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Prospects for biochar-based technologies in the remediation of military-impacted soils

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ABSTRACT

The paper aims at defining the core patterns for biochar-based remediation of soils contaminated after hostilities. The main ecological problem of combat-impacted zones is multicomplexes of soil pollution and degradation as well as co-contamination by potentially toxic elements (PTEs) and energetic compounds (ECs). Biochar produced from different feedstocks, including woody (oak, ash) and non-woody (digestate) biomass, were analysed for ash and carbon content, elemental composition and microstructure. Based on the purpose of using biochar for soil remediation and specification of contaminated soils laboratory biochar samples were produced by slow pyrolysis (600 °C, 5–7 °C min^{-1}, 2 h). Obtained results showed high ash contents in wood and digestate-derived biochars (≈33–36%) and elevated organic carbon in digestate-derived biochar, indicating strong sorption capacity for organic explosives (e.g., RDX) and capacity for heavy-metal immobilization. Review of main mechanisms for heavy metals and explosives degradation using biochar highlighted that core pathways like pore filling, π–π and hydrophobic interactions, electrostatic adsorption, cation exchange, surface complexation, redox transformations and microbially mediated degradation directly depend on feedstock, pyrolysis parameters and soil chemistry. Based on the study results pyrolysis production parameters were suggested (optimal pyrolysis window ~500–600 °C; slow heating; feedstock mixes). These findings highlight biochar-based technologies as promising approach to remediation of military-impacted soils, but field trials are needed to prove efficacy, long-term stability and ecological safety.

Keywords: pyrolysis conditions, biochar production, heavy metals, hostilities, explosives, removal mechanisms, soil contamination.

INTRODUCTION

War-conflict zones pose a serious ecological risk for soil, air, water and human health through military actions resulting in various environmental impacts. Explosions of aerial bombs, missile strikes, burning and destruction of military and special equipment as well as accumulation of toxic waste derived from ammunition cause severe chemical contamination, mechanical and physical disruption of soil and biodiversity losses. Soils after military actions are characterized by mechanical degradation including disturbance of the soil profile, mixing of soil horizons (Melnychenko, 2024), changes in mechanical structure and granulometric content with predominance of sand fraction and decrease of clay fraction (Solokha et al., 2024). However, our studies of soil samples from a deep crater after a guided aerial bomb explosion revealed that due to the mixing of soil layers, the clay fraction forms a "clay lock" that prevents water seepage deep into the arable layer. Moreover, movement of heavy machinery with following spills of fuels and lubricant materials has negative effects on physical, chemical and biological properties of soil. Fuel spills on soil surface cause soil compaction (Bonchkovskyi et al., 2025), porosity decrease, reduction of aeration and water-holding capacity (Melnychenko, 2024), changes of soil pH and organic matter, nutrient availability reduction (Biyashev et al., 2024).

Chemical contamination of soil after military actions is multispectral due to entering potentially toxic elements (PTEs), energetic compounds (ECs, explosive organic substances), chemical warfare agents (CWAs) and military chemical compounds (MCCs) (Fernandez-Lopez et al., 2022). The most frequently and simply analysed in soil samples in combat zones after explosions are PTEs such as heavy metals (HMs) and petroleum hydrocarbons (PHs), and ECs like explosive residues. Soil contamination with HMs and radionuclides after explosions and in zones of burned and destroyed military equipment poses ecological risk due to high concentrations of lead, cadmium, copper, chrome, nickel and zinc exceeding maximum permissible level by 3–6 times, sometimes up to 25 times (Petrushka et al., 2024).

2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine or royal demolition eXplosive (RDX) and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine or high melting explosive (HMX) are the most common explosives that belong to nitroaromatics (TNT) and cyclic nitramines (RDX and HMX). Concentrations of explosives can vary and reach huge levels in military-impacted soils as reported for such sites in USA, Canada and Korea (Broomandi et al., 2020). Soil pollution with organic and inorganic toxic compounds lead to changes of the ecosystem and biocenosis structure emphasizing significant increase in the quantities of micromycetes, pedotrophs, and oligotrophs (Solokha et al., 2024). Moreover, high levels of PTEs and ECs in soil negatively impact on biological properties of soils causing inhibition of soil microbial biomass and activity, decreases of soil microbiota biodiversity and enzymatic activities, particularly urease and dehydrogenase enzymes (Rodríguez-Seijo et al., 2024).

Land reclamation and soil remediation in the combat zones require precise cleaning-up techniques and methods providing restoration effect on mechanical, chemical and biological properties of soils (Kuzomenska et al., 2025). One of such approaches is biochar application due to its multivariate characteristics through modification into active bioformulation (Sharma et al., 2023) and possibility for integration into comprehensive land reclamation scheme. Biochar contains a high carbon content, alkaline medium reaction and a developed porous structure, which ensures the achievement of several positive effects in restoring fertility and cleaning the soil: reclamation, loosening, gradual restoration of humus reserves, sorption, immobilization and biodegradation of pollutants (Siddiqui, 2025). Biochar is effective in adsorption and chemical conversion for several groups of contaminants including explosives (Dong et al., 2024), HMs (Mehmood et al., 2018), and polycyclic aromatic hydrocarbons (T.-B. Nguyen et al., 2023).

It should be noted that biochar can be produced from wood biomass as well as agricultural residues, including digestate as by-product of anaerobic digestion process, that seems as effective management strategy for digestate to improve its quality as soil amendment. However, according to the International Biochar Initiative (IBI) guidelines, biochar obtained from processed feedstock like digestate should meet requirements associated with additional risks from the potential presence of toxicants in the feedstock and meet the toxicant assessment, including germination inhibition assay, content of some organic pollutants and HMs (Biochar Standards, 2026).

Depending on the type of contaminants mechanisms for their transformation on biochar can be different and specific modification of biochar could be required. Moreover, understanding target factors affected on biochar structure, content and properties allows us to manage the efficiency of chemicals degradations in the soil while biochar is applied as remediation approach. Therefore, the issue of researching the prospects for the use of biochar in soil protection technologies after military actions and establishing the mechanisms and patterns of the influence of biochar on the remediation process on the co-contaminated soil is relevant today.

The main aim of this paper is to establish synergistic patterns for the restoration and purification of co-contaminated soils using biochar.

To achieve the aim, the following research tasks were set:

1) identify target factors and biochar parameters influencing heavy metals and explosives degradation based on the literature review;

2) analyze characteristics of biochars derived from different biomass sources (including digestate);
3) identify effective biochar production strategies for the remediation of soils co-contaminated with heavy metals and explosive compounds by evaluating biochar properties, elucidating key remediation mechanisms, and determining optimal pyrolysis conditions.

BACKGROUND

Target factors influencing biochar structure and properties

Biochar is a carbon-rich solid product of pyrolysis that is thermo-chemical rection of heating under anoxic conditions. Besides biochar volatile substances such as bio-oil and syngas are produced during pyrolysis from organic feedstock of different genesis. The most common substrates for biochar production are biomass like wood and agricultural residues. The proportion of lignin, cellulose and hemicellulose in the feedstock defines the amount of the produced biochar and its surface properties (Mukherjee et al., 2022). Using substrates rich in lignin and cellulose increases the amount of biochar, while hemicellulose substrates improve its porous structure (total pore volume, porosity and pore size) and increase specific surface area (Bruun et al., 2012). Biochar has an alkaline pH (pH 6–12), due to oxygen-containing groups and inorganic minerals, such as carbonates. Biochar contains alkali and alkaline earth metals, usually present in the form of oxides/hydroxides, phosphates, silicates, carbonates, and sulphates (T.-B. Nguyen et al., 2023).

In terms of biochar application during soil remediation the most important parameters are porous structure, surface area and surface structure (functional groups and associated surface charge) and carbon content. Porous structure properties and surface area identify the efficiency of the contact between biochar and soluble exogenous redox components, thereby facilitating the transfer of electrons, promoting the adsorption of pollutants and supporting the growth of microorganisms (Dong et al., 2024). Presence of functional groups on the surface of biochar, including hydroxyl, carboxyl, carbonyl, quinone and lactone groups, determines the surface charge and cation exchange capacity (CEC). Surface charge determines the electrostatic interaction between biochar and pollutants. Cation exchange capacity plays an important role in the attraction of positively charged HMs and the absorption of chemicals by biochar (T.-B. Nguyen et al., 2023). A decrease in the number of oxygen-containing functional groups leads to a decrease in the CEC of biochar, and an increased content of alkali metals (K, Ca and Mg) increases it (Dong et al., 2024). Carbon content improves microorganisms' growth and enzyme activity intensifying biochemical processes of pollutants transformation.

There are several target factors influencing biochar structure and mentioned properties such as feedstock type, pyrolysis temperature, residence time, and heating rate (Dong et al., 2024). The relationships between target factors and biochar properties are illustrated on Figure 1, 2, and Table 1.

Biochar is most frequently generated from various forms of biomass, primarily encompassing timber industry by-products and agricultural waste (Figure 1). Feedstocks for biochar production from digestate are also varied and primarily include straw digestate, livestock manure digestate, sludge digestate, food waste digestate, and energy crop digestate (Fu et al., 2024).

Thus, to obtain biochar with a constant carbon content and higher biochar yield, it is preferable to use feedstock with a higher lignin content (T.-B. Nguyen et al., 2023), while cellulose- and hemicellulose-containing substrates improve its porous structure and increase the specific surface area (Anyebe et al., 2025). Therefore, wood biomass with lower ash content and higher C content compared to manure or agricultural residues is a better substrate for production biochar able to metal sorption and carbon sequestration in soil. Specific surface area was higher in biochar obtained from straw digestate compared to biochar obtained from pig and chicken manure digestate (Luo et al., 2023), however biochar from manure had higher amounts of nutrients that lead to crop yield increase (Siddiqui, 2025).

Temperature is the primary controlling parameter in the pyrolysis process and strongly influences both the yield and physicochemical properties of the resulting products (Figure 2). Pyrolysis is generally conducted within the temperature range of 300–900 °C and involves a series of complex reactions, including bond cleavage,

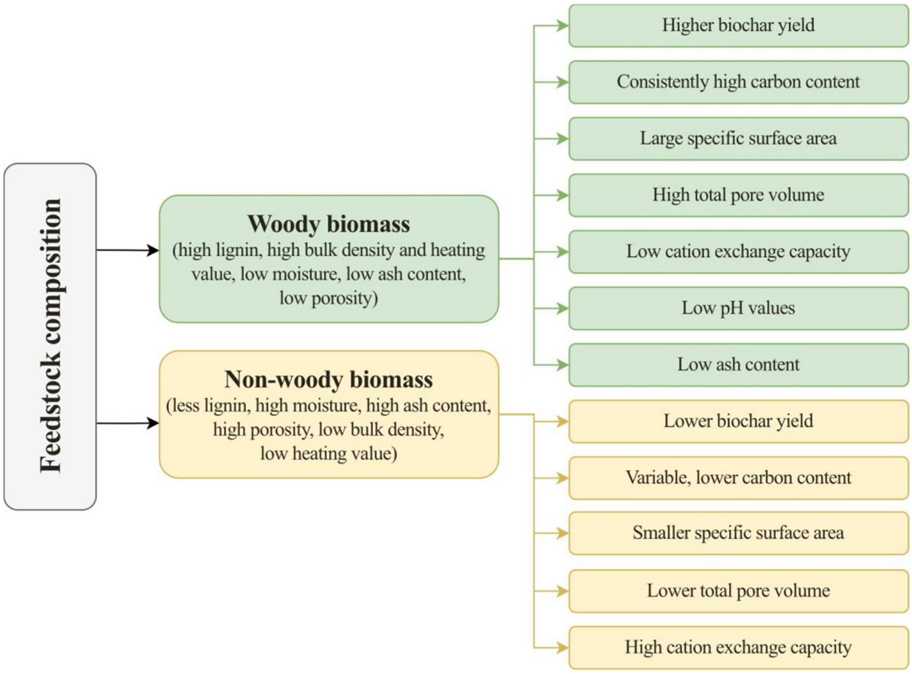

Figure 1. Dependence of biochar properties on the composition of the raw material
Compiled by authors based on (Bruun et al., 2012; Fu et al., 2024; T.-B. Nguyen et al., 2023)

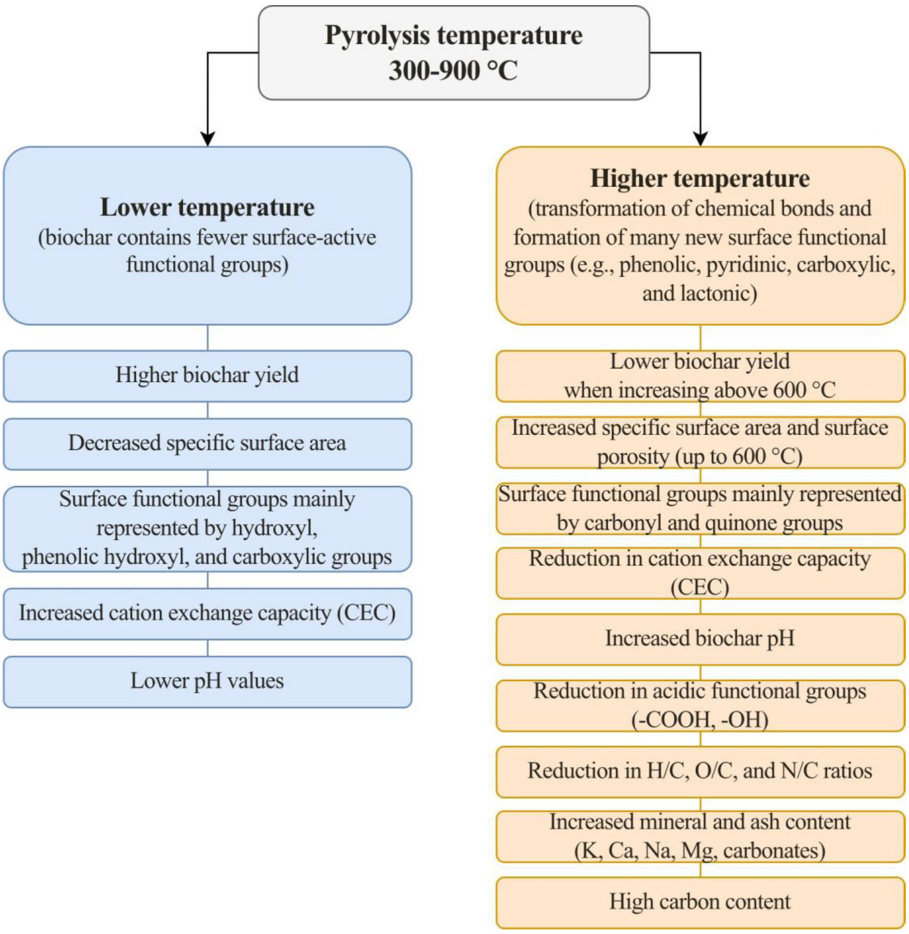

Figure 2. Dependence of biochar properties on pyrolysis temperature. Compiled by authors based on (Fu et al., 2024; Haghighi Mood et al., 2022; T.-B. Nguyen et al., 2023)

isomerization, and secondary recombination of smaller molecular fragments (Fu et al., 2024).

Biochar produced at higher temperatures exhibit lower O/C ratios and a greater degree of aromaticity, which enhances their structural stability and persistence in soil environments (Haghighi Mood et al., 2022). Several studies have reported a gradual decline in biochar yield as pyrolysis temperature increases from 400 to 600 and 800 °C (Al Afif et al., 2019; Alghashm et al., 2018). As temperature continues to rise, additional mass loss occurs due to continuous devolatilization, leading to reduced solid product yield. At moderate pyrolysis temperatures, biochar particles tend to exhibit smoother morphology and a reduced abundance of surface-active functional groups (T.-B. Nguyen et al., 2023).

The specific surface area (SSA) of biochar generally increases with rising pyrolysis temperature and longer residence times, primarily due to the progressive development of microporosity as volatile components are released. However, excessively high temperatures or prolonged residence times may cause pore collapse or structural shrinkage, resulting in a decline in SSA. For example, increasing the temperature above 600 °C for biochar derived from straw digestate, pig manure, and chicken manure, and above 800 °C for food waste digestate-derived biochar, has been shown to reduce the specific surface area (Liu et al., 2022; W. Wang and Lee, 2021).

Overall, within an optimal temperature window, increasing pyrolysis temperature enhances specific surface area, porosity, carbon content, thermal stability, pH, and ash content of digestate-based biochar. In contrast, biochar yield, polarity, and the abundance of acidic oxygen-containing functional groups decrease as temperature increases. Pyrolysis can be divided into three types depending on the heating rate: slow pyrolysis, fast pyrolysis and flash pyrolysis (Fahmy et al., 2020) that directly affects biochar properties playing a key role in its application for soil decontamination (Table 1).

To enhance soil remediation, improve soil properties and carbon sequestration, biochar should have developed porous structure and specific surface area, the formation of surface functional groups and cation exchange capacity, as well as carbon content, aromaticity (H/C < 0.5), and pH-buffering capacity. Thus, feedstock type should reflect balanced mix of lignin, cellulose and hemicellulose substrates with nutrient-rich substrates. The optimal pyrolysis temperature is 500–600 °C, residence time is 1–2 h, and slow heating rate 5–10 °C min^{-1} that improve carbon content and stability, SSA, porous structure, surface charge and pH of produced biochar.

Moreover, different types of biochar modification could be applied to increase surface area and porosity, enhanced functional groups, improve pollutant adsorption, and HMs immobilization, allowing to enhance soil remediation. The most common types of modification are physical, chemical, and composite and biological modification.

Table 1. Comparative characteristics of slow, fast, and flash pyrolysis of lignocellulosic biomass

Parameter	Slow pyrolysis	Fast pyrolysis	Flash pyrolysis
Heating rate	5–7 °C min^{-1}	~300 °C min^{-1}	~1000 °C s^{-1}
Vapor/solid residence time	Hours to days	< 5 s	30 ms–1.5 s
Temperature	Typically < 800 °C	High-temperature thermal decomposition (typically 400–600 °C)	High-temperature process (typically ≥ 600°C)
Primary objective	Biochar production	Bio-oil maximization	Rapid bio-oil production
Biochar yield	High (< 35 wt%)	Low	Low
Bio-oil yield	Low	High (~75 wt%)	High (< 70 wt%)
Syngas yield	Low	Moderate to low	Moderate
Carbon stability in solid product	Highly stabilized carbon; resistant to long-term microbial degradation	Lower stability compared to slow pyrolysis	Lower stability compared to slow pyrolysis
Specific surface area and pore area	Increases if residence time does not exceed 2 hours	Moderate porosity, moderate SSA, limited structural ordering	Porosity may increase initially but often decreases at very high temperatures

Note: Based on (Feng and Lin, 2017; Mukherjee et al., 2022).

Mechanisms for heavy metals and explosives degradation using biochar-based technologies

The removal of pollutants by biochar is achieved through the following mechanisms: pore filling, diffusion and partitioning, hydrophobic interactions, aromatic π-π interactions, hydrogen bonding, electrostatic interactions, cation exchange, induced precipitation, surface complex formation, interactions with amine groups, simultaneous adsorption and catalytic degradation, microbial mediation, and precipitation (Figure 3).

Biochar has multifunctional nature in contaminant removal and immobilization, through a combination of physical, chemical, and biological pathways, whose relative contributions depend strongly on its physicochemical properties (e.g., surface area, pore structure, aromaticity, functional groups, mineral content, pH, and pHpzc) and environmental conditions (e.g., solution pH, ionic strength, redox state, and contaminant speciation).

Physical mechanisms such as pore filling, diffusion, and size exclusion dominate if biochar has developed porosity and high SSA, which allows for the retention of dissolved metals and organic pollutants (Abhishek et al., 2022). Hydrophobic interactions, π–π aromatic interactions and hydrogen bonding are important mechanisms for sorption of organic contaminants, especially hydrophobic and aromatic compounds (Abhishek et al., 2022; V.-T. Nguyen et al., 2019). Nevertheless, electrostatic attraction and cation exchange play key role in HMs adsorption in the soil that depends on pH, meaning better HMs adsorption potential if the solution pH exceeds the pHpzc of biochar (Abhishek et al., 2022). Moreover, mineral-rich biochar and composites promote immobilization of HMs through cation exchange between surface cations (Gholizadeh and Hu, 2021). Furthermore, binding of HMs like Pb^{2+} and Zn^{2+} is developed by surface complexation via inner-sphere bonding with oxygen-containing functional groups (Amusat et al., 2021).

Redox transformation by biochar lead to reduction of Cr (VI) to Cr (III) or promote oxidation of As (III), often mediated by Fe- and Mn-containing minerals (T.-B. Nguyen et al., 2023). Cations like Pb^{2+}, Cd^{2+}, Cr^{3+} can be precipitated to compounds with less bioavailability $CdCO_3$, $Pb_3(PO_4)_2$, $Cr(OH)_3$), that are regulated by alkalinity and the release of carbonate, phosphate, sulphate, or sulphide (Bousdra et al., 2023). Processes of pollutants degradation in the soil are microbially regulated that enhance the effectiveness of biochar and provide a synergistic effect. Therefore, the type of mechanisms depends on biochar properties and structure that are influencing by feedstock type and thermochemical parameters of pyrolysis.

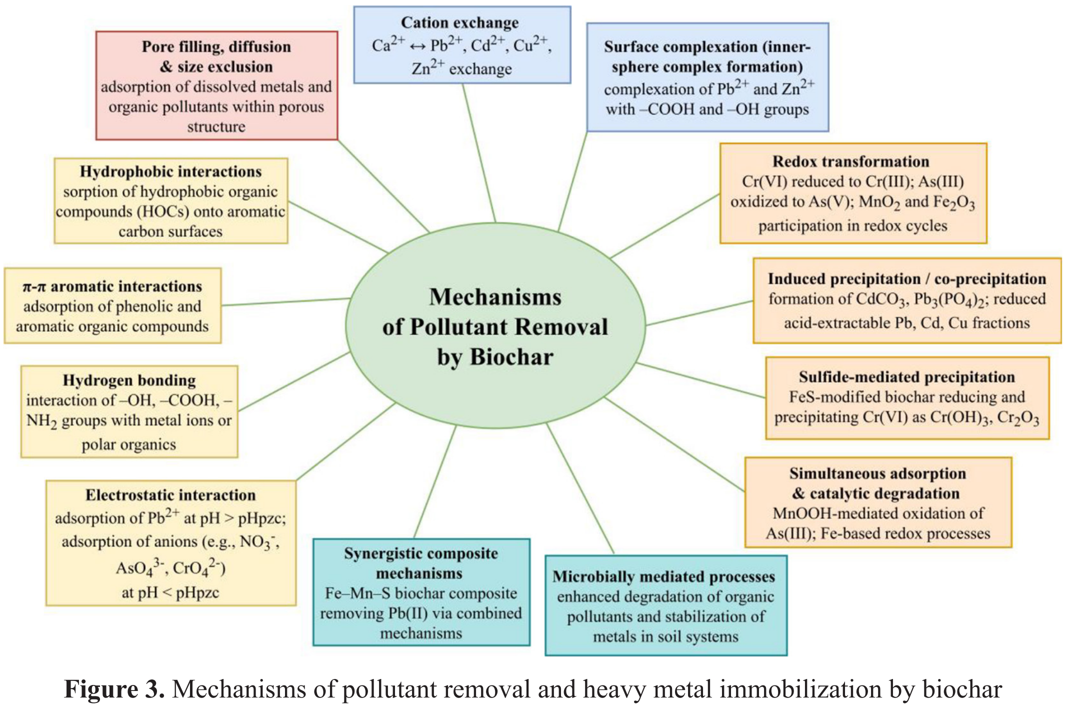

Figure 3. Mechanisms of pollutant removal and heavy metal immobilization by biochar
Note: Based on (Dong et al., 2024; T.-B. Nguyen et al., 2023).

Biochar has demonstrated strong potential for the adsorption of nitro-explosive compounds. The adsorption behavior of explosive substances (ES), such as TNT and RDX, is influenced by multiple operational and environmental parameters, including biochar dosage, contact time, solution pH, ionic strength, and the presence of competing solutes. Increasing the biochar dosage generally enhances the removal efficiency of TNT and RDX, primarily due to the greater availability of adsorption sites. However, beyond a certain dosage threshold, the rate of improvement declines and sorption efficiency approaches a plateau. This behaviour is attributed to the increased total number of active sites in the system, accompanied by a reduction in the effective utilization of adsorption sites per unit mass of biochar at higher dosages (Dong et al., 2024). Main mechanisms of removal of energetic substances (explosive organic substances) by biochar is presented in (Kuzomenska et al., 2026).

Thus, the physicochemical properties of biochar, which are largely determined by the type of feedstock and pyrolysis conditions, will influence the feasibility of implementing a particular mechanism for removing nitro-explosives from soil. Hydrophobic distribution, π–π electron donor–acceptor (EDA) interactions, and redox reduction processes are possible for high-temperature biochar with higher aromaticity, hydrophobicity, graphitic structure, and electrical conductivity. These mechanisms are effective for removing TNT, DNT, and RDX. Electrostatic effects, electron transfer capacity, and oxidant activation potential will be enhanced by optimal surface charge (pHpzc), ash/mineral content (e.g., Fe/Mn phases), and structural ordering. It is worth noting that the presence of competing metals (e.g. Cu^{2+}, Zn^{2+}) or co-pollutants determines whether adsorption, redox transformations or advanced processes such as oxidation dominate. Therefore, an important aspect is to influence the properties of biochar by optimizing the target factors of its production, which helps to adapt to the pollution conditions at a specific site and maximize the recovery efficiency.

MATERIALS AND METHODS

Feedstock for biochar production

Four distinct types of biomass feedstocks were strategically selected for biochar synthesis: dewatered digestate, natural peat, birch wood, and agricultural corn residues. The primary woody biomass, consisting of pristine birch fractions, was acquired from a commercial logging and forestry enterprise based in Bezdryk village (Sumy District, Sumy Region, Ukraine), ensuring a reliable regional baseline for timber-derived carbon. The non-woody organic matrices were sourced from diverse agricultural and geological origins: the dewatered digestate by-product was supplied by an industrial biogas plant in Lynovytsia (Pryluky District, Chernihiv Region, Ukraine) operating on high-yield maize silage, while the raw peat material was obtained from a specialized extraction and processing facility situated in Shalyhyne village (Shostka District, Sumy Region, Ukraine). Additionally, residual corn biomass was harvested directly from a designated agricultural field plot located in Stepanivka village (Sumy District, Sumy Region, Ukraine). Prior to undergoing the thermochemical pyrolysis process, all collected feedstocks were subjected to a uniform thermal conditioning protocol, being thoroughly dried in a laboratory oven at 105 °C for 6 hours to eliminate moisture variables and subsequently preserved in airtight plastic containers to maintain structural and chemical integrity.

Pyrolysis

The slow pyrolysis of the individual biomass feedstocks was conducted within a custom-engineered stainless steel reactor with a total volumetric capacity of 1.5 L. Thermal energy was supplied via a three-phase electrical heating element regulated by a computerized power management and control cabinet. To ensure precise mass balance tracking, the weight of the pyrolyzed material was continuously recorded using an analytical balance with an accuracy of ±0.001 g. To systematically investigate the influence of thermochemical process conditions on the physicochemical properties of the resulting biochar and evaluate its subsequent efficacy as a soil amendment, each feedstock was processed at two distinct peak temperatures: 300 °C and 600 °C. The operational heating rate was strictly maintained at 5 °C min^{-1} up to the target temperature, followed by a residence (holding) time of 40 min. The initial mass of the raw biomass input was standardized at 250 g for each experimental run. After cooling, biochars were kept in plastic containers.

Physico-chemical analysis

Prior to analysis, the biochar samples were pulverized using a TWISTER cyclone mill (Retsch GmbH, Haan, Germany) to achieve a uniform particle size distribution. The resulting homogeneous powder was subsequently compacted into solid analytical pellets using a laboratory hydraulic press under a uniform compaction force of 4 tons. This process yielded standardized cylindrical tablets with a diameter of 1 cm and a thickness of approximately 3–4 mm.

A comprehensive analytical workflow combining non-destructive X-ray fluorescence and high-temperature thermal oxidation was implemented to assess the chemical composition and quality of the resulting biochar matrix. Given that carbon is the main structural component that determines the stability and sequestration potential of bioproducts, its quantitative content was determined independently of other organic elements. Total carbon (C) content was measured by automated dry combustion using a high-temperature combustion carbon analyzer equipped with a non-dispersive infrared (NDIR) detector (LECO Corporation, St. Joseph, Michigan, USA). The macro- and microelement profiles (including mineral-forming elements and trace metals) of the biochar samples were analyzed using a ProSpector 3 bench-top energy-dispersive X-ray fluorescence (EDXRF) spectrometer (Elvatech Ltd., Kyiv, Ukraine). Measurement conditions: The analysis was performed directly on the prepared compressed biochar pellets to ensure a smooth, uniform surface and high reproducibility of the fluorescence signal. The spectrometer was operated using a high-voltage X-ray tube with a tungsten (W) anode operating at an accelerating voltage of up to 50 kV with automatic current control.

The morphology, surface microstructure and elemental analysis of the biochar samples were examined using a SEO-SEM Inspect S50-B (SEO Ltd., Sumy, Ukraine) scanning electron microscope equipped with an AZtecOne energy-dispersive spectroscopy (EDS) system and an X-MaxN20 detector (Oxford Instruments plc) for elemental analysis. The microscope is fitted with a tungsten thermionic emission cathode as the electron source. The instrument allows electromagnetic adjustment of the electron beam aperture without the installation of a mechanical diaphragm unit, enabling precise control of beam parameters. The system includes automatic optimization of the cathode heating current and automatic alignment of the electron gun, ensuring stable beam generation during imaging. SEM micrographs obtained with this system were used to evaluate the surface morphology, pore structure, and microstructural features of the biochar samples.

RESULTS AND DISCUSSION

Characteristics of biochars derived from different feedstocks

Within the framework of the conducted research, various bioproducts were obtained that can be used for remediation of degraded soils because of military operations. Data on the elemental content of the investigated samples are given in Table 2.

Based on spectroscopy analysis the results of surface elemental composition among 5 samples of biochar were different due to substrate type and conditions of pyrolysis that directly influence the ability of biochar for soil remediation. The corresponding spectrograms for all biochar samples are presented in (Kuzomenska et al., 2026). The content of carbon content was the highest for sample no. 4 (828.5 g kg^{-1}) indicating good properties for adsorption of organic contaminants, but biochar from digestate showed still high carbon content (sample no. 1) up to 723.5 g kg^{-1}. The adding of digestate and biochar into the soil contributes to the accumulation of organic carbon according to a meta-analysis (Ablieieva et al., 2024). Based on the studies conducted, it was found that biochar obtained from digestate has a high organic carbon content of 101 g kg^{-1} volatile and 523.2 g kg^{-1} non-volatile, therefore, it can be assumed that the RDX sorption process is intensified, since the RDX sorption coefficient depends on the organic matter content in the soil or sediment (Dontsova et al., 2009). As was found in the study (Temple et al., 2019), the content of total organic carbon in the soil at a level above 2% leads to an increase in RDX sorption by the soil, while the efficiency of RDX extraction decreases. Other researchers also noted the high carbon content in biochar. According to (Mukome et al., 2020), its highest values are observed in pyrolyzed coniferous residues – 924 g kg^{-1}, the lowest – in plant residues 44.6 g kg^{-1} (Amin, 2024) and chicken manure 79 g kg^{-1} (Narayanan

Table 2. Results of elemental analysis of the investigated bioproducts

Element, g kg^{-1}	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4
	Biochar from digestate, 6 hours	Biochar from peat	Biochar from birch	Sample from corn
C	723.5 ± 17.6	494.3 ± 22.3	828.5 ± 187.4	689.2 ± 31.3
Si	26.0 ± 0.8	90.4 ± 19.2	0.0 ± 0.0	37.4 ± 5.9
Ca	48.3 ± 4.0	21.2 ± 1.6	76.8 ± 104.0	37.5 ± 6.2
O	138.8 ± 16.0	253.5 ± 31.9	89.9 ± 80.3	171.7 ± 13.1
Mg	12.4 ± 0.4	3.0 ± 0.4	0.2 ± 0.2	5.0 ± 0.3
K	34.8 ± 2.9	8.8 ± 3.9	2.9 ± 2.2	34.3 ± 3.1
P	10.1 ± 0.4	0.0 ± 0.0	0.0 ± 0.0	9.8 ± 0.2
Al	1.7 ± 0.3	26.7 ± 7.1	0.8 ± 0.3	2.4 ± 0.4
S	2.5 ± 0.2	9.9 ± 0.1	0.0 ± 0.0	1.8 ± 0.2
Fe	1.5 ± 2.1	90.0 ± 20.9	0.0 ± 0.0	2.8 ± 0.8
Na	0.7 ± 1.0	1.0 ± 1.3	0.0 ± 0.0	2.8 ± 0.2
Cl	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	4.4 ± 0.3
Mn	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.5 ± 0.6
Cu	0.0 ± 0.0	0.0 ± 0.0	1.1 ± 1.5	0.0 ± 0.0
Ti	0.0 ± 0.0	1.7 ± 2.4	0.0 ± 0.0	0.0 ± 0.0

and Ma, 2022). The presence of carbon allows the use of biochar also for bioremediation of soils contaminated with organics and metals.

It should be noted the influence of residence time of pyrolysis on the elemental content of biochar from the same substrate on the example of sample no. 2. This sample had a decreased content of carbon (223.0 g kg^{-1}) and increased oxygen content (370.2 g kg^{-1}) meaning mineral-rich composition and privilege of ash-forming elements such as Ca, K, and Mg due to high residence time. Such properties of the sample no. 2 are suitable for heavy metal immobilization and soil pH adjustment. In another study dry ash content in biochar didn't show any significant difference between samples from wood (36.62%) and digestate (35.62%). Adding digestate to biochar decreases this parameter to 11.09 % while dry ash content in the digestate was estimated at 5.58%.

Samples no. 1 and no. 5 demonstrated a balanced composition, combining high carbon content (494.3 g kg^{-1} and 689.2 g/kg, respectively) with moderate mineral fractions (Ca, K, and Mg). These samples have good properties for soil remediation and nutrient supply that are important in terms of simultaneous contamination degradation and soil fertilization. Among all samples, sample no. 3 showed a significant content of Fe (90.0 g/kg) that indicates a high potential for enhanced metal binding and redox activity.

Biochar has a positive effect on the physicochemical properties of the soil, in particular, it increases its porosity, organic matter and organic carbon content, reduces bulk density, improves pH and increases CEC (Broomandi et al., 2020; Sharma et al., 2023; Temple et al., 2019). The final characteristics of digestate-derived biochar are primarily dictated by two factors: the initial feedstock composition used in anaerobic digestion and the peak pyrolysis temperature. This is because the content of nutrients and pollutants changes during fermentation and pyrolysis depending on its initial value in the feedstock. The process of lignocellulose decomposition during pyrolysis occurs more efficiently if the feedstock is already fermented biomass, respectively, most of the lignocellulosic residues present in the digestate are decomposed at a lower pyrolysis temperature.

Another important parameter for biochar is its surface structure and morphology that shows general structure, fragmentation, porosity distribution (low magnification, ≈200–300×), pore network formation, surface heterogeneity (medium magnification, ≈500–1000×) and adsorption sites, mineral phases, surface coatings (high magnification, ≈1500–2000×). SEM images of the surface for investigated samples are presented in Figure 4. These surface properties are directly connected to elemental content of biochar and presence of functional groups identifying the surface charge.

Evaluating the potential of digestate for biochar production

Digestate is a good co-substrate for pyrolysis to produce biochar for soil remediation technology (Soja et al., 2024; Y. Wang et al., 2023), however, the ecological safety and quality of such substrate remain important. To choose a substrate for anaerobic digestion, it is necessary to consider its level of contamination with various organic and inorganic pollutants. Given the global trend towards deteriorating environmental conditions, almost all habitats are polluted with various compounds due to human activities (Košnář et al., 2023). This, in turn, affects the quality of feedstock for bioproduct production.

The main contaminants in wastewater sludges are HMs, which enter wastewater from various enterprises. For waste from various sectors of the agro-industrial complex, dangerous contaminants include various groups of pesticides (mainly organochlorine and organophosphorus), antibiotics, hormones, and pathogenic microorganisms (Azizan et al., 2021; Zhang et al., 2023). The ecological safety of digestate usually significantly increases during the digestion process due to pollutants transformation.

Sewage sludge was identified as the most contaminated, but the level of removal of substances in the process of anaerobic digestion also varied widely. Summarized research data show that the lowest efficiency was noted for industrial chemicals and pesticides (no more than 5%); medium – for personal care products (25%), pharmaceutically active compounds (40%) and antibiotics (58%); the highest was for stimulants (100%).

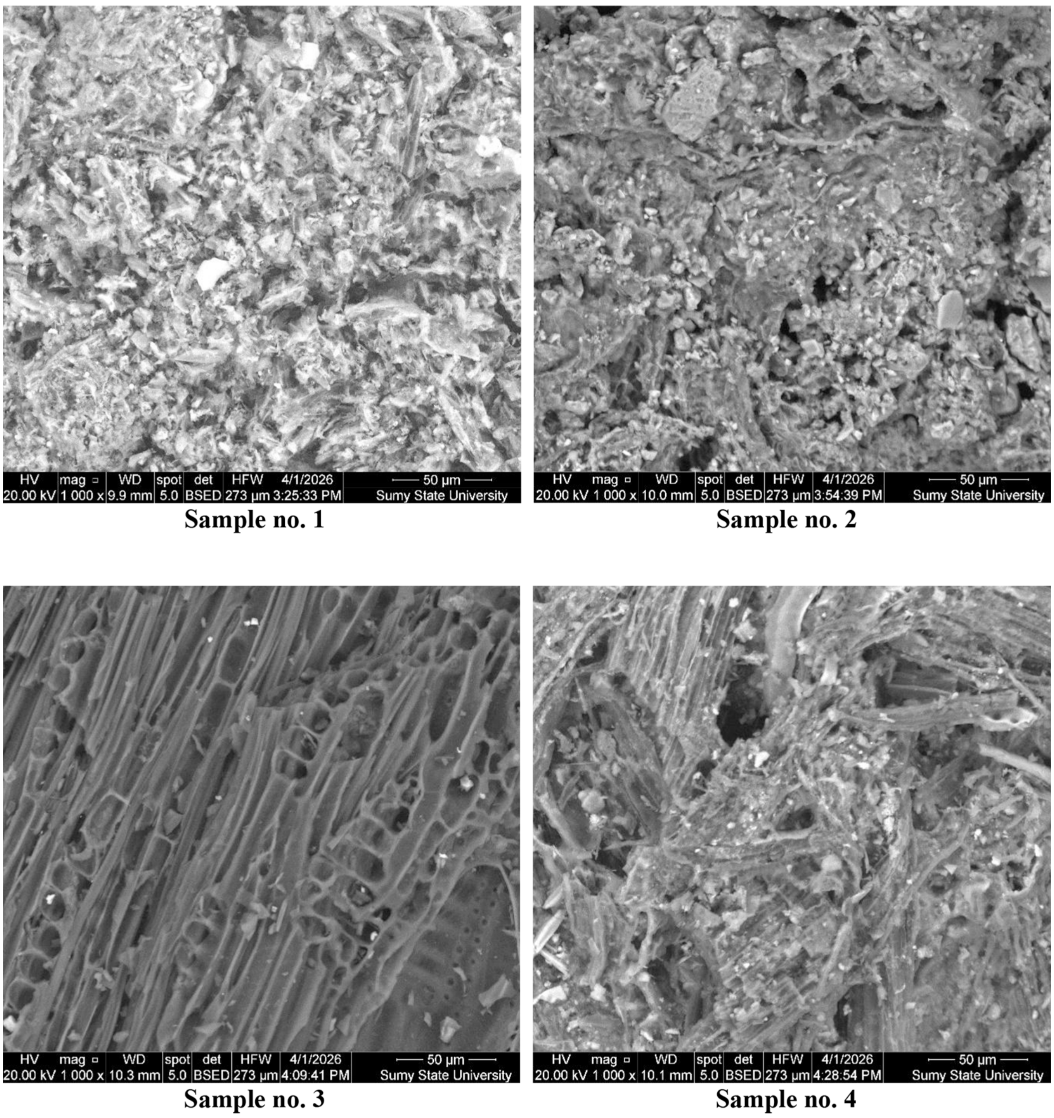

Figure 4. SEM images of the surface of biochar samples

According to (Anne et al., 2023) a negative effect on soil Zn accumulation, resulted in increasing of Zn content by 14.5%, was observed after the addition of biochar from sewage sludge digestate obtained at 450 °C. This may be because Zn is a metal that is often found in high amounts in sewage sludge that is in line with author's findings reported by (Paramonov et al., 2024; Sipko and Ablieieva, 2024) regarding sewage sludge as substrate for anaerobic digestion with the highest level of pollutants, particularly, HM content that exceeds permissible level.

Nevertheless, different factors, including thermal conditions, substrate pre-treatment technologies and digestate post-treatment technologies, influence the process of degradation for pharmaceuticals, antibiotics, pesticides, and HM during anaerobic digestion that is extremely important to obtain ecologically safe feedstock for pyrolysis from digestate that meets special requirements for biochar quality used for soil application (Zhao et al., 2020).

Thus, solid fraction of digestate after solid-liquid separation has higher levels of pollutants as was shown in the study by (Golovko et al., 2022). It means that persistent organic pollutants like pesticides and industrial chemicals move from substrate to solid fraction of digestate in concentrations depending on the above discussed factors. Thermal treatment of solid fractions of digestate can be one of the possible approaches to decrease concentration of chemicals up to maximum permissible level and increase the ecological safety of digestate. It was proved in some studies (Gulyás et al., 2022; Louati et al., 2025) that biochar produced by slow pyrolysis of solid digestate at low temperatures has a high potential as soil amendment. Therefore, the investigation of the effect of technological and operational parameters of the pyrolysis process on the organic pollutant's degradation could be the subject of our further research (Vaskina et al., 2025).

Biochar production strategies for remediation of soils co-contaminated with heavy metals and energetic substances

Biochar has emerged as a promising amendment for remediating soils contaminated with HMs due to its physicochemical properties that influence metal mobility and stability. For effective immobilization of HMs in amended soils, biochar should exhibit an alkaline pH, high ash content to facilitate metal precipitation, and a rich array of surface functional groups capable of complexing metal ions. Additionally, a low concentration of labile carbon is advantageous for limiting the re-mobilization of metals, while a moderate to high cation exchange capacity (CEC) enhances the retention of metal cations through ion exchange processes (Gusiatin et al., 2016).

From a broader soil quality perspective, biochar with lower electrical conductivity (EC) are preferable, as they help to reduce the risk of salinity buildup. Furthermore, biochar with high fixed carbon content contributes to long-term carbon sequestration, offering added environmental benefits beyond contaminant stabilization. Thermal treatment significantly influences biochar properties and related efficiency of soil remediation that should be discussed further. Pyrolysis temperature as a defined target factor influencing biochar surface chemistry, alkalinity, and sorption performance, and thus directly influences its environmental application performance.

Temperature increase lead to destruction of oxygen-containing functional groups (e.g., –COOH, –OH, C=O), that negatively influencing CEC and ion-exchange mechanisms to HM sorption. That's why in case of domination such mechanisms as electrostatic attraction and surface complexation dominate, where surface charge is core, biochar is proposed to produce at low- to moderate-temperature. On the other hand, soil remediation using biochar could proceed with other mechanisms like sorption, surface complexation and precipitation, where improved aromaticity, carbonization degree, and mineral concentration play key role and can be reached by temperature increase to 600 °C (Awasthi, 2022).

The increase in alkalinity observed in high temperature biochar is primarily attributed to the thermal degradation of acidic functional groups and the concentration of inorganic minerals during pyrolysis. According to (Cong et al., 2024), an increase in pyrolysis temperature from 300 to 700 °C leads to a significant rise in the pH of sewage sludge digestate biochar, specifically shifting from 7.05 to 9.29. Feedstock for biochar is even more important, for example, pH of biochar from food-waste digestate was higher (9.19) than in case of sewage sludge digestate at 400 °C as (Alghashm et al., 2018) observed, and increased to 12.52 at pyrolysis temperature 900 °C.

It should be noted that the pH level significantly affects the equilibrium absorption of metal ions in aqueous solution, as it determines the nature of the competition between hydrogen ions (protons) and metal ions for the active centres of the sorbent. In addition, the sorption efficiency largely depends on the chemical composition of the sorbent surface. One of the key factors determining the course of sorption processes is the pH of the medium, since it affects not only the form of existence of toxic metals in the solution, but also the degree of ionization of the adsorbate and the charge of the sorbent surface during interaction (Duwiejuah et al., 2020).

Moreover, in terms of feedstock influence on biochar properties woody biomass resulted in slightly acidic character regardless of pyrolysis conditions compared to non-woody substrates like municipal solid waste, sewage compost, and digestate residue (Gusiatin et al., 2016). Such enhanced alkalinity is important for soil remediation efficiency as it improves HMs precipitation (e.g., carbonates and hydroxides) and reduces metal solubility in contaminated soils. Therefore, these findings highlight that temperature selection and combination of woody substrate and digestate for pyrolysis could lead to optimization of biochar alkalinity that is important parameter for remediation and improvement of HMs-contaminated soils.

In contrast to HMs, the adsorption of nitro-explosives such as TNT and RDX can be highly efficient on specifically modified biochars (e.g., polymer/biomass-derived), where the presence of polymer residues plays a more critical role in enhancing sorption capacity than the pyrolysis temperature itself (S. Oh et al., 2018). According to the results obtained by (S.-Y. Oh and Yoon, 2016), the addition of biochar derived from rice straw to contaminated military training grounds in Korea reduced the RDX mobility and extraction rate to less than 10% of the initial concentration after 10 days. In this case biochar was pyrolyzed at 550 °C for 4 h and the sorption properties and mechanism of biochar were mainly determined by π–π electron donor–acceptor interactions.

Thus, biochar application for soils contaminated by military actions should consider different factors, including analysed target factors for biochar production, type of soil contamination influencing the dominant mechanism for

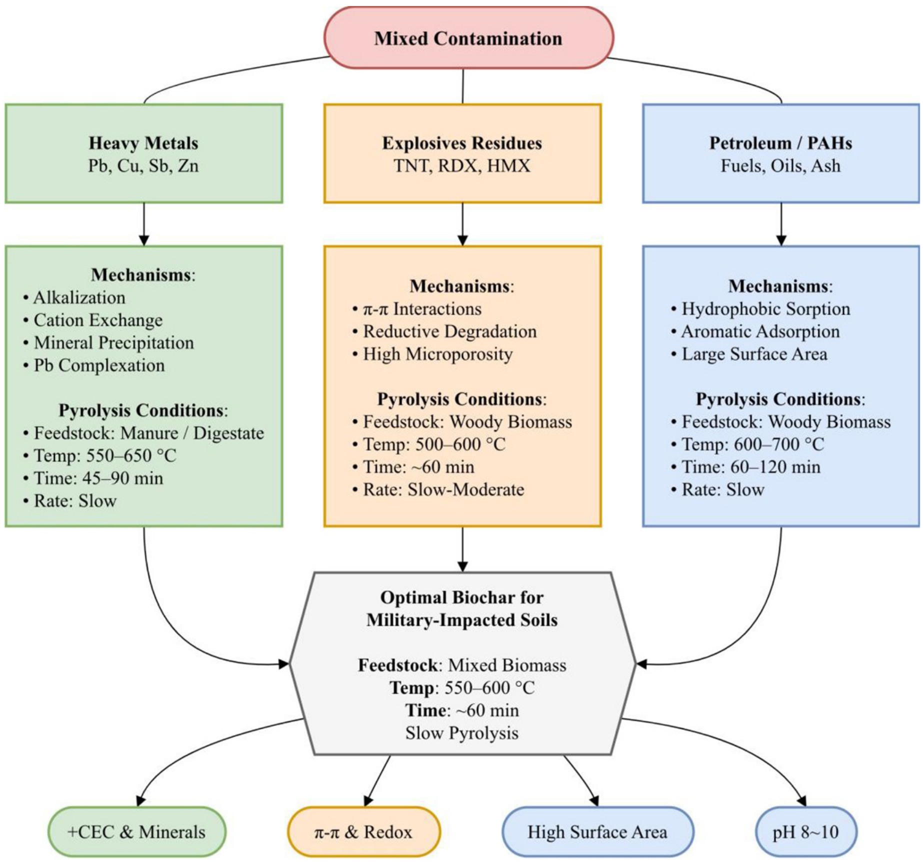

Figure 5. Decision tree for production parameters of biochar used for remediation of soils contaminated after military actions

pollutants degradation and soil remediation. Therefore, production of biochar should be optimized according to specific contaminated sites, where dominant contaminant type is defined at the first stage. Further, production parameters of biochar are assessed according to the decision tree presented on Figure 5.

Based on the above analysis, it is recommended to use not only biochar, but also immobilized bacteria, which increases the efficiency of pollutant transformation. Such statements are consistent with the results of studies on the use of a bioformula consisting of biochar obtained from coconut husk as a carrier and *Arthrobacter subterraneous* as an active ingredient (Sharma et al., 2023). The prepared bioformula was able to decompose up to 85.98% of hexogen (RDX) in contaminated soil within 30 days. In the soil treated with the bioformula, a significant increase in the concentration of nitrites, the main by-product of RDX biodegradation, was observed.

In the case of soil contamination by petroleum hydrocarbons, the work (Gielnik et al., 2019) shows that the use of bacteria immobilized on biochar, together with digestate, also increases the efficiency of bioremediation in both sandy and clay soils. Thus, biochar with immobilized bacteria is proposed to be used for soil treatment after military operations at the stage of chemical remediation. In this case, it is worth paying attention to the influence of feedstock and pyrolysis temperature on the sorption properties of biochar, carbon content, ash content and pH indicators. Field testing of the efficiency of the transformation of pollutants and soil cleaning from HMs and explosives in the case of using biochar with immobilized bacteria is the subject of further research.

CONCLUSIONS

The feasibility and effectiveness of using biochar for soil remediation after military operations are substantiated. The use of biochar ensures the restoration of the physicochemical properties of soils after military operations, stimulation of the degradation of explosives due to the high carbon content, as well as the sorption of these substances and heavy metals due to the developed porous structure and the presence of appropriate functional groups.

Mechanisms of positive influence on the physicochemical properties of soils and sorption mechanisms that depend on the pH of biochar, the presence of negatively charged functional groups and basic cations are established. It was identified that type of feedstock and pyrolysis temperature affect the mechanisms and efficiency of biochars' sorption. A higher pyrolysis temperature (500–600 °C), moderate heating rates and residence time allow to increase the carbon content, developed porosity and the hydrogen potential of the resulting biochar. This will positively affect the sorption of HMs and explosives.

The feasibility of using biochar, including digestate-derived biochar, for remediation of military-impacted soils was substantiated. The obtained bioproducts demonstrate physicochemical properties favourable for pollutant adsorption and improvement of soil quality. Digestate can serve as a promising feedstock for biochar production within circular resource management, although its environmental safety requires careful evaluation. The decision tree was developed for production parameters of biochar used for remediation of soil contaminated after military actions.

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