaminated substrates of Chemko Strážske area from previous work (Dudášová et al. 2014; Lászlóvá et al. 2018)) were added for another 14 days in Erlenmeyer flasks with cotton stopper due to oxidative bacterial biodegradation of PCBs in concentration 1 $g \cdot L^{-1}$, placed on the reciprocal shaker at 120 rpm (EB GmbH SM30, Germany) and 25 °C.



Remaining non-removed PCB congeners were extracted using a two-step n-hexane extraction according to EPA method 8082A. The resulting organic phase was analysed by gas chromatography with electron capture detection GC-ECD (HP 5890, Agilent, USA). Based on the calibration of a standard mixture of seven monitored PCB congeners (PCB 8; PCB 28; PCB 52; PCB 101; PCB 118; PCB 138; PCB 153 (analytical standards, Sigma-Aldrich, USA)), the percentage reduction of the individual PCBs (P) in the samples was evaluated using the peak areas and calculated with following Eq. (1):

$$P = \left(\frac{\text{control} - \text{sample}}{\text{control}} \right) * 100\% \quad (1)$$

Ecotoxicological effects of Fe-BNPs

Fe-BNPs derived from Merlot grape pomace were evaluated using two types of ecotoxicological tests: auxanograms (for bacteria) and a short germination test (for higher plants—yellow mustard). Synthesized Fe-BNPs were obtained by mixing an aqueous extract (1:100 in dH₂O, boiled at max. 70 °C, 2 h, pH 7) with three different volumes (1, 5, and 10 ml) and three masses (0.1, 0.5, and 1 g) of FeSO₄·7H₂O (p.a., Centralchem, Slovakia), resulting in final concentrations of 10, 20, 50, and 100 g·L⁻¹, followed by 24 h reaction, 25 °C, on a rotary shaker at 120 rpm (EB GmbH SM30, Germany); the resulting suspensions were centrifuged (4500 rpm, 10 min), decanted, and the pellet was resuspended in 5 ml dH₂O and used in the ecotoxicological experiments.

Auxanograms: The bacterial strain *Ochrobactrum anthropi* was inoculated onto a solid medium in a Petri dish, and sterile filter paper discs impregnated with various concentrations of Fe-BNPs were placed on the surface of the medium. Cultivation was conducted for 48 h in dark at 28 °C. Distilled water and ethanol were used as positive and negative controls. The inhibition zone around the disk indicates the sensitivity of the bacteria to the given concentration of Fe-BNPs.

Short-term germination and early growth test: Experiment with *Sinapis alba* was conducted according to ISO 18763 with specially selected mustard seeds (10x) (Bio-Sonnenrotor, Austria) in Petri dish with 5 mL of Fe-BNPs in various concentrations for 72 h at 20 °C. After cultivation the root growth inhibition I_{μ} (%) was evaluated by Eq. (2):

$$I_{\mu} = \frac{(L_c - L_v)}{L_c} \quad (2)$$

I_{μ} = root growth inhibition (%), L_c = arithmetic mean of root length in the control (mm), L_v = arithmetic mean of root length in the test solution (mm).

Results and discussion

Synthesis and characterisation of Fe-BNPs

For the synthesis and subsequent removal experiments, grape berries and pomace from *Vitis vinifera* cultivars Merlot and Blaufränkisch were utilized for the green synthesis of Fe-BNPs. The successful synthesis was initially indicated by a visible color change in the reaction mixture, reflecting the interaction between iron salts and bioactive compounds present in the aqueous agrowaste extract. This immediate transition in color—from light pink to dark brown or black—served as a preliminary visual confirmation of nanoparticle formation, attributed to the nucleation and growth of Fe nanoparticles (Bolade et al. 2020; Sahar et al. 2020). For further and more detailed characterization, Fe-BNPs synthesized from Merlot pomace were selected due to their notable efficiency in pollutant removal and their potential as a sustainable biomaterial. The aqueous extract from Merlot grape pomace is a complex organic matrix containing polyphenols, carbohydrates, proteins, organic acids, and other bioactive compounds. These components, particularly residual acids, can significantly influence the extract's redox behavior over time. In our previous study (Tlčáková et al. 2024), the total phenolic content of grape-derived substrates was quantified by the Folin–Ciocalteu method, demonstrating that both Merlot and Blaufränkisch berries contained more than twice the polyphenols compared to their respective pomace residues (Merlot berries: 8.87 ± 0.86 ; pomace: 4.10 ± 1.2 ; Blaufränkisch berries: 10.27 ± 0.93 ; pomace: 3.38 ± 0.51 mg GAE 100 g⁻¹). Budić-Leto et al. (2002), Giovinazzo et al. (2015) and Tang et al. (2018) performed HPLC screening with literature-based standards, which confirmed the presence of vanillic acid, ferulic acid, and rutin, with ferulic acid being particularly relevant as a structural component of pectin and lignin in lignocellulosic tissues. These findings support the notion that grape berries are richer in bioactive phenolics, while pomace retains a reduced yet still significant fraction relevant for redox processes and nanoparticle synthesis.

A gradual trend was observed in the redox potential (Eh) values of the grape extract over a monitored period of 5 to 120 min, aimed at capturing dynamic changes following the extraction of bioactive compounds. Initially, at the native acidic pH (2–3), the extract exhibited the highest Eh values (200–270 mV), which slightly decreased during the first hour. As the pH was gradually increased by NaOH and the incubation time prolonged, a consistent decline in Eh was observed. The lowest Eh values were recorded at strongly alkaline conditions (pH 11–12), reaching 50–51 mV, and at neutral pH (7–8) after 60 min, where the Eh dropped to approximately 60 mV. These findings



suggest that a resting phase of at least one hour allows for partial stabilization of reactive organic acids, while alkaline pH adjustment further reduces the redox potential, thus creating more favorable conditions for the green synthesis of Fe-BNPs. Also a visual observation of color changes were conducted on the aqueous extracts from Merlot pomace at various pH levels. As shown in Fig. 1, samples at pH 2–3 were left unaltered; while the others were adjusted using NaOH. Literature suggests that slightly acidic to neutral pH of polyphenol solution is ideal for both Fe(III) reduction and complex formation. At higher pH, deprotonated –OH groups in polyphenols favor iron chelation over reduction, while Fe(II)/Fe(III) may precipitate as iron oxides/hydroxides (Baldelli et al. 2025; Dzah et al. 2024; Jovanović and Miličević, 2017). The ability of polyphenols to chelate metal cations—particularly those with high charge density such as Fe(III), Fe(II), Cu(II), and Zn(II)—is closely related to the number of hydroxyl groups present on their aromatic rings. Polyphenols with a higher number of –OH groups exhibit stronger binding affinity, with the most effective interactions typically occurring with trivalent cations. This chelating ability is attributed to the lower dissociation energy of the phenolic –OH bond compared to the aromatic C–H bond, which increases the reactivity of hydroxyl groups toward metal ions (Hider et al. 2001; Silva et al. 2006). Our results, however, indicate that the most significant Eh decrease occurs at neutral to slightly basic pH. This discrepancy may arise from the complex composition of the extract, where non-polyphenolic components—such as sugars, proteins, and acids—also influence redox processes beyond what is observed in studies using pure model compounds (Feng et al. 2023).

Following the addition of Fe(III) in the form of $\text{Fe}_2(\text{SO}_4)_3$ (green synthesis of Fe-BNPs), a gradual decrease in Eh values was observed, indicating that a redox reaction between

ferric ions and antioxidants present in the extract was taking place. The most significant Eh decrease occurred at pH 6–8 after 24 h of synthesis (200 mV), which aligns with literature identifying this pH range as optimal for the reduction of Fe(III) in plant-based systems (Akanda et al. 2023). In the case of $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, the most effective conditions appeared to be at pH 8–10 after 24 h, as these solutions exhibited the lowest recorded Eh values (170 mV). This was followed by stabilization or a slight increase in Eh, which may be related to the consumption of reducing agents or the oxidation of residual Fe(II) in the solution.

FT–IR spectroscopy provided important insights into the processes occurring during the synthesis of Fe-BNPs with Fe(III) and pomace extract from Merlot variety (Fig. 2). The spectra revealed distinct changes in the O–H stretching vibration region ($\sim 3300\text{ cm}^{-1}$), as well as in the bands corresponding to aromatic C=C and carbonyl C=O groups ($\sim 1600\text{--}1700\text{ cm}^{-1}$), confirming the occurrence of chemical interactions between polyphenols and iron ions. These spectral shifts are characteristic of metal–ligand complex formation. Additionally, the appearance of a new band in the region of $\sim 800\text{ cm}^{-1}$ indicates the presence of Fe–O bonds, suggesting the formation of iron (most likely oxide-based) nanoparticles. Similar results were reported by Hao et al. (2021), who utilized green tea extract for the synthesis of iron nanoparticles. Their FT–IR analysis showed notable shifts in the C=C (aromatic) and C–N stretching vibrations, indicating that bioactive compounds within the extract acted as both reducing and stabilizing (capping) agents during nanoparticle formation. In addition, the appearance of a new absorption band at 869 cm^{-1} was assigned to Fe–O stretching vibrations, corresponding to the presence of FeOOH. Additionally, other studies support these findings by reporting peaks at 1087.29 cm^{-1} , 520.34 cm^{-1} , and 435.70 cm^{-1} , which confirm the capping of iron oxide nanoparticles by phytochemicals; specifically, the bands at ~ 520 and $\sim 435\text{ cm}^{-1}$ are

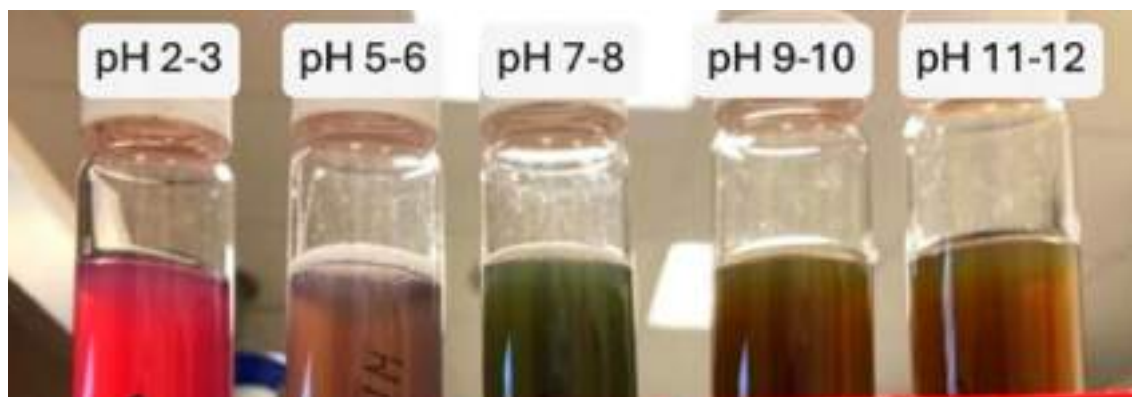
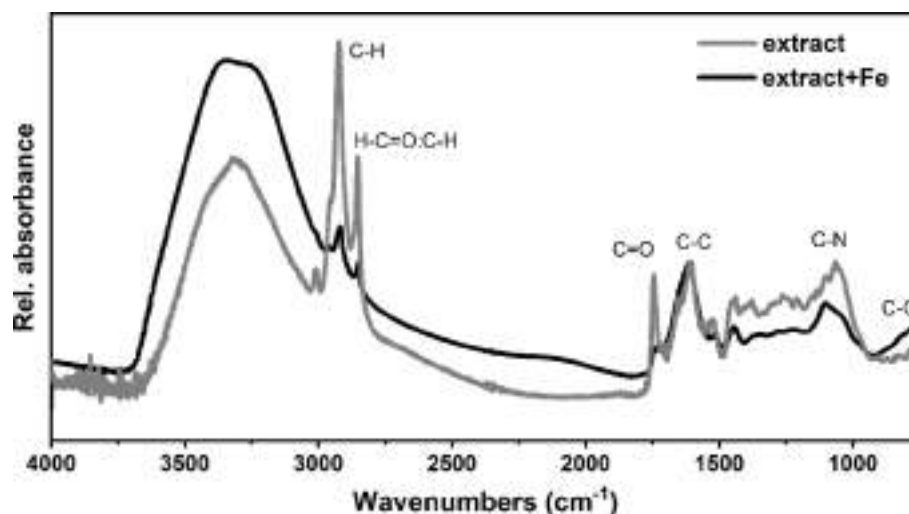


Fig. 1 The aqueous extracts from Merlot grape pomace at different pH values (Extract with pH 2–3 was unaltered, while the pH of the remaining extracts was adjusted using NaOH)



Fig. 2 FT-IR absorbance spectra of Merlot pomace extract (extract) and Fe-BNPs synthesized from Merlot pomace (extract+Fe)



assigned to Fe–O bonds, while the peak at 1087.29 cm^{-1} is attributed to C–O stretching of phytochemical constituents involved in nanoparticle stabilization (Hussain et al. 2023).

TEM revealed that the Fe-BNPs exhibited predominantly spherical morphology with nanoscale size in a wide size range from 50 to 300 nm (Fig. 3B). SEM provided complementary information of the surface topology, showing aggregated clusters with a porous and irregular structure (Fig. 3A). This morphology is favorable for applications requiring high surface area, such as sorption or catalysis. EDS analysis indicated a homogeneous distribution of elements within the sample, with porous domains corresponding to the clustered regions observed in SEM images. This elemental uniformity supports the structural integrity and functional potential of the synthesized material. Elemental analysis further confirmed that carbon, iron and oxygen were the predominant elements, reflecting the core composition of the synthesized Fe-BNPs. The abundance of iron confirms the successful synthesis and also emphasizes the potential efficiency in redox processes, such as contaminant removal through this biomaterial. Other elements detected included Mg, P, K, Ca or Si, which is consistent with the natural origin of the synthesis precursors. These elements are typically present in biological matrices and may contribute to the structural stability and functional properties of the bionanoparticles. For example, magnesium and calcium could support structural integrity, while phosphorus might influence surface reactivity through its involvement in interfacial interactions (Wieszczycka et al. 2021). XRD analysis revealed that the Fe-BNPs are amorphous (Fig. 3F), lacking detectable crystalline phases, which indicates a disordered atomic structure. The amorphous nature enhances surface reactivity and catalytic performance due to the high density of reactive sites and flexibility in structure. This structural disorder could be advantageous for environmental remediation applications, as it supports enhanced pollutant degradation

capabilities (Guo et al. 2024). Mössbauer spectroscopy demonstrated that iron in the Fe-BNPs is predominantly present in the Fe(III) oxidation state, with a smaller fraction of Fe(II)–doublet formation (Fig. 3E). This suggests that partial oxidation of Fe(II) to Fe(III) may occur due to pH shifts from acidic to neutral conditions or upon exposure to atmospheric oxygen. Therefore, the synthesis of Fe-BNPs should be conducted under anoxic or oxygen-free conditions to minimize unwanted oxidation and preserve the desired redox properties. Further characterization of Fe-BNPs synthesized from Merlot pomace was performed using N_2 adsorption–desorption measurements (Fig. 3C) to evaluate their specific surface area (SSA) and pore structure (Fig. 3D). The analysis revealed a high SSA of $398\text{ m}^2\cdot\text{g}^{-1}$ and confirmed the mesoporous structure of Fe-BNPs which supports findings from electron microscopes. For comparison, iron nanoparticles (nFe) synthesized using aqueous extract of potato peel exhibited the SSA of $61\text{ m}^2\cdot\text{g}^{-1}$ (Himanshu et al. 2025). In another study, $\alpha\text{-Fe}_2\text{O}_3$ magnetic nanospheres prepared with *Bridelia retusa* leaf extract demonstrated the SSA of $75\text{ m}^2\cdot\text{g}^{-1}$ (Selvaraj et al. 2021). Particles of nFe synthesized using green tea extract were reported to have the SSA of $42\text{ m}^2\cdot\text{g}^{-1}$, with particle sizes ranging from 50 to 80 nm (Hao et al. 2021). These findings indicate that Fe-BNPs derived from Merlot pomace possess excellent sorption capacity, primarily due to their porous architecture and large surface area. Such characteristics enhance their potential for pollutant removal, supporting their applicability in environmental remediation.

To better understand their mode of action, it is essential to explore the underlying mechanisms by which Fe-BNPs interact with contaminants. Current data do not yet confirm whether sorption is the dominant process, or whether other mechanisms such as reductive dechlorination may also occur. To clarify this, detailed adsorption studies—including kinetic modeling, sorption isotherms, and mechanistic



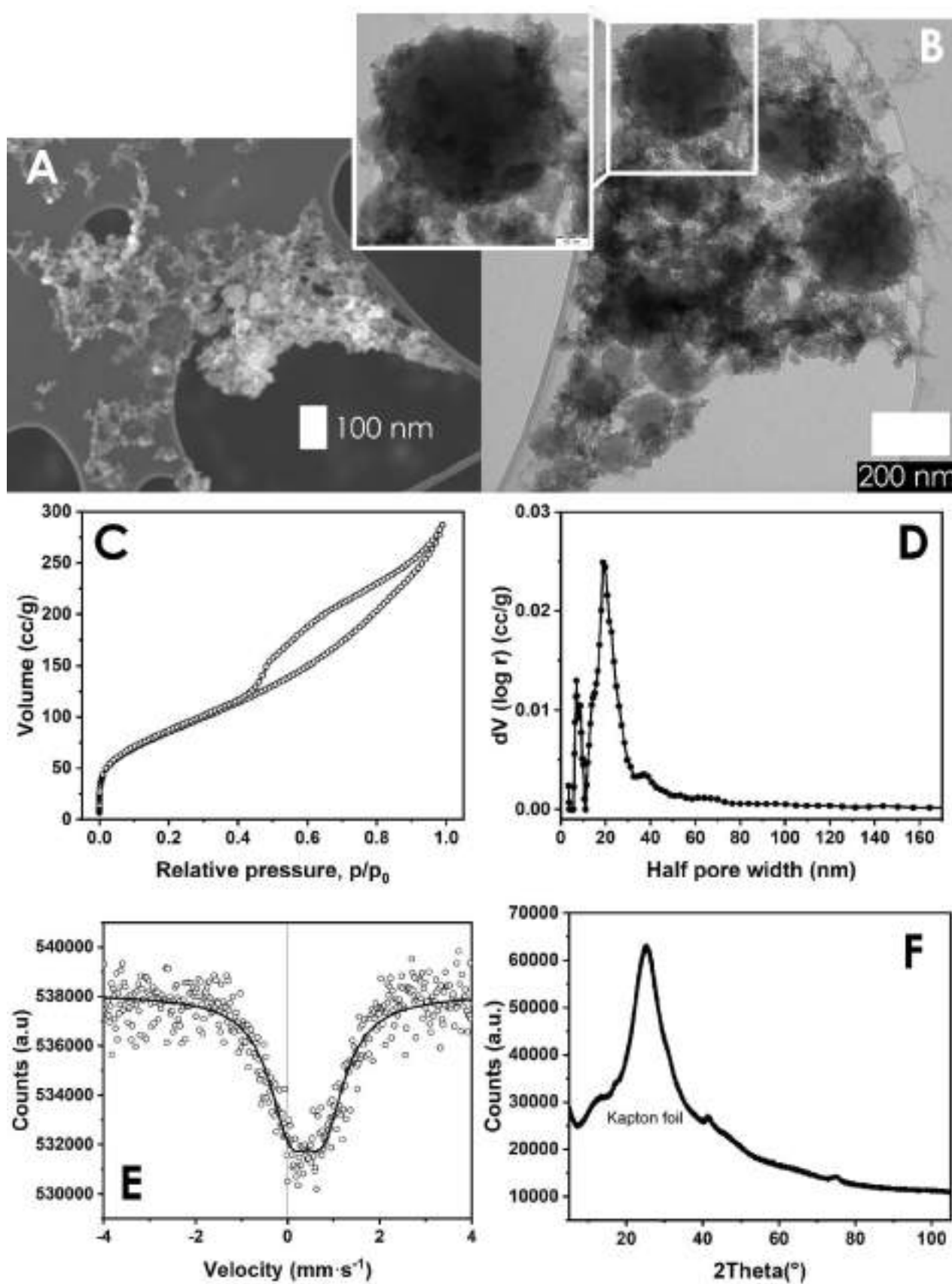


Fig. 3 Characterization of Fe-BNPs from Merlot pomace: **A** SEM images (100 nm), **B** TEM images (200 nm), **C** adsorption–desorption isotherm, **D** pore size distribution, **E** Mössbauer spectra with fitted spectral lines, **F** XRD diffractogram

evaluations—are required. Based on the material's physico-chemical properties, it could be hypothesized that Fe-BNPs may not only adsorb pollutants but could also facilitate the reductive dechlorination of chlorinated compounds such as PCBs, potentially via electron transfer processes involving chelated iron and redox-active functional groups originating from plant-derived polyphenols (Smuleac et al. 2011; Tratnyek et al. 2001; Wang et al. 2020). To verify this hypothesis, targeted experiments using a well-characterized PCB congener with known chlorination pattern are necessary. Monitoring the degradation products could reveal whether dechlorination occurs (evidenced by the formation of lower-chlorinated congeners), or if simple sorption is the prevailing process (reflected by a concentration decrease without congener transformation). While these conclusions are currently theoretical, they provide a strong basis for further experimental work. Given the exceptionally high specific surface area and mesoporosity of the Fe-BNPs, this biomaterial holds great promise not only for chlorinated organic contaminants, but also for the removal of toxic heavy metals, pharmaceuticals, and other xenobiotics from the water, soil and sediment.

Removal of PCBs

Fe-BNP-mediated PCBs removal (solely Fe-BNPs)

All four types of Fe-BNPs were applied in removal experiments, including Fe-BNPs from synthesized from grape berries and grape pomace of the *Vitis vinifera* cultivars Merlot and Blaufränkisch. The Fe-BNPs synthesized from Merlot grape pomace and grape berries exhibited significant efficacy in decreasing PCBs concentrations, achieving a removal of 62% and 60% of the sum of monitored PCB congeners over a 14-day period, respectively (Fig. 4). The similar removal efficiencies observed for both varieties indicate the potential of Fe-BNPs in environmental remediation. Longer exposure times are expected to further enhance PCB abatement, as results showed greater efficacy over 14 days compared to 7 days. The experiments were conducted under anoxic conditions, which favored the activity of Fe-BNPs. Exposure to oxygen could lead to Fe-BNP oxidation and reduced reactivity. Increasing the concentration of Fe-BNPs or adjusting the dosing frequency could potentially improve removal rates and extend their effectiveness over time. The observed diminution of PCB levels could be linked to the high specific surface area measured by BET analyses. These

findings highlight the feasibility of using Fe-BNPs derived from agricultural waste, supporting the broader goals of food waste valorization and the circular economy by converting waste materials into functional nanomaterials for pollutant removal.

The commercial mixture Delor 103 used in the experiments contains mainly lower chlorinated PCB congeners. Complete composition of Delor 103 can be found in Taniyasu et al. (2003); the monitored congeners make up approximately 30% w/w, such as PCB 8 (6%), PCB 28 (22%), PCB 52 (2%), PCB 101 (0.28%), PCB 118 (0.23%), PCB 153 (0.09%), and PCB 138 (0.09%). The removal effects of Fe-BNPs derived from grapes and grape pomace Blaufränkisch and Merlot varieties were comparable, with a significant difference observed only for PCB 118. Less chlorinated PCBs are generally less susceptible to reductive dechlorination compared to highly chlorinated PCBs due to the increase in the energy of the lowest unoccupied molecular orbital as chlorine atoms are progressively removed from the PCB molecule. Chlorine atoms in *para*- or *meta*- positions are dehalogenated more rapidly than those in *ortho*- positions. An increased number of chlorine atoms in *ortho*- positions can hinder the dechlorination process by increasing the torsional angle between the benzene rings, which may obstruct the sorption or degradation process (Lowry et al. 2004).

Numerous studies have demonstrated the effectiveness of such green-synthesized iron bionanoparticles (Fe-BNPs) for remediation both inorganic and organic pollutants. Wei et al. (2016) synthesized Fe-NPs from *Citrus maxima* peels, capable of reducing Cr(VI) to Cr(III). Machado et al. (2013) achieved 54–66% removal of ibuprofen using Fe-NPs derived from grape marc, black tea, and vine leaves in both water and soil. Moringa-based FeO-NPs exhibited superior fluoride adsorption and reusability (Silveira et al. 2017), while green tea-derived Fe/Pd-NPs immobilized in membranes provided stable TCE degradation over 3 months (Smuleac et al. 2011). Sun et al. (2024) synthesized iron nanoparticles using pomegranate leaf extract, achieving approximately 45.5% removal of indole within 20 min and 51.4% after 90 min. In a different study, Öter (2023) reported an adsorption capacity of 116.3 mg·g⁻¹ for nafcillin on green-synthesized iron oxide nanoparticles with 90% capacity retention after five reuse cycles, highlighting potential for pharmaceutical pollutant remediation.

Synergistic removal of PCBs (Fe-BNPs + bacteria)

The efficiency of Fe-BNPs in decreasing PCB levels monitored over 7 days was followed by the addition of a bacterial strain for an additional 14 days. This sequential approach combines abiotic and biotic processes, which is expected to enhance PCBs abatement. Theoretically, Fe-BNPs reductively dechlorinate highly chlorinated PCB congeners that are



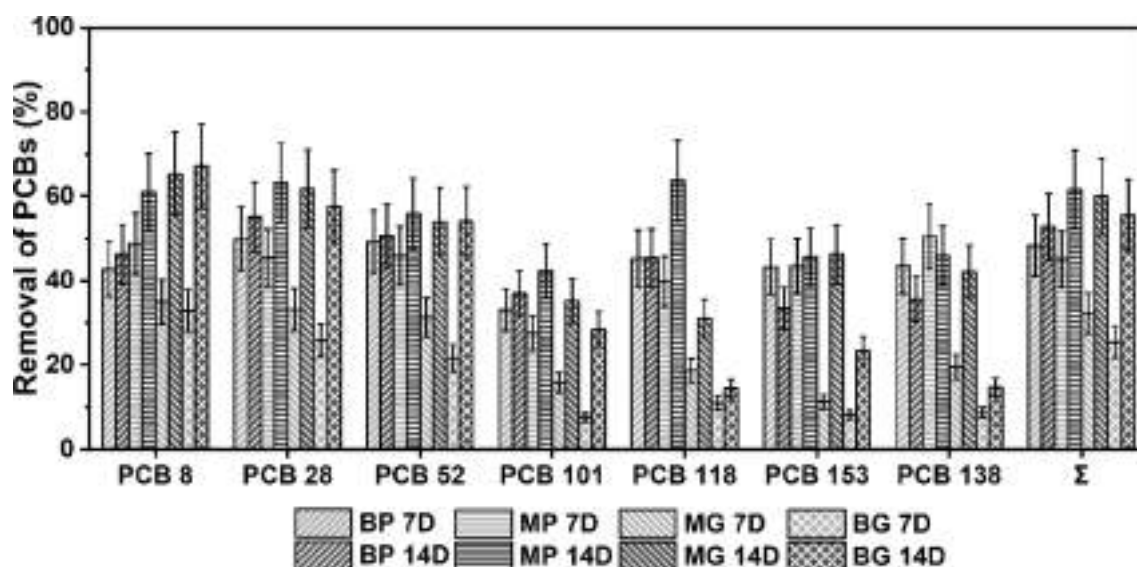


Fig. 4 Removal of PCBs by Fe-BNPs derived from Blaifränkisch grape berries (BG), Blaifränkisch grape pomace (BP), Merlot grape berries (MG) and Merlot grape pomace (MP)

less bioavailable to bacteria, enabling subsequent biological biodegradation of lower chlorinated PCBs following bacterial inoculation. Using sequential approach, the highest overall PCBs removal (76%) was achieved with Fe-BNPs derived from Merlot grape pomace combined with the bacterial strain *Ochrobactrum anthropi* (Fig. 5). Fe-BNPs from Blaifränkisch grape pomace, as well as those from both grape varieties supplemented with *O. anthropi*, achieved approximately 63% removal of the sum of 7 monitored PCB congeners. The addition of the bacteria *Stenotrophomonas maltophilia* also resulted in the significant PCB removal (70%) when

combined with Fe-BNPs from Merlot pomace. Fe-BNPs synthesized from plant sources contain various organic acids and compounds that can influence (inhibit or stimulate) bacterial growth and metabolism. Grapes contain many organic acids which could negatively affect bacterial viability; however, Fe-BNPs synthesis occurs at physiological pH, which partially neutralizes the effect of these acids. Carbohydrates present in the plant matrix may serve as an additional carbon source, although their content in the Fe-BNPs suspension is likely negligible (Bolade et al. 2020; Priya et al. 2021).

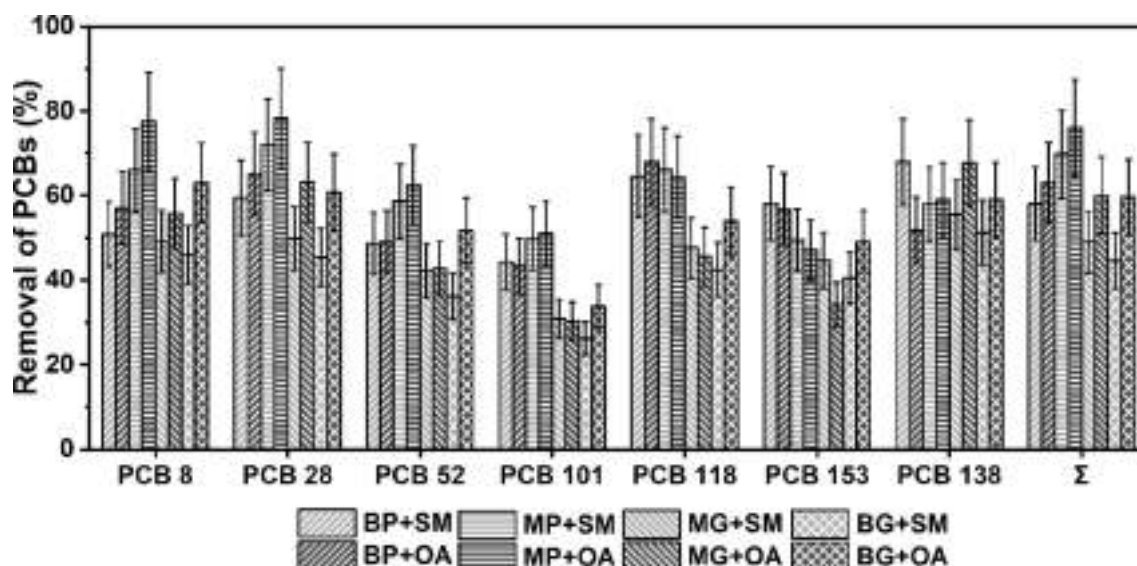


Fig. 5 Removal of PCBs by Fe-BNPs derived from Blaifränkisch grape berries (BG), and pomace (BP), Merlot grape berries (MG), and pomace (MP), and subsequently added bacterial strains *O. anthropi* (OA) or *S. maltophilia* (SM)



Fe-BNPs synthesized from Merlot grape pomace achieved up to 60% PCB removal during a 14-day cultivation period when applied as a standalone nanomaterial-based treatment. In a separate experiment (Tlčíková et al. 2024), the bacterial strains *O. anthropi* and *S. maltophilia* were also cultivated without addition of Fe-BNPs, achieving comparable PCB biodegradation efficiencies of 62–63% after 14 days (Fig. 6). However, when combined with Fe-BNPs in a sequential nano-bio approach, the removal efficiency increased markedly, reaching up to 76% with *O. anthropi*, highlighting this synergistic strategy as the most effective. Fe-BNPs synthesized from both grape pomace of the Blaufränkisch and Merlot varieties exhibited similar removal trends with variations within approximately 6%. This consistency underscores the potential for repurposing agrowaste as a sustainable precursor for bionanomaterial synthesis, thereby supporting the principles of the circular economy. A particularly important finding is that the total polyphenol content in the plant matrix is not necessarily the key factor influencing removal efficiency. Instead, the specific composition and dominance of individual phenolic compounds play probably a more decisive task. In previous study (Tlčíková et al. 2024), a variety of plant-based substrates were screened for their polyphenol content. Interestingly, Fe-BNPs synthesized from the grape pomace of the Merlot variety, despite its lower total polyphenol content (4.10 ± 1.2 mg GAE 100 g^{-1} ; Tlčíková et al. 2024) compared to grape berries, achieved the highest PCB removal efficiency—both when applied independently as Fe-BNPs and also when combined with bacteria in a synergistic approach. Although Merlot pomace exhibited a

comparatively lower polyphenol concentration than other tested materials, it was found to be effective in the removal process. The most effective PCB removal was observed with Merlot-derived Fe-BNPs in combination with *O. anthropi* in a sequential nanobiodegradation setup. Furthermore, the findings emphasize that in nanobioremediation approaches, the selection of both the nanomaterial substrate and the bacterial strain is critical. A well-matched combination is essential to maximize the synergistic effects between abiotic and biotic processes, ultimately enhancing the overall removal efficiency of persistent pollutants such as PCBs.

Recent studies on living biocomposites show that combining engineered materials with microbial activity can enhance remediation performance, highlighting the broader potential of material–microbe synergy across different pollutant types and mechanisms (Chen et al. 2024). Xie et al. (2011) demonstrated enhanced degradation of HCH using Pd/Fe-NPs combined with *Sphingomonas* bacteria, while Rizwan et al. (2019) achieved 90% degradation of PAHs using LaFeO₃ and biochar from *Trapa natans*, which also improved microbial diversity. Alabresm et al. (2018) achieved near-complete removal of Pb and Cd within 48 h using PVP-coated FeO-NPs combined with *Halomonas* sp., compared to the limited efficiency achieved by bacteria alone. Muthukumar et al. (2024) demonstrated that an integrated system of *Pseudomonas aeruginosa* PP4 and iron oxide nanoparticles achieved 67% biodegradation of anthracene, indicating enhanced PAH removal relative to microbial degradation alone. Similarly, in a soil co-contamination study, a biosurfactant-producing *Bacillus*–*Paenibacillus*

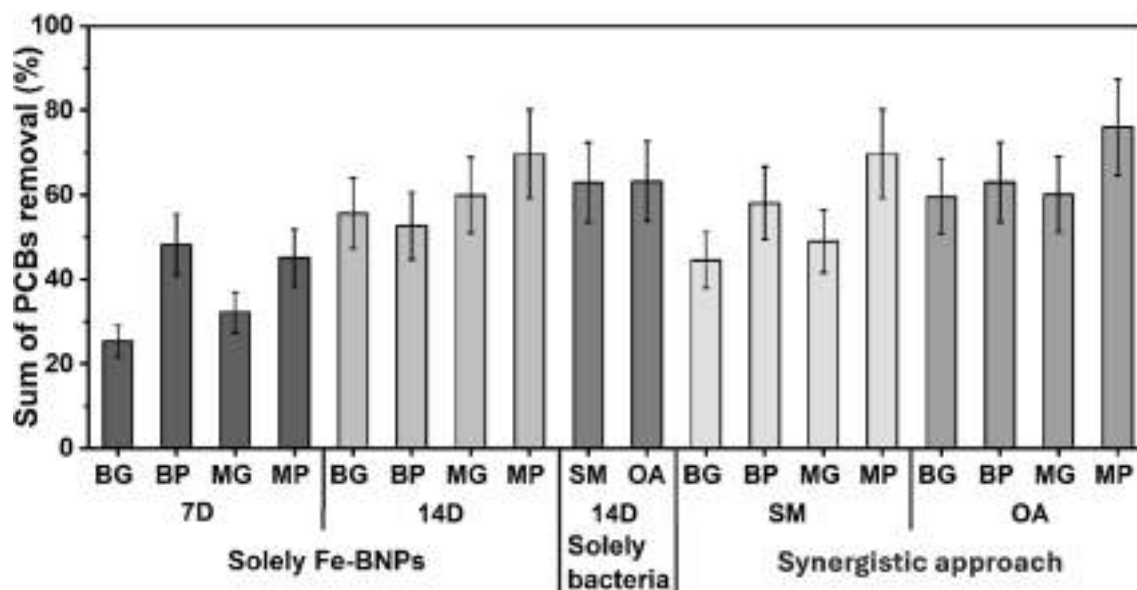


Fig. 6 Comparison of the removal of total PCBs by: (i) Solely Fe-BNPs derived from Blaufränkisch grape berries (BG), and pomace (BP), Merlot grape berries (MG), and pomace (MP) for 7 and 14 days; (ii) Solely bacteria—*O. anthropi* (OA) or *S. maltophilia* (SM)

for 14 days (Tlčíková et al. 2024); (iii) Synergistic removal as sequential approach with Fe-BNPs (BG, BP, MG, MP) and bacteria (SM, OA) for 7 + 14 days, addition of the bacterial strain inoculum after 7 days



consortium combined with green-synthesized iron oxide nanoparticles reached up to 99% bioremediation efficiency of crude oil and associated heavy metal contamination under optimized conditions within 15 days (Elumalai et al. 2024).

In the present study, during removal experiments employing solely Fe-BNPs, concentration of both, lower- and higher-chlorinated PCB congeners (e.g., PCB 118) was found to be decreased or eliminated. This indicates that Fe-BNPs alone may initiate abiotic transformation processes through sorption or reductive dechlorination, where chlorine atoms—particularly at *meta* and *para* positions—could be replaced by hydrogen under locally reducing conditions (Smuleac et al. 2011; Tratnyek et al. 2001; Wang et al. 2020). Such partial dechlorination may result in the formation of less-chlorinated congeners that are more bioavailable and potentially more susceptible to subsequent microbial biodegradation. The selected bacterial strains, *S. maltophilia* and *O. anthropi*, previously characterized by Dudášová et al. (2014), Horváthová et al. (2019), and Lászlóvá et al. (2018) exhibit moderate ability to utilize biphenyl, dibenzofuran, and PCBs as sole carbon sources. However, both strains lack the *bphA* gene encoding 2,3-dioxygenase, which is essential for initiating the upper aerobic biphenyl/PCB degradation pathway, as we observed in previous experiments (Dudášová et al. 2014). Only a single bacterial inoculation was applied; therefore, a continued increase in PCBs removal beyond a limited incubation period was not anticipated. Over time, residual PCBs, transformation byproducts, and the introduced Fe-BNPs may act as stressors that progressively diminish bacterial viability. For this reason, the biotic phase was limited to 14 days, a timeframe consistently employed in previous experiments to enable reliable comparison of results (Dudášová et al. 2014; Horváthová et al. 2019; Lászlóvá et al. 2018; Tlčková et al. 2024). Based on these observations and the obtained results, it is hypothesised that the PCBs clean-up proceeds through a sequential mechanism: an initial abiotic phase mediated by Fe-BNPs, followed by aerobic bacterial metabolism. Firstly, PCBs are sorbed or dechlorinated via reductive dehalogenation by Fe-BNPs under anoxic conditions. The results of material characterization of Fe-BNPs indicates, that the more likely mechanism is adsorption of the PCBs to the Fe-BNPs (large SSA detected by gas sorption analysis). Alternatively, PCBs are subjected to initial abiotic reductive transformation mediated by Fe-BNPs. Upon transition to aerobic conditions, PCBs associated with Fe-BNPs may become bioavailable to bacterial cells at the nano-bio interface. The sorbed PCBs and/or dechlorination products, depending on the dominant mechanism, are subsequently biodegraded in aerobic phase by bacteria. Biodegradation likely proceeds via alternative metabolic routes, since *bphA* is absent. Enzymes such as monooxygenases, peroxidases, or hydrolases present in *S. maltophilia* and *O. anthropi* may

mediate further transformation (Bhaumik et al. 2024; Jahns et al. 1997). These pathways could be enhanced by polyphenols and other redox-active plant-derived compounds associated with Fe-BNPs, which may act as mediators or inducers of gene expression related to pollutant degradation (Rolli et al. 2024). For example, according to Suman et al. (2021), the degradation of flavonoids may prime or stimulate secondary metabolic pathways for PCB degradation, suggesting a plausible enzymatic activation cascade for PCBs within the microbial system studied. Also in the absence of complete mineralization, alternative processes such as sorption or bioaccumulation may be involved. PCBs may adsorb to bacterial surfaces—particularly to the lipopolysaccharide outer membrane of Gram-negative bacteria (Sowers and May 2014). This sequential or combined system thus mimics a “nano-bio-reactor”, where abiotic and biotic transformations are not merely additive, but mutually reinforcing. To clearly elucidate the degradation pathways and distinguish between primary, secondary, and terminal metabolites, advanced analytical techniques (e.g., NMR, GC/MS, HPLC, or LC-MS/MS) are needed for structural identification. Additionally, sorption studies and isotherm modeling are essential to evaluate the involvement of non-degradative processes and to determine the dominant mechanism.

Ecotoxicological effects of Fe-BNPs

To assess the potential toxic impact of Fe-BNPs synthesized from Merlot grape pomace waste on components of the ecosystems, auxanogram analysis was performed on the bacterium *O. anthropi*, and a germination test was conducted on yellow mustard (*Sinapis alba*). The tested concentrations of Fe-BNPs were 10, 20, 50, and 100 g·L⁻¹. This concentrations represents an extreme stress condition rather than environmentally relevant scenario. Fe-BNPs synthesized via green routes may exhibit properties with the potential to affect environmental components; however, the avoidance of toxic precursors during their production is expected to result in improved tolerance by biological indicators (Kumar et al. 2023). This is further supported by the fact that the nanoparticles were not present in a highly reduced state, as Mössbauer spectroscopy confirmed the absence of Fe⁰ and the dominance of Fe³⁺ species. While more reduced iron phases are often associated with higher remediation efficiency, they are also linked to increased reactivity and potentially greater biological impacts (Dowlath et al. 2021).

In the auxanogram test, no inhibition zones were observed on any solid medium in the Petri dishes, except for the control containing ethanol. Based on this test, we can conclude that the synthesized Fe-BNPs from grape pomace do not exhibit inhibitory effects on the tested bacterium *O. anthropi* at concentrations ranging from 10 to 100 g·L⁻¹. Studies on the potential toxicity of bionanoparticles are



crucial indicators for their future application directly into the environment. Synthetic nanoparticles are generally considered more harmful than bionanoparticles due to their production processes and high reactivity. Kotchaplai et al. (2017) highlighted the microbial adaptability to repeated exposure to synthetic iron nanoparticles. During the initial exposure, the cell surface became permeable; however, subsequent applications resulted in smaller bacterial phenotypes that were more resistant to iron nanoparticles. In previous experiments, it was found that synthetic zero-valent iron nanoparticles (nZVI) (NANOFE 25S – NANO IRON, Ltd., Czechia) in concentration of $2 \text{ g}\cdot\text{L}^{-1}$ reduced the cell density of the bacterial strains *S. maltophilia* and *O. anthropi* by up to 75%, but more commonly by a lower percentage (Horvátová et al. 2019). Hsueh et al. (2017) investigated the antimicrobial effects of synthetic nZVI particles on two Gram-positive *Bacillus* strains and two Gram-negative *Escherichia coli* strains. The data indicate a pronounced toxic effect on both *Bacillus* strains, as determined by X-ray photoelectron spectroscopy (XPS). Extended X-ray absorption fine structure analysis confirmed that *Bacillus* cells contained primarily Fe_2O_3 and FeS, suggesting that nZVI particles penetrated the cells and oxidized to hematite. In contrast, the Gram-negative *E. coli* strains showed no significant changes at the cellular level when exposed to the same nanoparticle doses. The toxic effects of nanoparticles depend on their shape, size, and the coating material in which the nanoparticle is encapsulated. The increased inactivation effect of nanoparticles is primarily attributed to the production of reactive oxygen species (ROS), the release of iron corrosion products (Fe(II) and Fe(III) ions), and the direct interaction of nanoparticles with bacterial cell membranes (Sadek et al. 2021). Synthetic nanoparticles and bionanoparticles composed of other metals, such as silver, exhibit significantly higher toxicity and antibacterial effects compared to iron-based nanoparticles. This is due to the widespread natural occurrence of iron in rocks and the human body (Elumalai and Velmurugan 2015). The short germination test performed on *Sinapis alba* (yellow mustard) demonstrated root growth inhibition of 46% and 35% at concentrations of $10 \text{ g}\cdot\text{L}^{-1}$ and $20 \text{ g}\cdot\text{L}^{-1}$, respectively. Higher concentrations of the synthesized Fe-BNPs almost completely inhibited seed germination (Table 1).

Libralato et al. (2016) compared the phytotoxicity of ionic, micro-, and nano-iron on *Sinapis alba*. Signs of toxicity were observed only at the highest concentration of ionic iron (FeCl_3) at $1570 \text{ mg}\cdot\text{L}^{-1}$. Macroscopic aggregates of nanoparticles were recorded on all roots of the tested plants, particularly at high concentrations. No significant phytotoxic effects were observed for nano- or micro-scale iron. Mielcarz-Skalska et al. (2021) assessed the phytotoxicity of synthetic nZVI particles (NANOFE 25 and NANOFE 25S) on *Lolium westerwoldicum*. Their findings revealed that nZVI particles at low

Table 1 Achieved percentage inhibition of root growth in yellow mustard seeds

c ($\text{g}\cdot\text{L}^{-1}$)	10	20	50	100
I_{μ} (%)	46.12 ± 5.4	35.85 ± 1.8	93.29 ± 2.1	97.27 ± 1.3

c = concentration of Fe-BNPs from Merlot pomace ($\text{g}\cdot\text{L}^{-1}$); I_{μ} = root growth inhibition (%).

concentrations are transported from the soil into the root, where they remain localized and do not translocate further into the plant. It is likely that iron accumulates in the outer layer of the root or aggregates on its surface, potentially obstructing nutrient uptake. Both types of synthetic nZVI particles were found to be non-toxic to plant growth, although they reduced plant tissue mass. These results on the potential toxic effects of Fe-BNPs demonstrated seed germination capability at concentrations up to $20 \text{ g}\cdot\text{L}^{-1}$ within a 3-day period. It is possible that extending the experiment's duration would allow slower-germinating seeds to sprout. In this type of test, it is crucial to select dry seeds of similar size and shape, free from damage or deformities, as an imperfect selection process can affect the final germination assessment. The tested concentrations of Fe-BNPs from Merlot pomace were deliberately chosen to be relatively high in order to identify the limits of their environmental compatibility. Due to the limited number of studies focused on the ecotoxicity of green-synthesized Fe-BNPs derived from agro-industrial waste, existing literature on synthetic nZVI particles was used for comparison. These studies consistently report adverse environmental effects at significantly lower concentrations. Such findings support the hypothesis that Fe-BNPs obtained from renewable organic sources may exhibit a higher degree of ecological compatibility.

Conclusion

The Fe-BNPs synthesized from grape pomace exhibit excellent sorbent properties (amorphous bionanomaterial with SSA of $398 \text{ m}^2\cdot\text{g}^{-1}$). All four Fe-BNP variants were tested in nanoremediation alone and in sequential nanobioremediation of PCBs. A time-dependent removal trend was observed, with the removal of the sum of PCBs increasing from 45% after 7 days to 60–62% after 14 days of Fe-BNPs application alone. The highest removal efficiency (76%) was achieved through a sequential application of Fe-BNPs from Merlot pomace and *Ochrobactrum anthropi*, confirming the synergistic potential of nanobioremediation strategies. Other combinations, such as Fe-BNPs with *Stenotrophomonas maltophilia* or Fe-BNPs from Blaufränkisch pomace, also showed high removal efficiency (63–70%), though slightly less effective. Ecotoxicological assessment based on *Sinapis alba* seed germination assays and auxanogram tests with *Ochrobactrum anthropi* indicated only moderate effects of



Fe-BNPs derived from Merlot pomace on early plant germination, with partial inhibition observed at the lowest tested concentration ($10 \text{ g}\cdot\text{L}^{-1}$). Nevertheless, no visible inhibition zones were detected in the auxanographic assays, suggesting no detectable adverse effects on bacterial growth.

This work demonstrates an effective integration of waste valorization, green nanotechnology, and microbial bioremediation into a sustainable remediation platform for persistent organic pollutants. The findings support the use of food processing by-products as precursors for functional bionanomaterials and confirm the feasibility of combining nanoremediation with bioremediation for enhanced environmental cleanup. This approach contributes to the development of circular economic practices, while addressing environmental and toxicological safety for environmental remediation technologies.

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Data availability The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Declarations

Conflict of interest Author Hana Horváthová was employed by the Centre of Environmental Services, Ltd. The Centre of Environmental Services, Ltd. had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict

of interest. All authors declare that they have no conflict of interest and certify that they have no financial or non-financial interests in the subject matter discussed in this manuscript.

Ethics approval Compliance with ethical standards.

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