BioCompWaterClean Workshop

New applications in wastewater treatment on the way to zero-waste technology

20-21 October, 2025, Novi Sad, Serbia

BOOK OF PROCEEDINGS

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NEW APPLICATIONS IN WASTEWATER TREATMENT ON THE WAY TO ZERO-WASTE TECHNOLOGY

Science and Technology Park Novi Sad
20-21 October, 2025, Novi Sad, Serbia

BOOK OF PROCEEDINGS

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CONTACT

office@biocompwaterclean.org

WELCOME

On behalf of the Scientific and Organizing Committee, it is our great pleasure to warmly welcome you to the BioCompWaterClean Workshop, “New applications in wastewater treatment on the way to zero-waste technology”.

In a world facing the greatest challenges of current and future generations, innovation in water treatment and clean water is not just a scientific and professional task—it is also a social responsibility. In this context, and in line with current global demands and the UN Sustainable Development Goals (SDGs), the BioCompWaterClean Workshop aims to add value by providing high-quality knowledge exchange that contributes particularly to SDG 4 (quality education) and SDG 6 (clean water and sanitation).

Multidisciplinary teams of researchers and experts in various fields of chemistry and technology will present at this two-day international workshop, sharing innovative methodologies and advances in processes for wastewater treatment, pollutant removal, new materials, and potential solutions for zero-waste technologies or waste material utilization and valorization. These efforts generate new resources to ensure the sustainable management of water and improve water quality.

Furthermore, the exchange of knowledge, best practices, and problem-solving ideas may drive new initiatives for further cooperation and joint projects.

Enjoy sharing your valuable time with us!

Prof. Dr. Slavica Ražić
BioCompWaterClean Project Leader

SRažić

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SUSTAINABLE WASTEWATER TREATMENT: UTILIZATION OF BIO-WASTE IN LEAD AND COPPER REMOVAL

Nataša Gajić[1*], Dragana Radovanović[1], Marija Štulović[1], Nikola Jovanović[1], Dragana Medić[2], Jovana Đokić[3]

[1] Innovation Center of the Faculty of Technology and Metallurgy, Belgrade Ltd, University of Belgrade, Karnegijeva 4, 11000 Belgrade, Serbia
[2]University of Belgrade, Technical Faculty in Bor, Bor, Serbia
[3]Innovation Centre of the Faculty of Chemistry in Belgrade Ltd, University of Belgrade, Studentski Trg 12-16, 11000 Belgrade, Serbia
*ngajic@tmf.bg.ac.rs

Abstract

The increasing demand for low-cost and sustainable adsorbents in wastewater treatment has drawn attention to agricultural bio-waste, which provides an abundant, renewable, and environmentally friendly alternative to conventional materials. Among various types of agricultural bio-waste, plum stones represent a promising but still less explored adsorbent, especially in regions with high fruit processing output, such as Serbia. Nevertheless, their practical application requires pre-treatment to enhance adsorption efficiency. High-energy ball milling applied to waste plum stones successfully enhanced its adsorption capacity by reducing particle size, increasing surface area, and exposing functional groups—without any chemical or thermal modification. The resulting samples were characterized by XRD, FTIR, SEM, and particle size distribution analyses. Milling parameters significantly influenced the morphology and surface chemistry, with optimized conditions (500 rpm, 1 h, 20:1 bpr) yielding the highest adsorption efficiencies of 97% for Pb^{2+} and 52% for Cu^{2+}. The results demonstrate that optimized mechanical activation can convert waste plum stones into effective adsorbents for wastewater treatment, with potential for further applications in environmental remediation.

Introduction

The increasing amount of industrial and urban wastewater containing hazardous heavy metals such as lead (Pb^{2+}) and copper (Cu^{2+}) is a major environmental challenge. Even at low concentrations, these pollutants can have a negative impact on the ecosystem and human health as they tend to accumulate in living organisms and persist in the environment [1,2]. Therefore, the development of efficient, cost-effective, and environmentally friendly technologies for the removal of toxic heavy metals from wastewater has become a key research priority [3].

Adsorption has emerged as one of the most promising and effective methods for heavy metal removal due to its simplicity, efficiency, and potential for resource recovery [4]. However, the general application of adsorption processes is often limited by the high cost and limited availability of conventional adsorbents such as widely used activated carbon and synthetic ion exchangers [5]. Consequently, the valorization of agricultural residues into bio-adsorbents has become a promising alternative in line with circular and economic principles. Fruit stones and similar by-products represent low-cost, eco-friendly, and sustainable bio-sorbents [6].

Serbia is among the world's leading plum producers [7], generating large quantities of stone residues during processing. Most of the production is used in the domestic industry for the manufacture of plum brandy (*šljivovica*), with approximately 80% of the total yield being processed into spirits [8]. These plum stones are rich in lignocellulosic components (cellulose ≈ 13%, hemicellulose ≈ 30%, lignin ≈ 36%) and have a high carbon content (>60%), making them suitable precursors for bio-adsorbent materials.

While chemical and thermal activation of such residues has been widely studied [9-11], these methods typically involve the use of chemical agents (e.g., acids, bases) or high-temperature treatment to enhance porosity, surface area, and functional group development. Although effective, they often require significant energy input, generate chemical waste, and may not be economically feasible on a large scale. In contrast, mechanical activation remains underexplored despite its simplicity and low environmental impact. Mechanical milling, especially high-energy ball milling, can improve surface properties, reduce particle size, and expose functional groups responsible for metal ion adsorption [12].

Therefore, this study aims to optimize mechanical milling parameters for waste plum stones and to evaluate their adsorption efficiency in removing Pb^{2+} and Cu^{2+} ions from aqueous solutions.

Materials and methods

The waste plum stones obtained from a Serbian fruit-processing facility were washed, dried at 105 °C, and crushed. XRD analysis of the raw material was performed to determine the phase composition using a Proto AXRD Benchtop Powder X-ray Diffractometer (Proto Manufacturing Inc., LaSalle, ON, Canada) with a Cu Kα tube operated at 30 kV and 20 mA over a 2θ range of 12–30°. FTIR spectra of the milled plum stone samples were recorded in transmission mode in the range of 400–4000 cm^{-1} using a Nicolet iS10 spectrometer (Thermo Scientific, Sweden). The obtained spectra were used to identify functional groups on the surface and to evaluate structural changes induced by mechanical milling. SEM micrographs were obtained on a JEOL JSM-7001F field emission scanning electron microscope (JEOL Ltd., Tokyo, Japan) operated at an accelerating voltage of 20 kV. Particle size distributions were determined by digital image analysis in CellProfiler software v. 4.2.8. Mechanical activation was carried out in a planetary ball mill (SFM-1, model QM-3SP2; MTI Corporation, Richmond, CA, USA) using 500 mL alumina jars and 10 mm alumina balls. Sample codes (Xt–Yr–Zb) denote the milling time (t, in hours), rotational speed (r, in rpm), and ball-to-powder ratio (b), respectively. Adsorption experiments were conducted using aqueous metal salts solutions 100 mg/L solutions of $Pb(NO_3)_2$ and $CuSO_4$ at 40 °C, 120 rpm, and 24 h contact time. The remaining metal ion concentrations were measured by a PerkinElmer Analyst 300 atomic absorption spectrophotometer (PerkinElmer, Waltham, MA, USA). Each adsorption experiment was carried out in triplicate, and the obtained data are presented as mean values of three independent measurements (n = 3).

Results and discussion

Figure 1 shows the surface morphology and particle size distribution of the untreated plum stone sample. The majority of particles have an average diameter of 120 µm and range in size from 80 to 160 µm. The particles have visible agglomerates and irregular, compact structures with limited fragmentation. This morphology, typical of lignocellulosic materials, limits surface area and mass transfer paths, suggesting that mechanical milling is necessary to enhance adsorption performance.

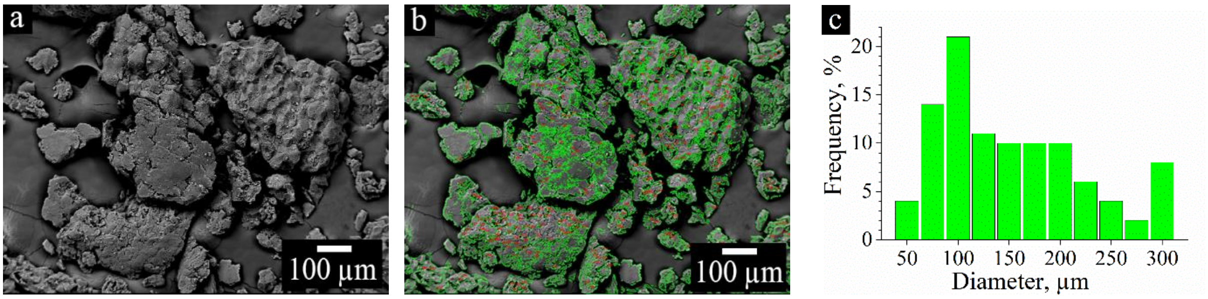

Figure 1. (a) SEM photomicrograph of raw plum stone sample, (b) particle boundaries overlaid using CellProfiler analysis, and (c) particle size distribution histogram

The X-ray diffraction pattern of the raw sample is shown in Figure 2**.**

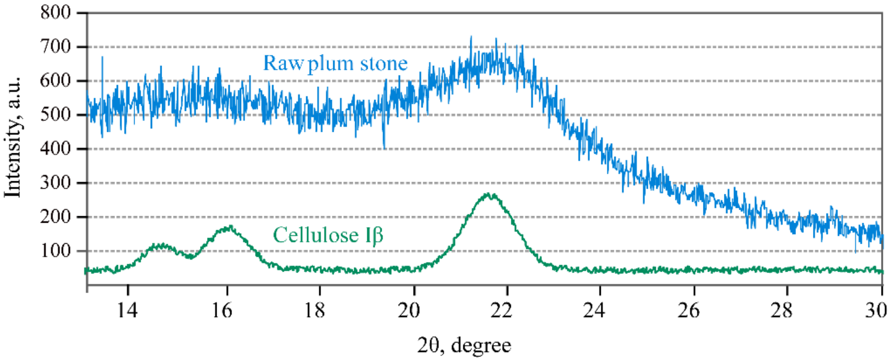

Figure 2. XRD pattern of the raw plum stone sample and reference cellulose Iβ

The diffraction peak around 2θ ≈ 22° corresponds to amorphous cellulose Iβ (PDF 00-056-1718). The absence of sharp reflections confirms the low crystallinity typical of lignocellulosic structures.

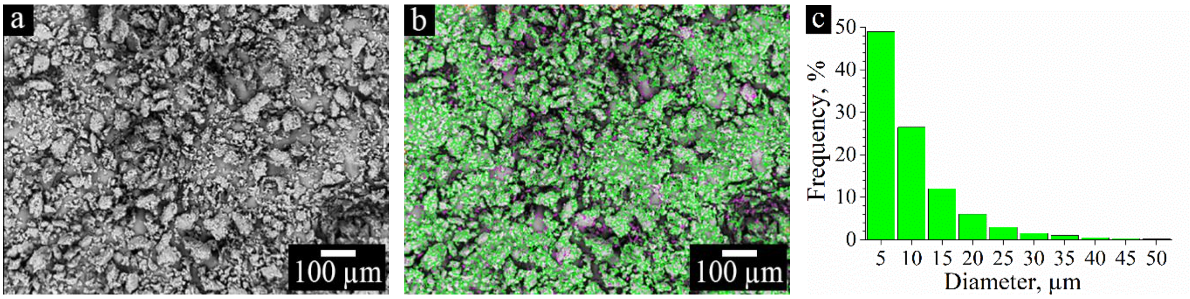

Figure 3. (a) SEM photomicrograph of the optimally milled plum stone sample (1h-500r-20b), (b) particle boundaries overlaid using CellProfiler analysis, and (c) particle size distribution histogram

The SEM photomicrograph of the milled sample, milled for 1 h at 500 rpm with a 20:1 ball-to-powder ratio (Figure 3), shows irregular particles with a rough surface. These morphological changes, including significant particle size reduction and the appearance of cracks and edges, indicate intense mechanical deformation during milling. The resulting roughness and fragmentation are expected to increase the overall surface area and improve the accessibility of adsorption sites, thereby enhancing the contact between the adsorbent surface and Pb^{2+}/Cu^{2+} ions.

Figure 4 shows the FTIR spectra of the milled plum stone samples obtained under different milling conditions.

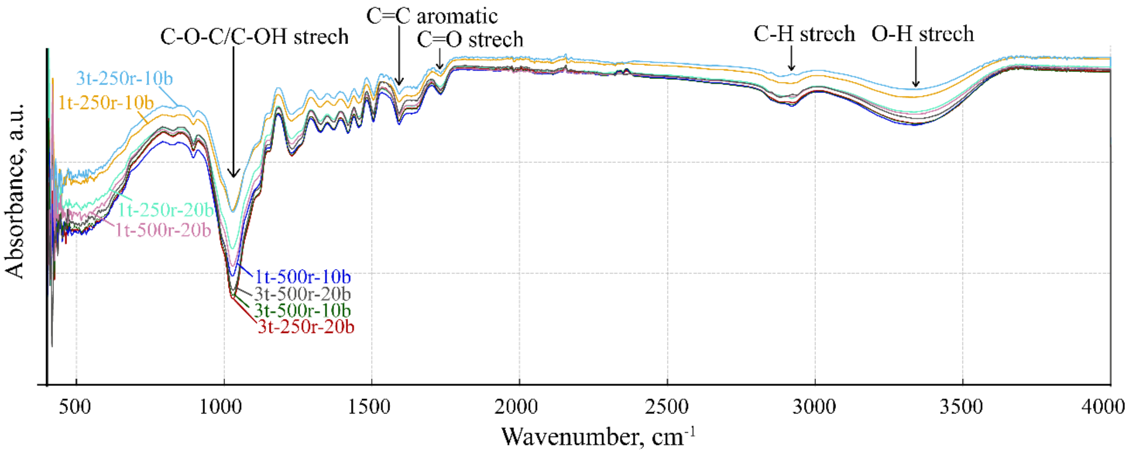

Figure 4. FTIR spectra of the milled plum stone samples

The FTIR spectra of the milled plum stone samples (Figure 4) show characteristic bands of lignocellulosic biomass, including O–H stretching (~3400 cm^{-1}), C–H stretching (~2900 cm^{-1}), C=O stretching (~1730 cm^{-1}), and C–O–C/C–OH vibrations (~1000–1200 cm^{-1}). Among the analyzed samples, 1t-500r-20b exhibited the most pronounced band broadening and intensity reduction, indicating a higher degree of structural modification compared to the other milling conditions. The extension of the O–H stretching band at ~3400 cm^{-1} indicates the disruption of hydrogen bonding in cellulose and hemicellulose, increasing the accessibility of hydroxyl and carbonyl groups. Moreover, mechanical milling led to a decrease in the intensity of the 1730 cm^{-1} carbonyl band, suggesting partial cleavage of ester linkages within hemicellulose, which further contributes to the generation of new active sites for cation coordination. Such structural changes enhance the surface reactivity and thus promote better interactions with Pb^{2+} and Cu^{2+} ions during adsorption.

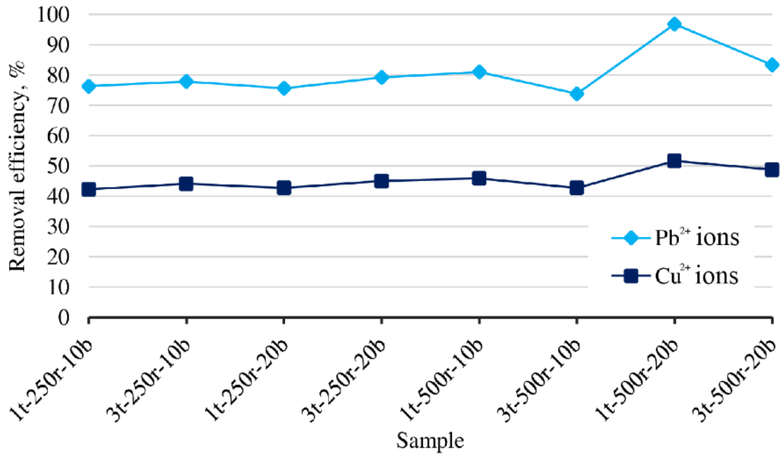

Figure 5. Removal efficiency of Pb^{2+} and Cu^{2+} ions by milled plum stone samples (mean of three measurements, n = 3)

As shown in Figure 5, in terms of adsorption performance, the sample 1t-500r-20b achieved the highest removal efficiency of approximately 97% for Pb^{2+} and 52% for Cu^{2+}**.** These results indicate that the milling intensity, primarily regulated by rotational speed and ball-to-powder ratio, has a more pronounced effect on adsorption performance than milling time, as higher energy input promotes greater surface activation and exposure of adsorption sites.

Conclusion

This paper showed that mechanical activation in a planetary ball mill is a feasible and sustainable method for valorizing waste plum stones into efficient bio-sorbents for heavy metal removal from wastewater. Optimizing milling parameters, 500 rpm, 1 h, and 20:1 bpr offered optimal particle size reduction and surface modification, leading to an increase in the exposure of oxygen-containing functional groups responsible for metal ion binding. The sample milled under optimized conditions (1t-500r-20b) developed the highest adsorption efficiencies, namely, 97% for Pb^{2+} and 52% for Cu^{2+}. Milling intensity, mainly determined by rotational speed and ball-to-powder ratio, proved to be the dominant factor influencing surface activation and adsorption performance. These results emphasize that planetary milling offers a purely mechanical, chemical-free, and low-cost route for the valorization of agricultural bio-waste into functional materials for sustainable wastewater treatment.

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COST-BENEFIT EVALUATION OF THE ADSORPTION MEDIA EFFICIENCY AT PILOT PLANT FOR GROUNDWATER TREATMENT

Nenad Grba[1*], Vesna Vasić[2], Miloš Dubovina[3]

[1]*Faculty of Sciences, University of Novi Sad, 21102 Novi Sad, Republic of Serbia*
[2]*Faculty of Technology Novi Sad, University of Novi Sad, 21101 Novi Sad, Republic of Serbia*
[3]*University of Belgrade, Institute of Chemistry, Technology and Metallurgy 11000 Beograd, Republic of Serbia*
*nenad.grba@dh.uns.ac.rs

Abstract

Groundwater treatment requires cost-effective and technologically reliable solutions capable of removing priority contaminants such as iron (Fe), manganese (Mn), ammonium (NH_4^+), and organic matter. This Pilot study was conducted at the Public Utility Company “Water and Sewerage”, Novi Sad, Republic of Serbia, as semi-industrial tests in order to evaluate the performance of different adsorption media. Five filter bed configurations were tested in a specially designed Pilot unit consisting of two serially connected gravity columns: first with aeration, filtration and sedimentation processes and second with Granular Activated Carbon (GAC), natural zeolite, and three GAC-zeolite mixtures (ratios 1:1, 3:2, and 2:3). The aim was to identify the optimal balance between contaminant removal efficiency and economic feasibility. The results showed that pure GAC consistently achieved high removal of Fe and absorption of organic matter, with average efficiencies above 90% and effluent concentrations well below maximum permissible limits. However, due to its high market cost (8–10 times higher than zeolite), GAC exhibited the lowest economic index (8.0), making it less favorable for resource-limited systems. Zeolite demonstrated the highest average efficiency (96.2%) and the best cost-effectiveness, with an economic index of 68.4. Zeolite excelled in ammonium and manganese reduction (e.g., native 456–653 µg/L to below 50 µg/L prescribed manganese value), particularly when used alone or in a 2:3 mixture. Mixed configurations provided sustainable solutions, with the GAC:zeolite = 2:3 ratio achieving 89.9% average efficiency and an economic index of 18.2. This mixture proved particularly suitable for waters rich in ammonium and manganese, while the 1:1 configuration showed reduced stability in maintaining Fe removal below regulatory thresholds. Research indicates that tailoring adsorbent composition to raw water quality and local economic constraints is essential for ensuring stable, efficient, and affordable drinking water treatment, also regarding the most challenging aspects of climate change.

Introduction

The project aimed to investigate technological solutions based on the application of geomaterials in groundwater treatment, as well as to determine the adsorption performance of zeolite in comparison with the standard commercial adsorbent (GAC). A particular focus was placed on examining different mass ratios between GAC and zeolite in the adsorption media. In line with the given technical and technological challenges, the groundwater in the pre-aeration system was subjected to pilot testing to reduce the concentrations of manganese, iron, organic matter, and ammonia from the best available techno-economic aspects.

Materials and methods

All experiments are conducted in Pilot system that consists of two serially connected gravity columns: 1) with aeration, filtration and sedimentation processes and 2) with Granular Activated Carbon (GAC), natural zeolite, and three GAC-zeolite mixtures (ratios 1:1, 3:2, and 2:3). The first column functions as an introductory transitional module and simulates the initial steps of raw water treatment. Water enters the column through a showerhead, allowing dispersion and direct contact with air (aeration mode). This process achieves oxygen saturation, which is necessary for the oxidation of reduced forms of metals and ammonium. Subsequently, water passes through a drainage layer composed of gravel and manganized sand, where mechanical filtration and partial oxidation occur. However, this part of the treatment unit primarily serves a preparatory and stabilization role, while complete effective treatment and contaminant analysis take place in the second column (Figure 1).

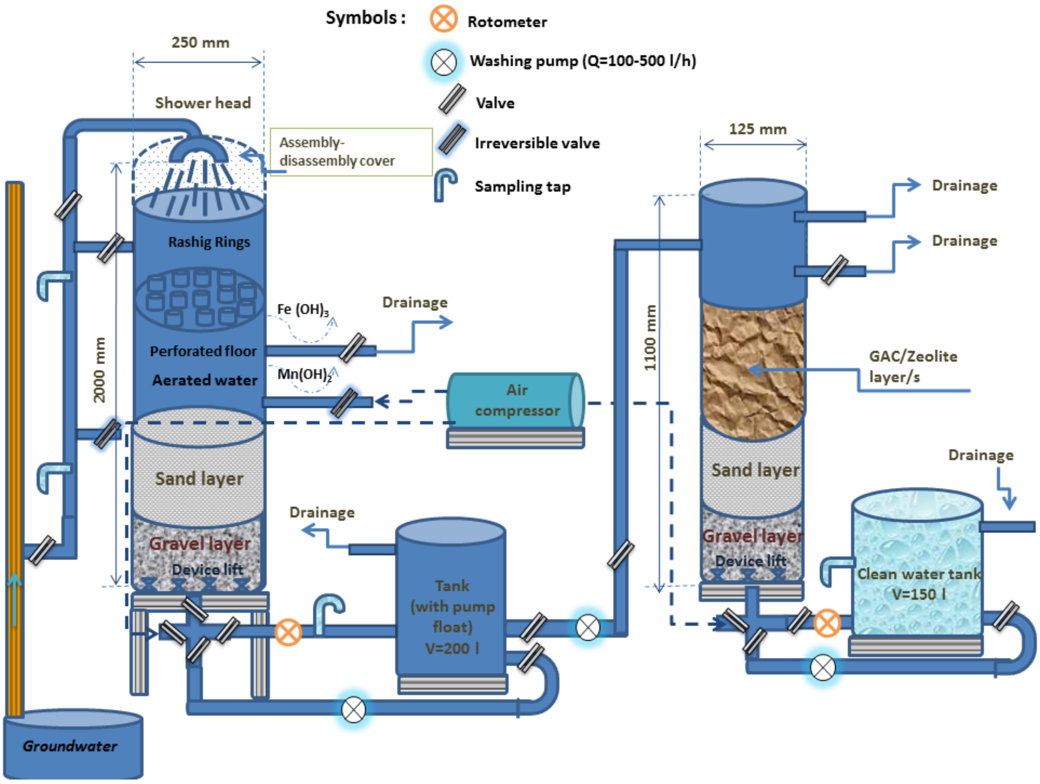

Figure 1. Schematic view of the Pilot system for groundwater treatment

By comparing the performance of different filter media, it is determined which material: GAC, zeolite, or their combination ratios, demonstrates the highest efficiency and stability in removing metals and organic components under real field conditions, while also considering the economic aspects of applying the mentioned configurations. These investigations were carried out with consideration of the quality of the groundwater, the adsorption efficiency as a function of water composition, and the technological requirements of the treatment process under real operating conditions.

Results and discussion

For systems with high concentrations of manganese and/or ammonia, zeolite alone or in configurations with a lower proportion of GAC (2:3) showed high cost-efficiency performance. In Figure 2, manganese and ammonium concentrations in groundwater samples of inlet groundwater (S1) and treated outlet water (S4) during Pilot testing experiments are described. Measurements of parameters were taken every 30 minutes during 12 hours of filtration on Granular Activated Carbon and zeolite at a ratio of (GAC):zeolite = 2:3.

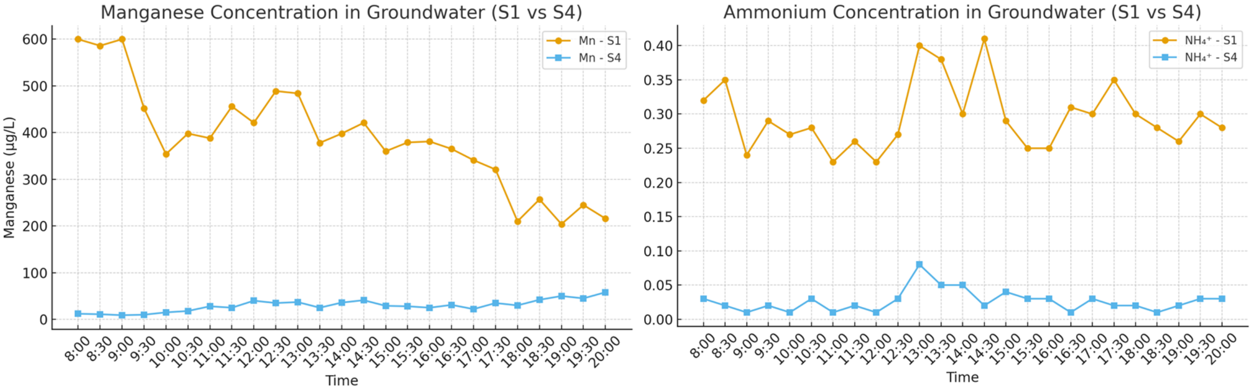

Figure 2. Manganese and ammonium concentration in inlet (S1) vs outlet (S4) water during Pilot testing experiments at GAC:zeolite ratio of 2:3.

Manganese (Figure 2) was initially significantly above the maximum allowable concentration (MAC) [1] (from 600 to 204 µg /L). At the outlet, concentrations ranged from 9 to 58 µg /L, with an average of 36 µg/L, which is lower than the averages observed in all other variants, including GAU. More than half of the samples met the regulatory standard for manganese: 50 µg/L [1]. This configuration thus stands out as the most effective for manganese removal, which can be attributed to the higher zeolite content providing a surface suitable for catalytic activity and potential support for biological processes, in combination with GAU serving as a biofilm support.

Ammonia removal (Figure 1) in this configuration exhibited very good stability. Initial concentrations were all below the MAC of 0,5 mg/L [1] and at the outlet, concentrations were reduced to below 0.04 mg/L in all cases, indicating over 90% removal efficiency. This performance is comparable to the GAU:zeolite 1:1 and 3:2 configurations, but with fewer fluctuations in concentration. Given the higher zeolite content, such behavior is expected, as the zeolite provides favorable conditions for NH_4^+ ion adsorption, with additional support from microbial transformation.

Comparative Analysis of Filtration Test Results and Economic Assessment

Within the experimental investigation carried out at the pilot-scale groundwater treatment facility, five different filter media configurations were tested in the second, key filtration column. The tested media included GAC, natural zeolite, and three mixed variants with different mass ratios of the two materials. All configurations were analyzed under continuous 12-hour filtration.

Table 1 presents the removal efficiency achieved for the monitored contaminants compared to influent values, an indicative economic index reflecting material costs, as well as a qualitative note on the ability of each medium to remove organic matter based on UV-254 absorption. These data serve as a basis for evaluating the optimal technological and economic configuration for potential application in real groundwater treatment systems.

Table 1. Comparative overview of removal efficiencies and economic justification of different filter media configurations at the Pilot facility

Filter configuration	**Fe removal (%)**	**Mn removal (%)**	**NH_4^+ removal (%)**	**UV-254 removal (%)**	**Economic index (relative)**
GAC	95,2	89,6	91,4	84,0	8,0
Zeolite	**95,9**	**91,5**	**97,6**	**99,8**	**68,4**
GAC:Zeolite 1:1	75,6	86,2	94,3	80,0	13,3
GAC:Zeolite 3:2	87,6	90,8	91,4	84,0	11,2
GAC:Zeolite 2:3	91,2	93,9	94,3	80,0	18,2

Analysis of the comparative data highlights significant differences in removal efficiencies and cost-effectiveness among the tested filter media. The price gap, at the national level, between GAC (cca. 6,0–10,0 € per kg) and natural zeolite (cca. 0,5–1,2 € per kg) is substantial, averaging an 8:1 ratio in favor of zeolite. Consequently, any configuration in which GAC is partially replaced by zeolite, while still maintaining acceptable contaminant removal, represents a realistic and measurable economic advantage. Pure GAC achieved an average efficiency of 90,05% and is technologically reliable, especially in cases where iron and organic matter are predominant. However, due to its high material cost, its economic index (8,0) makes it the least cost-effective option. Zeolite alone achieved the highest average efficiency (96,19%) at the lowest cost, resulting in an economic index of 68,4, more than eight times higher than GAC. Its ion-exchange capacity, porosity, and synergy with microbiological processes make it particularly useful in decentralized water systems with limited budgets. Among the mixed configurations, the 2:3 GAC-to-zeolite ratios proved to be the most cost-effective compromise, achieving an average removal efficiency of 89,85% and an economic index of 18,2. This configuration showed strong performance in manganese and ammonium removal while reducing costs significantly compared to pure GAC. The 1:1 and 3:2 ratios also improved cost-effectiveness, but were less competitive overall. In summary, replacing GAC with zeolite partially could significantly improve the economic sustainability of groundwater purification systems without a reduction of technological performance. The optimal choice depends on the dominant contaminants: higher GAC fractions are recommended when iron and organic matter predominate, whereas zeolite-rich configurations are preferable under conditions of elevated ammonium and manganese.

Conclusion

The pilot-scale study conducted at the Public Utility Company "Water and Sewerage", Novi Sad, Republic of Serbia, at the preaeration system, evaluated five adsorbent configurations: GAC, zeolite, and their mixtures at mass ratios of 1:1, 3:2, and 2:3, for groundwater treatment, focusing on iron, manganese, ammonia, and organic compounds (UV-254).

Results demonstrate that the combination of GAC and zeolite represents a compromise solution between efficiency and cost-effectiveness. The best results in this research were achieved by the GAC:zeolite ratio of 2:3. This configuration is particularly suitable for conditions with elevated concentrations of manganese and ammonia, while iron is present in moderate amounts. On the other hand, the 1:1 ratio, although technically acceptable, shows somewhat lower stability in achieving maximum allowable concentration (MAC) values, especially for iron. In summary, the results suggest the following application recommendations:

- For systems where iron and organic matter are the priority contaminants, GAC alone or in combination with zeolite in a GAC higher proportion could be used,
- For systems with high concentrations of manganese and/or ammonia, zeolite alone or in configurations with a lower proportion of GAC (3:2) showed high cost-efficiency performance and
- For economically limited systems, zeolite as the primary or sole filter bed configuration represents the most cost-effective solution.

The pilot project demonstrated not only the potential application of alternative natural adsorbents but also the necessity of dynamically adapting treatment technologies according to the groundwater and available water resources. The achieved results open possibilities for further optimization, improvement, and the combination of adsorption and biological processes to ensure a stable and economically sustainable water supply in both urban and less developed areas.

Reference

[1] Official Gazette of the FRY, No. 42/98, 44/99, and Official Gazette of the RS, No. 28/2019.

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ADSORPTION OF METOLACHLOR ON WOODCHIPS

Klára Novotná*, Karel Hrich, Jitka Malá

Brno University of Technology, Faculty of Civil Engineering,
Institute of Chemistry, Brno, Czech Republic
*klara.novotna@vut.cz

Abstract

Denitrifying woodchip bioreactors (DWBs) are utilized for reducing nitrate levels in agricultural runoffs. They typically take the form of excavations filled with woodchips. Other substances, including pesticides and their metabolites, were also identified at the inlet to the DWBs. Their decomposition time often reaches tens of days. Extending their retention time through adsorption on woodchips could foster their biodegradation. The hydraulic retention time in DWBs can be up to 24 h. Therefore, a 24-hour test was designed that allows to determine the adsorption rate of pesticides onto the bioreactor filling. The adsorption test was carried out with metolachlor as a model compound in 16 two-liter glass bottles. 48 h before the start of the test, 30 g of poplar shavings and 2 L of liquid medium containing 15 mg NO_3-N/L were added to each bottle. The bottles were bubbled with argon, closed, and incubated at a temperature of 15 °C. At the start of the experiment, a mixture containing metolachlor and its 4 metabolites was added to each bottle, so that the initial concentration of metolachlor was 0.25 $\mu g.L^{-1}$, and its metabolites 0.5 $\mu g.L^{-1}$. The pH, dissolved oxygen, NO_3-N, and the concentration of pesticide substances were measured. Every 6 h, the adsorption process was terminated in 4 bottles. The previously mentioned parameters, plus COD and NO_2-N concentrations, were determined. During the test period, denitrifying conditions were sustained in the bottles, as evidenced by the low oxygen concentration (<1 $mg.L^{-1}$) and the NO_3-N decrease. The average COD was 408 $mg.L^{-1}$. The loss of the pesticide substances increased during the experiment and after 24 h reached the following values: 60% metolachlor NOA 413173, 32% metolachlor CGA 368208, 25% metolachlor, 18% metolachlor ESA, and 15% metolachlor OA.

Introduction

Nitrogen fertilisers increase agricultural production. Nitrogen compounds also enter the soil via manure and plants. However, these compounds can contaminate water through runoff, and a denitrifying bioreactor provides a simple, cheap, and passive solution to remove this pollution. It involves a trench filled with organic material (usually wood chips) to enhance natural denitrification [1]. Heterotrophic denitrification is a four-stage process, converting nitrates (NO_3^-) into gaseous nitrogen (N_2) [2]. This natural soil reaction is caused by denitrifying bacteria, which need nitrates for respiration without oxygen [3].

Case studies regarding the reduction of nitrate concentrations in denitrifying bioreactors have been published in the USA, Australia, and New Zealand, while in Western European countries (Denmark, Belgium, Germany, etc.), the technology remains in the research phase [4].

In the Czech Republic, following the findings of earlier laboratory studies, a pilot-scale denitrifying bioreactor was initiated in 2023 in Němčice in the South Moravian Region, to ascertain the efficacy of this technology within local conditions [4].

Nitrates, pesticides, and veterinary pharmaceuticals all contaminate agricultural runoff. Several factors influence how these substances behave in a denitrifying bioreactor, including bioreactor filling, retention time, and interaction between different substances [5]. A denitrifying bioreactor can remove pesticides and pharmaceuticals by adsorption or decomposition [6]. The decomposition time of these substances is relatively long, up to tens of days, so retaining them in the bioreactor creates favourable conditions for this [7].

The design hydraulic retention time in a denitrifying bioreactor is usually in the order of hours; studies indicate that substances are adsorbed onto wood chips during this time. Adsorption prolongs their retention time and extends the action time of denitrifiers. Approximately 50% abiotically reduced metolachlor concentration was seen in 7-day and 28-day laboratory tests [7]. Atrazine was tested in a laboratory denitrifying bioreactor. After four hours, its concentration had decreased by 25%; after 72 h, it had decreased by 53%. In a bioreactor supplemented with biochar, 90% of atrazine was removed within 72 h [8].

In this study, a laboratory test was conducted to verify whether and how quickly pesticide substances and their metabolites are adsorbed onto the bioreactor filling. The test substance was metolachlor, a pre-emergent and early post-emergent herbicide often used on corn. This compound is among the most frequently detected in surface and groundwater in the Czech Republic, with levels around 0.6 $\mu g.L^{-1}$ [9][10].

Materials and methods

The experimental design of the adsorption test lasted 24 h. Forty-eight hours before the beginning of the experiment, 30 g of poplar shavings (1.0-1.5 cm) and 2 L of liquid medium, i.e. solution of KNO_3 (15 $mg.L^{-1}$ NO_3-N) and $NaHCO_3$ (0.5 $g.L^{-1}$) in deionised water, were added to sixteen glass bottles with a volume of 2 L. The bottles were then bubbled with argon until the concentration of dissolved oxygen (O_2) decreased below 0.5 $mg.L^{-1}$. The bottles were thereafter sealed with a rubber glove and placed in an incubator thermostat set at 15°C.

At the beginning of the experiment (time 0 h), 0.6 ml of a mixture containing metolachlor and its metabolites metolachlor CGA 368208, metolachlor ESA, metolachlor NOA 413173, and metolachlor OA was added, so that the initial concentration of metolachlor was 0.25 $\mu g.L^{-1}$ and that of its metabolites 0.5 $\mu g.L^{-1}$. The pH, dissolved oxygen, and NO_3-N concentrations were measured in all bottles, and samples were taken to verify the initial concentration of the test substances.

Every six hours (6 h, 12 h, 18 h, and 24 h), four bottles were removed from the thermostat, and all of the above parameters were measured. In addition, the chemical oxygen demand (COD) and the concentration of nitrite nitrogen (NO_2-N) were determined, and samples were taken to determine the concentration of metolachlor and its metabolites. The test was gradually completed in all bottles.

The pH and dissolved oxygen concentrations were determined by a multiparameter analyser (Hach HQ440d). The Nitratax plus sc Sensor probe was employed to measure the NO_x-N concentrations; meanwhile, the photometric method with alpha-naphthol was used to measure the NO_2-N concentrations. The NO_3-N concentrations were calculated as the difference between the NO_x-N and NO_2-N concentrations, and the COD was measured using a dichromate micro-method with a photometric endpoint. Photometric endpoints were measured using a HACH DR3900 VIS device. Samples for the determination of pesticides by liquid chromatography coupled with tandem mass detection (UPLC-MS/MS) were pre-treated by solid phase extraction (SPE).

Results and discussion

Table 1 provides a summary of the parameters monitored during the experiment. These values are representative of the mean value, with the standard deviation determined for four bottles in a given hour of the test. It can be concluded that the test was conducted under denitrifying conditions, as evidenced by the O_2 concentration of less than 1 mg.L^{-1} and the decrease in NO_3-N concentration.

Table 1. Parameters monitored during the test

Time	**pH**	**O_2**	**NO_x-N**	**NO_2-N**	**NO_3-N**	**COD**
h	**-**	**mg.L^{-1}**	**mg.L^{-1}**	**mg.L^{-1}**	**mg.L^{-1}**	**mg.L^{-1}**
6	8.14 ± 0.01	0.6 ± 0.05	14.7 ± 0.05	0.8 ± 0.26	13.87 ± 0.3	422 ± 29
12	7.78 ± 0.06	0.6 ± 0.05	14.3 ± 0.08	1.56 ± 0.23	12.74 ± 0.31	436 ± 11
18	7.54 ± 0.13	0.51 ± 0.03	14.2 ± 0.1	2.22 ± 0.69	12.01 ± 0.77	385 ± 22
24	7.68 ± 0.06	0.67 ± 0.04	13.8 ± 0.22	2.9 ± 0.6	10.88 ± 0.75	387 ± 4

The mean final concentrations of metolachlor and its metabolites measured during the test are presented in Table 2. Their concentrations were analysed at the beginning of the test (time 0 h) in all sixteen bottles, and then at the relevant hours of the test in four bottles, in which the test was subsequently terminated. Due to the methodological configuration, it was not possible to achieve identical initial concentrations. However, the loss of metolachlor and its metabolites was always calculated as a difference between the initial and final concentration of the respective compound in one bottle. Table 3 shows the absolute values of the decrease in the monitored substances during the test.

Table 2. Average concentration of metolachlor and its metabolites

Time	**MET**	**MET CGA 368208**	**MET ESA**	**MET NOA 413173**	**MET OA**
h	**µg.L^{-1}**	**µg.L^{-1}**	**µg.L^{-1}**	**µg.L^{-1}**	**µg.L^{-1}**
6	0.2564	0.3855	0.5863	0.2771	0.4539
12	0.2116	0.3657	0.5873	0.2827	0.4957
18	0.2032	0.3721	0.5453	0.2258	0.5074
24	0.1970	0.3545	0.5256	0.2256	0.4964

Table 3. Average loss of metolachlor and its metabolites

Time	**MET**	**MET CGA 368208**	**MET ESA**	**MET NOA 413173**	**MET OA**
h	**µg.L^{-1}**	**µg.L^{-1}**	**µg.L^{-1}**	**µg.L^{-1}**	**µg.L^{-1}**
0-6	0.0332	0.0579	0.0532	0.0595	0.1014
0-12	0.0378	0.0764	0.0288	0.0683	0.0406
0-18	0.0286	0.0501	0.0410	0.1288	0.0646
0-24	0.0739	0.1713	0.1260	0.3511	0.0993

The loss of metolachlor and its metabolites is exhibited in Figure 1 as a percentage of their initial concentrations. Concentration levels of 100% are equivalent to the mean initial concentration of individual substances; the mean decrease in individual hours was converted to a percentage decrease compared to the mean initial concentration. A significant decrease in concentration was observed in all cases. Following 24 hours, the relative decrease in individual substances was as follows: 60% metolachlor NOA 413173, 32% metolachlor CGA 368208, 25% metolachlor, 18% metolachlor ESA, and 15% metolachlor OA. The increase in the concentration of pesticide substances during the test can be explained mainly by the test setting.

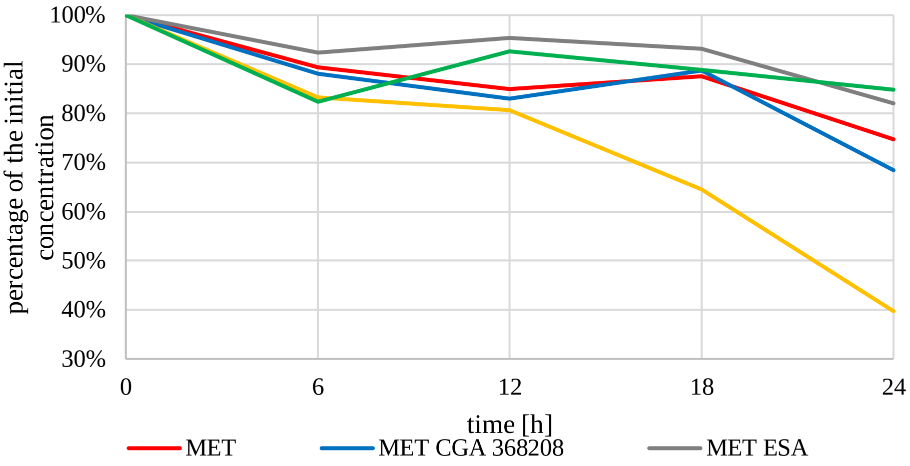

Figure 1. Percentage concentration of metolachlor and its metabolites

The results obtained in this study are consistent with the data measured in a preceding 7-day and 28-day test, where approximately 50% metolachlor was abiotically removed [7]. Those findings indicated that metolachlor was rapidly adsorbed onto wood chips in the initial days and that the adsorbed amount did not increase significantly with prolonged incubation time. In the present study, for all substances, adsorption levels increased during the 24-hour test period. However, the adsorption is not immediate. Considering its course (Figure 1), further growth can be expected.

Conclusion

In a 24-hour laboratory adsorption test, a relative reduction of 25% was achieved for metolachlor (parent substance), and between 15-32% for its metabolites, with a maximum of 60% reduction observed for metolachlor NOA 413173. The results show that metolachlor is adsorbed very rapidly onto wood chips under denitrifying conditions. In a denitrifying bioreactor, this would cause an extension of its retention time, which would improve the conditions for its biological degradation.

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WWTP SUBOTICA MUNICIPAL WASTEWATER - ON THE WAY FROM WASTE TO RESOURCE

Petar Pižurica

PUC “Waterworks & Sewerage” Subotica, Serbia
*pizurica@vodovodsu.rs

Abstract

The use of wastewater as a resource is a key step towards sustainable water management and environmental protection. Instead of viewing wastewater exclusively as a burden and environmental problem, modern approaches increasingly recognize it as a valuable source of water, energy, and nutrients. This concept fits into the principles of the circular economy, where resources are used efficiently and repeatedly, thus reducing the pressure on natural resources.

This paper presents those parts of the treatment of municipal wastewater at WWTP Subotica, which can generate "products" usable as a resource either raw or through further processing. Some of these “products” are: treated wastewater, which can be used for irrigation, due to its nutrient content, sludge, which, together with green biomass, can be used as a raw material for obtaining compost, and separated bio-gas from the anaerobic digestion as an energy source for combustion on CHP units for the production of heat and electricity.

The work is focused on the problems, solutions, and examples of good practice established during the work of the WWTP Subotica and future moves to improve the water quality in the lakes Palić and Ludaš.

Picture 1. WWTP Subotica

Keywords: irrigation, compost, biogas, resource

Introduction

Wastewater from the city of Subotica is collected by a combined sewage system and transported to the Wastewater Treatment Plant in Subotica (WWTP Subotica) located on the shore of Lake Palić.

In order to improve the ecological status of Palić Lake and other downstream surface waters, a reconstruction and extension of the existing WWTP Subotica started in 2007. The hydraulic and organic capacity of the plant was increased, new biological pools were constructed, the removal of nitrogen and phosphorus was improved, and a sludge line was introduced. The sludge line "solved" the problem of sludge disposal.

Table 1. Projected parameters and quality of effluent at WWTP Subotica

Capacity		150 000 PE	
Hydraulic load		36 000 m^3/day – dry season 72 000 m^3/day – rainy season	
Parameter	Unit	Projected value	Average 2011. – 2024. year
BOD_5	mg/l	25	5,6
COD	mg/l	125	35,8
Total nitrogen	mg/l	10	8,5
Total phosphorus	mg/l	1[1]	0,8
Suspended solids	mg/l	35	11,1

Technological progress has enabled the development of efficient methods for the treatment and reuse of wastewater, both in agriculture, industry, and in urban areas. Some of the products of municipal wastewater treatment, ***treated wastewater***, ***sludge cake*** and ***biogas*** on the path from waste to resource.

Treated Wastewater:

After reviewing and monitoring the quality of treated wastewater and surface water in the lakes Palić and Ludaš, it was concluded that the amount of total phosphorus discharged from the WWTP into Lake Palić exceeds the lake's capacity. Therefore, work continued on improving wastewater treatment with additional phosphorus removal, through the Ecolacus[2] project "Protection of Biodiversity and Water of Lakes Palić and Ludaš" and the preparation of a Feasibility Study "Improving the water quality of Lake Palić" [3] for the management of treated water.

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[1] Palić Lake is a sensitive recipient, the WWTP Subotica capacity is over 100,000 PE.

[2] Project "Protection of Biodiversity and Water of Palić and Ludaš Lakes" - 2018 - 2021 - KfW Bank Development Grant

[3] Feasibility study "Improving the water quality of Lake Palić" - 2021, VTK INNOSYSTEM VÍZ-, TERMÉSZET- ÉS KŐRNYEZETVÉDELMI KFT, Budapest

Table 2. Load of nutrients from different sources in Palić Lake

Source	Phosphorous load (t/year)	Nitrogen load (t/year)
Treated wastewater	**12-15**	**590-600**
Other point loads	1-2	10-20
Diffuse load	24-26	168-182
Load from air	1-2	33-44
Groundwater inflow	negligible	not applicable
Total external load	38-45	minimum 801-846
Internal load	20-25	not applicable
Total	**58-70**	**minimum 801-846**

In all sources of loading, a significant amount of surplus nitrogen appears in relation to the weight ratio of 7:1. Regardless of the nitrogen "overload" already existing in the sector IV of Lake Palić, and especially in Lake Ludaš, the dominance of nitrogen-fixing heterocystic cyanobacteria indicates that the water flowing from Lake Palić to Lake Ludaš lacks nitrogen. The reason for this is the significant ammonification, nitrification, and denitrification processes happening in Lake Palić, i.e. subsequent treatment of wastewater from nitrogen. Lake Palić can be well used for nitrogen removal. For this reason, emphasis is primarily placed on the removal of phosphorus, which should be a limited element in the lake (currently it is not).

Through the implementation of the Ecolacus Project "Protection of Biodiversity and Water of Palić and Ludaš Lakes", a facility for additional removal of phosphorus from treated water was built. Before it is discharged into the recipient, treated water from the existing plant is brought to the facility for additional phosphorus removal. The facility has a maximum hydraulic capacity of 2,100 m³/h.

The installed process of additional phosphorus removal includes:

- the capturing of treated water from the existing efluent channel;
- water pressuring in flocculation basins;
- the dosing of coagulant into the pressure pipeline with intensive mixing with static mixers;
- the measurement of the quantity of water pushed into the flocculation basins;
- the retention of water in flocculation basins for the formation of larger flocs before filtration
- water filtration on rotary disk filters with a free passage of 10μm to retain the formed flocs;
- measuring the quantity and sampling of the water that is discharged[4] into the 1st sector of Lake Palić;
- acceptance of water from the disk filter washing and pumping it into the excess activated sludge pumping station;

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[4] The possibility of installing UV lamps for disinfection is left.

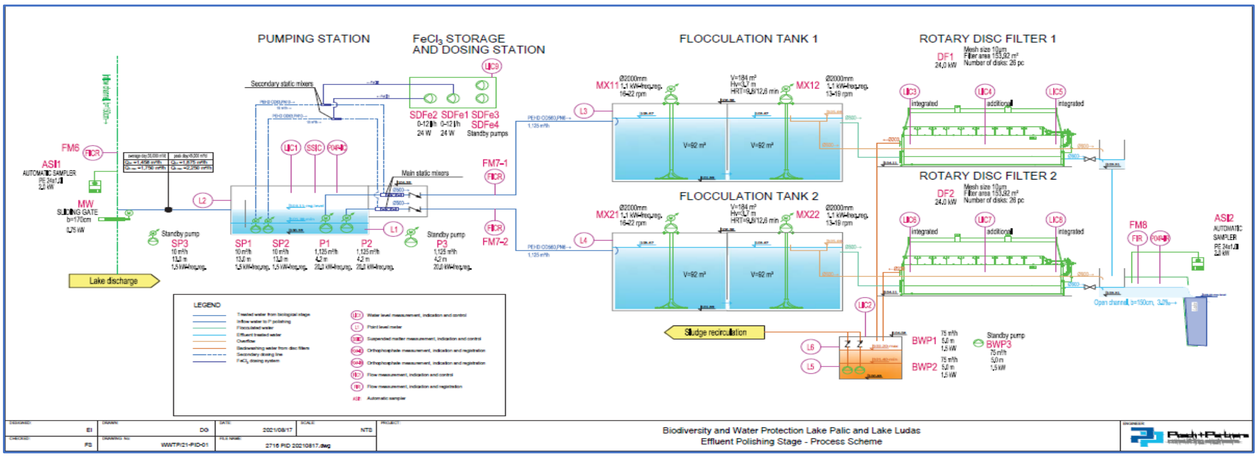

Figure 1. Technological scheme of the line for additional phosphorus removal

After the treatment of water through this facility, the maximum allowed concentration of total phosphorus is reduced from 1mg/l to 0.27 - 0.4 mg/l (depending on the input concentration), and the concentration of suspended solids is reduced from 25mg/l to 4-8 mg/l, which ensures the protection of the sensitive ecosystem of Lake Palić.

The feasibility study "Improving the water quality of Lake Palić" for the management of treated water starts from the constructed line for additional phosphorus removal and addresses several variant solutions. A variant without any development measures - where the influence of the constructed line and its influence in the following period are processed - was immediately rejected, as well as 12 different variants with development measures.

All considered variants contain measures to reduce external and internal load through the following procedures.

Reduction of external load: Separation of lagoon I, sector I from sector II, construction of retention for receiving storm water with a capacity of 30,000 m^3 within the plant area, reduction of diffuse loads (change in soil cultivation, planting forest belt, elimination of point sources of pollution), redirection of treated water and its reuse. By closing the connection between sectors III and IV, sector IV would be separated. Sectors I, II, and III would serve nature protection purposes, and they would function as reservoirs. The target status of sector IV stands out, where the goal would be to provide water of a quality suitable for swimming. Lake Ludaš would be filled with water from sector II, and in this way, the surplus water for sector IV would be used and drained. In addition, bearing in mind EU Regulation 2020/741 of the European Parliament and the Council (May 25, 2020) on minimum requirements for water reuse, it would ensure the possibility to reuse treated wastewater by injecting it into the already built Tisa-Palić irrigation system.

Picture 2. WWTP Subotica and lagoon sistem

Reduction of internal load: Sludge should be extracted[5][6] from all sectors of Lake Palić. Based on the method of analyzing variant solutions with multiple aspects, variants 4th and 7th received the most points. In both of the selected variants, the sludge would be removed from the bottom of the lake trough dry skimming, however, the intervention would last longer, according to an estimate cca. 5 years. Dredging with floating dredges would cost more, take less time, but according to the expectations would last 3 years. During the cost/benefit analysis, in order to be able to assess whether the economic benefit gained by the performed works of a shorter duration would be balanced with the higher investment costs, the 6th variant was also analyzed. This variant differs from the 4th variant only in the applied grinding technology. Based on all analyses, Option 4th was selected.

Table 3. Estimated cost value of individual variants

Variant	Description	Investment cost million €
Variant 4.	Reconstruction of the "Odušni" channel, separation of sector IV with direct water supply from the WWTP, use of water in the Tisa-Palić subsystem with water intake from sector III, sludge extraction in dry conditions.	45,7
Variant 6.	Reconstruction of the "Odušni" channel, separation of sector IV with direct water supply from the WWTP, use of water in the Tisa-Palić subsystem with water intake from sector III, sludge extraction from lake with floating dredges	107,1
Variant 7.	Reconstruction of the "Odušni" channel, separation of sector IV with direct water supply from the WWTP, redirection of water towards Kereš with water intake from the Palić-Ludaš canal, sludge extraction in dry conditions.	45,7

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[5] Extraction of the I sector was carried out in 2008, so it is not foreseen in this study.
[6] It should be removed 1.900.160 m^3 of sludge – Study Institute "Jaroslav Černi", 2011.

Results and discussion

The construction of a line for additional phosphorus removal ensures high-quality of treated wastewater, as a significant resource that can be reused, especially in areas with limited clean water supplies. Its application in irrigation enables the preservation of natural water resources and supports sustainable agriculture. At the same time, a high degree of wastewater treatment contributes to the improvement of the quality of recipients (natural watercourses), thus creating conditions for the safe use of water for swimming and recreation. This approach combines ecological and economic benefits, while respecting prescribed sanitary standards.

Sludge from the treatment of municipal wastewater:

Stabilization of sludge at WWTP Subotica is ensured by anaerobic, mesophilic digestion, which represents the breakdown of organic and inorganic substances present in sludge, in the absence of molecular oxygen at temperatures of 34-38°C. During the process, organic matter is brought to a state where it is no longer susceptible to decomposition, i.e., it is no longer harmful to the environment (the number of pathogenic organisms is reduced, unpleasant odors are removed, and sludge/sludge cake is prevented from rotting at the disposal site).

Anaerobic decomposition of organic matter is a process that takes place in several steps, the end result of the reaction is, in addition to water and ammonia in the liquid phase, a gas mixture (CH_4) and carbon dioxide (CO_2) in an approximate ratio of 3:1.

After anaerobic mesophilic digestion and thickening on a belt filter press, a sludge cake is obtained, which is taken to the Bikovo Regional Landfill, where it is mixed with green biomass in the composting process. The Regional Landfill Bikovo, to obtain a permit for the termination of the status of waste and the possibility of its further use, performed testing and classification of the compost. In the conclusion of the Examination Report I-3141/25-13 dated July 17, 2025. prepared by INSTITUTE MOL doo states: "According to Rulebook[7] point 5.2.4, this type of compost meets the values for class I, II, III according to chemical and microbiological tests, however, according to the process of creation and index number (19 05 03), the compost belongs to class III compost. The results of the test can confirm that the material has, according to the regulation, lost the status of waste, and can be used as regulated." (for use on land that is not used for food production, on forest land, in parks, for landscaping or land reclamation, and for making the final reclamation layer of the landfill).

Compost obtained by processing sludge from WWTP Subotica and adding green biomass is currently classified as third-class compost, which significantly limits its use. Nevertheless, analyses of the quality of compost show that it meets the requirements for second-class compost in terms of its chemical and microbiological composition, which has a wider application, especially in agriculture. The main limiting factor is not the quality of the compost itself, but the place of its creation, because according to the current regulations. This indicates the need for a revision of the regulations in order to enable a wider and environmentally justified use of this resource.

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[7] Rulebook on types of waste for which a request can be submitted, allowed procedures and treatment technologies for types of waste and other special elements for determining the end of the status of waste (Official Gazette of the RS No. 19/2024, 47/2024)

Produced Biogas:

The produced biogas is used at the WWTP Subotica as an energy source, the combustion of which provides the heat and electricity needed in the daily treatment of wastewater.

The total CHP unit capacity is 500 kW (two generators of 250 kW each). They work in 2+0 mode. Two generators from the Cogeneration units (CHP) G 9408 series were adopted, which can use biogas and natural gas as fuel. In order to obtain 250 kW of electricity at the output of each of the units, it is necessary to ensure a flow of biogas of 131 mN 3/h, i.e., an input thermal power of the gas of 357 kW. In the work done so far, one CHP unit is usually working, and the other is turned on only when needed.

Table 4. Consumption of electricity at WWTP Subotica from different sources

Year	Electricity taken from the distribution system	Electricity produced	Total consumed electrical energy	The ratio of produced and consumed electricity
	kWh	kWh	kWh	%
2012	2,019,185	1,255,576	3,274,761	38.34%
2013	2,217,947	1,167,705	3,385,652	34.49%
2014	2,564,630	759,910	3,324,540	22.86%
2015	2,886,075	841,051	3,727,126	22.57%
2016	2,442,126	1,453,795	3,895,921	37.32%
2017	4,078,168	666,528	4,744,696	14.05%
2018	3,601,674	789,838	4,391,512	17.99%
2019	3,520,790	826,201	4,346,991	19.01%
2020	2,706,500	1,281,310	3,987,810	32.13%
2021	2,895,640	1,221,820	4,117,460	29.67%
2022	2,902,166	1,288,820	4,190,986	30.75%
2023	3,547,077	993,270	4,540,347	21.88%
2024	3,321,876	1,109,560	4,431,436	25.04%

According to the project, it is envisaged that 30% of the required electricity for WWTP operation will be produced in the treatment of sludge. It can be seen from Table 4 that this is not the case every year, partly due to equipment maintenance costs as well as increased energy consumption by building an additional phosphorus removal unit.

In order to reduce electricity costs, the construction of a station for the reception of easily degradable waste (permeate from the dairy, oil, and grease from the kitchen) has started, and a project was drawn up for the construction of a 150 kW solar power plant.

It is expected that by taking waste rich in biomass and dosing it directly into the digesters, we will increase biogas production by 10%, and by building a solar power plant, we will provide an additional 170,000 kWh per year, which would further reduce the operating costs of the WWTP Subotica. It is estimated that the savings would be an additional 8 to 12%, depending on the amount of stormwater.

WWTP Subotica uses biogas to reduce dependence on external electricity. The construction of a storage tank for easily degradable biomass and its dosing in digesters will increase biogas production, while solar panels will additionally contribute to energy efficiency. Such a system will reduce the cost of electricity, increase the energy independence of the plant, and contribute to the protection of the environment through the reduction of CO_2 emissions. This represents a step towards the implementation of the Directive adopted by the European Parliament on March 1, 2024, on the Energy neutrality of wastewater treatment devices and deadlines for achieving them.

Conclusion

WWTP in Subotica is an example of good practice in sustainable wastewater management, where modern technologies are used not only for environmental protection, but also for the production of useful resources. One of the key segments of the plant's operation is the production of electricity from biogas, which is produced during sludge processing. In this way, WWTP contributes to energy efficiency and reduction of greenhouse gas emissions, and at the same time provides part of its energy needs from renewable sources. Also, purified wastewater, thanks to a high level of treatment, can be used for irrigation in agriculture, which reduces the pressure on natural water resources, especially in dry periods.

Another important aspect is the use of stabilized sludge as raw material for composting. This turns the sludge into a useful organic material that can be reused, while respecting sanitary and ecological standards

All these activities indicate that WWTP Subotica does not function only as a wastewater treatment plant, but as a multifunctional system that turns waste into a resource. This approach is fully aligned with the principles of circular economy and sustainable development, and can serve as a model for similar projects in the region and beyond.

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EVALUATION OF STABILIZED DREDGED SEDIMENT'S POTENTIAL FOR USE IN SUBGRADE MATERIAL WITH LIFE CYCLE ASSESSMENT

Nataša Slijepčević[1]*, Dragana Tomašević Pilipović[1], Boris Agarski[2], Miloš Šešlija[2], Milana Ilić Mićunović[2]

[1]*University of Novi Sad, Faculty of Sciences, Trg Dositeja Obradovića 3, Novi Sad, Serbia*
[2]*University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, Novi Sad, Serbia*
*natasa.slijepcevic@dh.uns.ac.rs

Abstract

Stabilization/solidification (S/S) treatment processes are widely employed for the remediation of contaminated sediments, aiming to immobilize hazardous substances and reduce environmental risks, for potential further use in the construction industry. To comprehensively evaluate the environmental sustainability of these remediation techniques, life cycle assessment (LCA) serves as a pivotal tool, analyzing impacts from material extraction through to the end-of-life stages.

This study applies the LCA approach to assess the environmental footprint of various S/S treatment strategies. The research investigates different formulations using cement, lime, and alternative binders to immobilize heavy metals effectively. Key environmental indicators, including global warming potential, energy consumption, and resource depletion, are analyzed across all treatment stages—ranging from material extraction to final disposal. Experimental results are integrated into the LCA framework to compare the impacts of different stabilization strategies.

This study underscores the necessity of integrating LCA into the design of sediment remediation technologies, ensuring that treatment processes align with circular economy principles and sustainability goals. The results contribute to a better understanding of the trade-offs between contaminant stabilization and environmental impact, providing valuable insights for scaling up S/S applications in sediment management.

Introduction

Serbia recognizes the need to move from a linear to a circular economy. Converting waste into raw materials or substitutive secondary raw materials and transition to a circular economy is directly related to sustainable development goals as it contributes to faster economic growth, responsible consumption and production, climate action, and better health of Serbian citizens. The construction sector usually relies on the utilization of natural aggregates as building materials [1]. However, increasing pressure for sustainable roads highlights the importance of replacing natural materials with some not added-value environmental wastes like dredged sediments and industrial by-products [1,2]. In view of this ecological transition, earth constructions are an interesting solution given their low environmental impact and their hydrothermal properties. On the other hand, the rivers must be regularly maintained by dredging operations in order to provide the necessary water depth for navigation.

This induces huge amounts of sediments that should be valorized as they cannot be discharged in the river with the evolution of dredging practices laws. Managing contaminated sediment presents more complexity than handling non-contaminated dredged sediment. Typically, it entails a multi-step process: first, identifying the contamination sources and determining the extent of the pollution, then implementing suitable remediation strategies. These strategies often involve treating the sediment to eliminate or minimize contaminants, or responsibly removing and disposing of the sediment [3,4].

Stabilization/solidification (S/S) techniques have emerged as effective methods to immobilize contaminants and improve the geotechnical properties of dredged sediments. The process involves mixing sediments with binders such as cement, lime, or industrial by-products (e.g., red mud, fly ash, or sewage sludge ash) to enhance mechanical strength and reduce leachability of hazardous components. Despite its technical feasibility, the environmental sustainability of these treatments must be evaluated systematically [4,5].

Life cycle assessment (LCA) provides a comprehensive framework for quantifying environmental impacts associated with material production, processing, and end use. By integrating LCA into the assessment of stabilized sediment, it becomes possible to identify the most sustainable formulations and to compare them with conventional subgrade materials such as natural aggregates.

This research includes the potential and suitability of an industrial by-product—composed of lime, fly ash, and cement—for producing a substitutive infrastructural material using treated river sediment. The resulting material was subjected to a series of leaching tests and mechanical property evaluations, including assessments of durability and strength, to determine its applicability as a subgrade material. The research was conducted within the framework of a life cycle assessment (LCA), which involved the compilation and evaluation of the inputs, outputs, and potential environmental impacts of the product system throughout its entire life cycle.

Materials and methods

The first phase of research focused on the environmental risk assessment of untreated river sediment and sediment chemically immobilized with an industrial by-product used as a binder. Several analytical methods were applied in this phase, including measurement of key parameters such as pH value, electrical conductivity, particle size distribution, organic matter content, and moisture content, as well as pseudo-total metal and organic content. Leaching behavior was assessed using the ANS 16.1 dynamic leaching test, the German standard leaching test (DIN 38414-4 S4), the Toxicity Characteristic Leaching Procedure (TCLP), and a sequential extraction procedure for metals. This second phase focused on testing the treated sediment as a substitute infrastructural material for road construction. Applied methods included the Proctor compaction test (for determining optimal moisture content), California Bearing Ratio (CBR), linear swelling, grain size distribution, dry and maximum bulk density determination, material consistency tests, and classification according to USCS and AASHTO standards. The third phase involved a comprehensive Life Cycle Assessment (LCA) to compare the environmental impact of the newly developed material with conventional road construction materials. This analysis further confirmed the ecological advantages of the developed material. The LCA methodology followed the four phases outlined in ISO 14040: definition of goal and scope, life-cycle inventory analysis, life-cycle impact assessment, and interpretation [6-8]. Figures 1 and 2 are steps of the S/S treatment and mention leaching tests, and Figure 3 shows mechanical strength tests.

Figure 1. Steps in the stabilization/solidification process

Figure 2. Steps from leaching test analysis

Figure 3. Yield strength (left image) and plasticity limit (right image)

Results and discussion

These results provided insights into the efficiency of the stabilization/solidification treatment and supported the development of the substitutive infrastructural material for controlled utilization. Notably, all examined metals show higher percentages in the residual (fourth) fraction compared to the mixture without binder. Metals in this fraction are firmly bound within the crystal lattice of primary and secondary minerals, also mixtures showed very low leaching percentages, below 3% for most tested metals, indicating that the stabilization/solidification treatment was very effective.

After the second phase of the experiment, the results confirmed favorable mechanical properties of the material, indicating its potential durability, strength, and suitability for commercial application [9]. Untreated sediment meets all the prescribed criteria defined, and based on that, clean sediment can be used to construct embankments up to 3 m and over 3 m.

Stabilized sediment with 3% binder content does not meet the requirements for road transport applications; Stabilized sediment with a participation of 5% binder meets the condition that it can be used for foundation soil; Stabilized sediment with a participation of 7% meets the conditions that it can be applied for foundation soil, embankment, and bedding; Stabilized sediment with a participation of 9% binder meets the conditions that can be applied for foundation soil, embankment, and bedding. None of the mentioned mixtures meets the condition that they can be applied for the carrier layer [9].

The LCA examines the environmental impact of dredged sediments as pavement construction materials on a laboratory scale. The LCA for the laboratory scale was conducted for the production of 1 kg of material without the installation phase. Life cycle inventory was presented in Tables after collecting and calculating consumption, while the used datasets were from the ecoinvent v3.7 cut-off system model. OpenLCA v 1.10.3. life cycle assessment software was used for the calculation of environmental impacts [6-8]. The comparative LCIA results show that the laboratory scale scenario generates the largest environmental impacts across all impact categories.

Table 1 ReCiPe 2016 impact categories (midpoint indicators)

Abbreviation	**Impact category**	**Unit**
FPMF	Fine particulate matter formation	[kg PM2.5 eq]
FRS	Fossil resource scarcity	[kg oil eq]
FECOT	Freshwater ecotoxicity	[kg 1,4-DCB]
FEUT	Freshwater eutrophication	[kg P eq]
GW	Global warming	[kg CO_2 eq]
HCT	Human carcinogenic toxicity	[kg 1,4-DCB]
HNCT	Human non-carcinogenic toxicity	[kg 1,4-DCB]
IR	Ionizing radiation	[kBq Co-60 eq]
LU	Land use	[m^2a crop eq]
MECOT	Marine ecotoxicity [kg 1,4-DCB]	[kg 1,4-DCB]
MEUT	Marine eutrophication	[kg N eq]
MRS	Mineral resource scarcity	[kg Cu eq]
OF, HH	Ozone formation, Human health	[kg NOx eq]
OF, TE	Ozone formation, Terrestrial ecosystems	[kg NOx eq]
SOD	Stratospheric ozone depletion	[kg CFC11 eq]
TA	Terrestrial acidification	[kg SO_2 eq]
TECOT	Terrestrial ecotoxicity [kg 1,4-DCB]	[kg 1,4-DCB]
WC	Water consumption	[m^3]

Conclusion

Key conclusions include: i) Stabilized dredged sediment can meet subgrade strength and leaching criteria for construction applications; ii) LCA provides valuable insights into material selection and process design for sustainable sediment management; iii) Incorporating industrial by-products supports circular economy goals by valorizing multiple waste streams; iv) Scaling up requires attention to logistics, energy efficiency, and long-term performance monitoring. Overall, the integration of stabilization/solidification with LCA represents a robust approach for transforming dredged sediments from waste into valuable construction resources, promoting sustainable infrastructure development and environmental protection.

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REUSABILITY OF BIOCHAR AS A CATALYST IN PERSULFATE SYSTEMS FOR ATRAZINE AND SIMAZINE DEGRADATION

Tijana Marjanović Srebro*, Jasmina Anojčić, Sanja Mutić, Nina Đukanović, Tamara Apostolović, Sabolč Bognar, Jelena Beljin

University of Novi Sad, Faculty of Sciences, 21000 Novi Sad, Republic of Serbia
*tijanam@dh.uns.ac.rs

Abstract

The reusability of biochar (BC) in persulfate (PS) activation remains insufficiently explored, although it is one of the key factors for the potential practical application of this process in wastewater treatment. In this work, BC prepared at 700 °C from hardwood, corn cob, and wheat straw was tested through five consecutive degradation cycles for the triazine herbicides atrazine and simazine. In previous experiments, degradation efficiencies were monitored for up to 48 h, confirming that equilibrium was reached after 4 h. Based on this, all reusability experiments were conducted within this time frame, with degradation efficiencies determined at 0.5, 1, 2, and 4 h. After each cycle, the recovered BC was rinsed, dried, and reused under identical conditions (100 µg/L initial pesticide concentration, PS 3.0 mM, BC 0.2 g/L, pH 7.02, 180 rpm). The results revealed clear differences between the two triazine herbicides. Atrazine removal depended on the BC source: hardwood-derived BC retained >85% degradation efficiency after five cycles (4 h), while corn cob and wheat straw BC showed moderate declines. In contrast, simazine degradation remained consistently >90% across all BC and cycles, showing that simazine maintained stable degradation efficiency in this system over multiple cycles. These results suggest that both the pesticide type and the BC feedstock significantly influence the reusability of BC/PS systems, in which BC functions as a catalyst, indicating their potential in water treatment.

Introduction

Biochar (BC) is a carbon-rich material produced through the pyrolysis of various biomass sources [1]. A wide variety of organic wastes, including agricultural residues, forestry by-products, industrial sludge, and municipal solid waste, can serve as feedstocks for its production [2-3]. The use of waste biomass to produce BC not only reduces waste but also promotes resource reuse and supports sustainable environmental management [3]. Depending on the feedstock type and pyrolysis conditions, the physicochemical properties of BC, including surface area, porosity, elemental composition, and functional groups, vary significantly, directly affecting its adsorption and catalytic performance [4-6]. To enhance these characteristics, numerous modification and activation methods have been developed, including physical, chemical, and composite-based treatments [7-13]. Such modifications improve its surface reactivity, functional group density, and overall stability, making BC suitable for various environmental applications [10,13]. However, while numerous studies have addressed the modification and activation of BC, its long-term catalytic stability and reusability in advanced oxidation processes remain insufficiently explored.

BC has been successfully applied in several environmental fields, including soil remediation, pollutant adsorption, and water treatment, as well as in climate change mitigation through carbon sequestration and reduced greenhouse gas emissions [14-16]. Its effectiveness in removing both inorganic and organic contaminants mainly relies on functional surface groups such as carboxyl and hydroxyl, which enable ion exchange and surface complexation mechanisms [17]. Although BC demonstrates great potential as an adsorbent and catalyst, further research is required to fully evaluate its reusability and stability in practical applications.

This study therefore aims to evaluate the reusability of BC derived from hardwood, corn cob, and wheat straw (pyrolyzed at 700 °C) as a PS activator for the degradation of triazine herbicides, atrazine and simazine. By examining its performance over multiple degradation cycles, the work provides new insights into the long-term stability and practical potential of BC/PS systems in wastewater treatment.

Materials and methods

BC samples were produced via pyrolysis of hardwood, corn cob, and wheat straw at 700 °C and subsequently applied as catalysts in persulfate (PS) systems for the degradation of triazine herbicides (atrazine and simazine) over five consecutive reuse cycles. All experiments were performed under previously optimized conditions: PS concentration of 3.0 mM, BC dosage of 0.2 g/L and an initial pesticide concentration of 100 µg/L. The degradation experiments were carried out at pH 7.02 with a stirring rate of 180 rpm. The contact time was 4 h, and samples were collected at 0.5, 1, 2, and 4 h for analysis. After each degradation cycle, the reaction mixture was filtered through a 0.45 µm membrane, and the recovered BC was thoroughly rinsed with Milli-Q water, dried, and reused under identical conditions in the subsequent run. All experiments were carried out in duplicate.

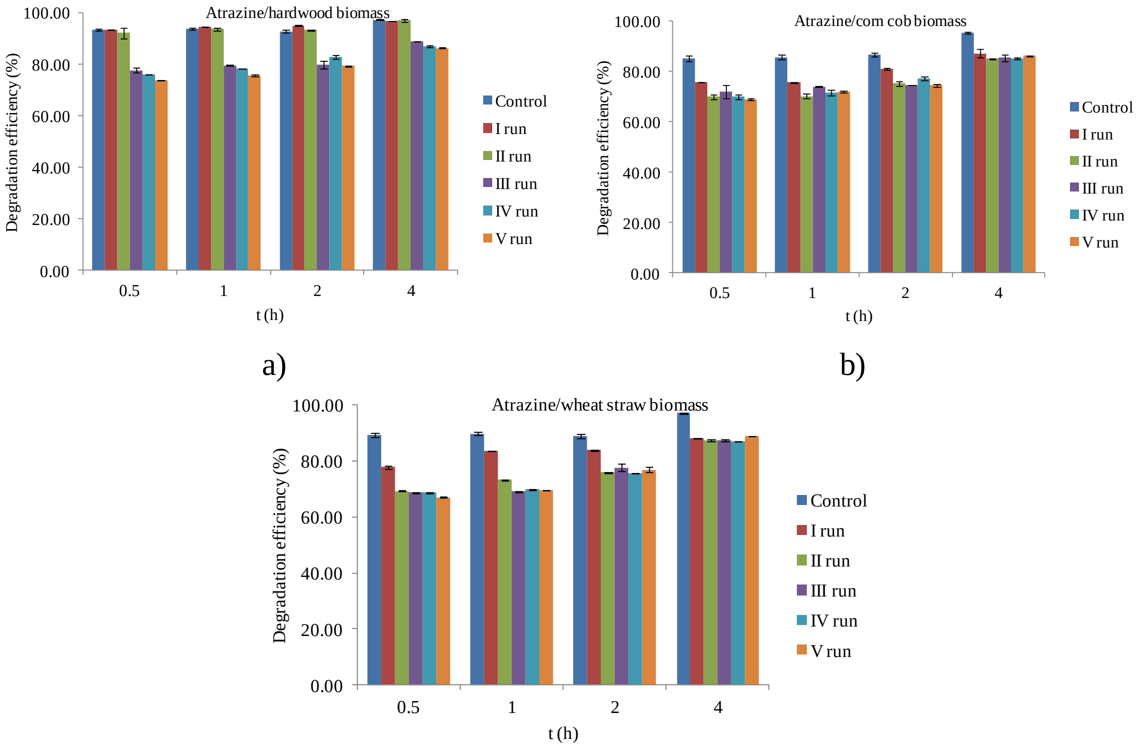
The concentrations of atrazine and simazine were determined using gas chromatography coupled with mass spectrometry (GC-MS, Agilent Technologies 7890A Gas Chromatograph/5975C Mass Spectrometer, Santa Clara, CA, USA). The samples were prepared by liquid-liquid extraction prior to analysis. Separation was carried out on a DB-5MS capillary column (30 m × 0.25 mm × 0.25 µm; J&W Scientific, Santa Clara, CA, USA).

Results and discussion

The reusability of BC in PS systems was evaluated through five consecutive degradation cycles performed under identical experimental conditions. The obtained results for atrazine and simazine degradation are shown in Figure 1 and Figure 2, respectively. In both figures, part a) refers to hardwood BC, b) to corn cob BC, and c) to wheat straw BC. The results illustrate how degradation efficiency evolves across reuse cycles, offering insight into the long-term catalytic stability of BCs derived from different feedstocks. Comparison of the two triazine herbicides further reveals the combined influence of BC origin and pesticide type on the overall performance of the BC/PS system. All experiments were carried out in duplicate, and the data are presented as mean values with standard deviations below 5%.

As shown in Figure 1, the degradation efficiency of atrazine decreased gradually with successive reuse cycles for all BC, indicating partial deactivation of active surface sites. However, the extent of this decline varied depending on the BC type.

Hardwood-derived BC (Figure 1a) exhibited the highest catalytic stability, maintaining over 85 % degradation efficiency even after the fifth reuse cycle. This stability can be attributed to its well-developed porous structure and the presence of persistent functional groups that remain active during repeated PS activation. In contrast, corn cob BC (Figure 1b) showed a moderate reduction in efficiency after the third cycle, likely due to partial pore blockage and a gradual loss of active sites. Wheat straw BC (Figure 1c) demonstrated the most pronounced decline in catalytic performance, which can be associated with its less stable structure and the higher content of oxygen-containing surface groups that are more susceptible to oxidation and deactivation.



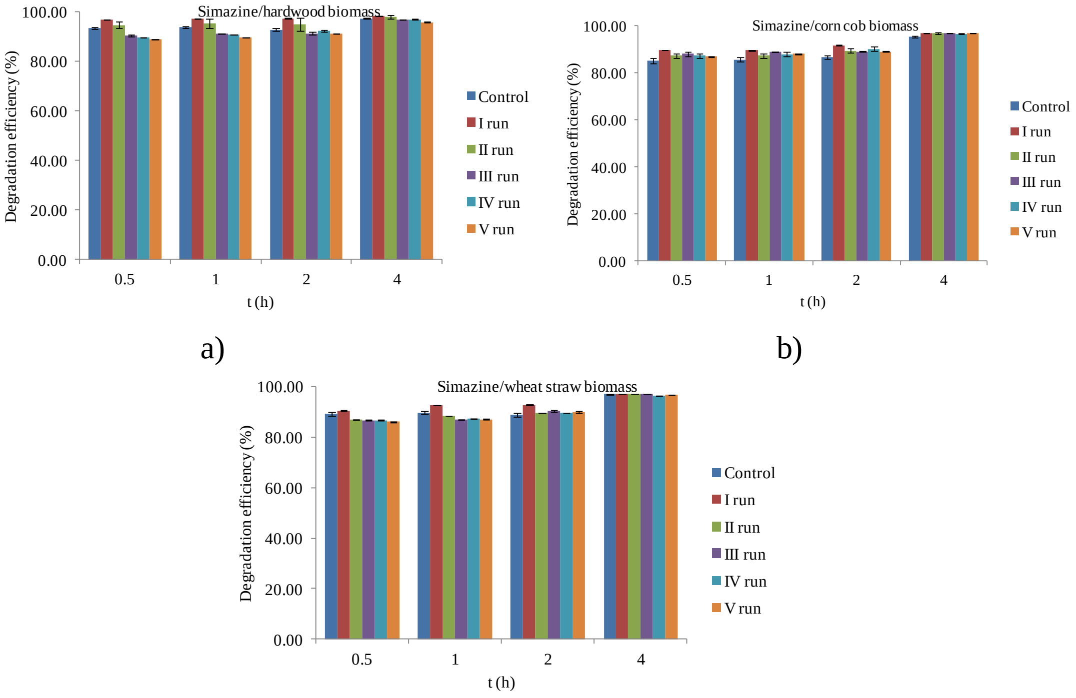
a) b)

c)

Figure 1. Degradation efficiency of atrazine (c_0=100 µg/L) over five consecutive reuse cycles: persulfate dose 3 mM; contact time: 0.5-4 h; catalyst: biochar (c=0.2 g/L), pyrolyzed at 700 °C, derived from: a) hardwood biomass, b) corn cob biomass, c) wheat straw biomass; pH 7.02

The degradation performance of simazine in the same systems is shown in Figure 2 (a-c). In contrast to atrazine, the efficiency of simazine remained highly stable across all reuse cycles for each BC type. Only negligible variations were observed between consecutive runs, confirming that no significant deactivation occurred during repeated use. Hardwood BC (Figure 2a) maintained nearly constant efficiency (> 90 %) throughout all five cycles, while corn cob (Figure 2b) and wheat straw BC (Figure 2c) also preserved similarly high and stable degradation rates. This consistent performance suggests that simazine interacts differently with the catalyst surface compared to atrazine, resulting in less fouling or blockage of active sites.

In our previous research [18], the reusability of BC produced from hardwood and wheat straw at 700 °C was investigated in PS-based systems for the degradation of organochlorine pesticides, lindane and β-endosulfan. The results revealed that the removal efficiency of lindane decreased markedly with successive cycles, particularly when wheat straw BC was used, whereas β-endosulfan exhibited much higher stability, with only a slight decline after multiple reuses. These findings, together with the present results for atrazine and simazine, demonstrate that the long-term catalytic performance of BC in PS oxidation systems is governed by the interplay between the physicochemical properties of the catalyst and the molecular characteristics of the pesticides. Differences in molecular structure, polarity, and reactivity among pesticides determine the extent of surface fouling and deactivation of active sites, thereby controlling the overall stability and reusability of BC during repeated catalytic use.



a) b)

c)

Figure 2. Degradation efficiency of simazine (c_0=100 µg/L) over five consecutive reuse cycles: persulfate dose 3 mM; contact time: 0.5-4 h; catalyst: biochar (c=0.2 g/L), pyrolyzed at 700 °C, derived from: a) hardwood biomass, b) corn cob biomass, c) wheat straw biomass; pH 7.02

Conclusion

The results of this study confirm that BC can be effectively reused over multiple pesticide degradation cycles while maintaining high catalytic activity. The stability and performance of BC were found to strongly depend on the feedstock origin and its structural features, with hardwood-derived BC exhibiting the most consistent catalytic behavior. The nature of the pesticide also influenced the preservation of activity during repeated use, as differences were observed between atrazine and simazine, with the latter showing more stable degradation throughout all cycles.

These findings highlight the strong potential of BC as a sustainable and reusable catalyst in PS-based advanced oxidation processes for water treatment. Future studies should focus on optimizing regeneration strategies and enhancing the long-term durability of the catalyst.

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COST-BENEFIT ANALYSIS AS A DECISION-SUPPORT TOOL FOR THE ASSESSMENT OF INNOVATIVE CONSTRUCTION MATERIALS

Jovana Topalić[1*], Slavica Ražić[2]

[1]*University of Novi Sad - Faculty of Technical Sciences, Novi Sad, Serbia*
[2]*University of Belgrade – Faculty of Pharmacy, Belgrade, Serbia*
* jovanatopalic90@uns.ac.rs

Abstract

The introduction of innovative materials in the construction industry requires careful evaluation to ensure their economic viability and long-term performance. Cost-benefit analysis (CBA) provides a structured framework for comparing new materials with conventional alternatives by quantifying key parameters, such as production costs, service life, energy consumption, and maintenance requirements. Beyond economic efficiency, CBA can incorporate environmental and regulatory considerations, supporting more informed, sustainable material selection.

This paper discusses the potential of CBA as a practical tool in early-stage assessment of novel construction solutions. By identifying relevant input parameters and outlining methodological steps, the aim is to demonstrate, through qualitative analysis, how CBA can guide decision-making in material development and application, particularly in contexts where performance, sustainability, and cost must be balanced.

Key words: *cost-benefit analysis, construction, materials*

Introduction

In recent decades, the construction sector has been identified as a major contributor to global economic growth and to ecological footprints [1,2]. It is estimated that buildings worldwide consume over 40 percent of global energy annually, according to a 2019 report by the Global Building Alliance [3]. Additionally, estimates indicate that these built-up structures are responsible for up to one-third of total carbon emissions, amounting to 10 gigatons of CO_2, as stated by the United Nations Environment Program in its Emission Gap Report 2020 [4]. The literature highlights the role of the public sector — primarily national governments — in mitigating the negative impacts of construction activity.

In [5], it is stated that in 2023, buildings accounted for 32 per cent of global energy demand and 34 per cent of CO_2 emissions, with operational emissions reaching a record 9.8 gigatons, while embodied carbon was around 2.9 gigatons (Figure 1). Despite a minor reduction in embodied carbon emissions and increased adoption of renewable energy, 17 percent of total buildings' energy demand by 2023—efficiency improvements remain insufficient to meet the Paris Agreement goals. The [5] highlights both positive trends—such as the increased adoption of renewable energy, the electrification of heating and cooling, and the growing uptake of green building certifications—and persistent challenges, including inadequate policy frameworks, limited green financing, and the high embodied carbon of conventional materials.

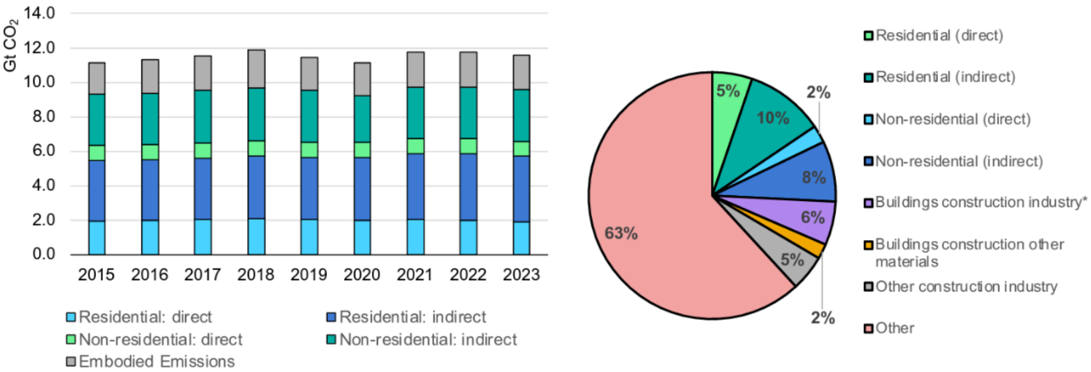

Figure 1. CO_2 emissions in buildings 2010–2023 (left) and share of buildings in global energy and process emissions in 2023 (right) (International Energy Agency 2024a) [5]

Energy-efficient buildings are designed to reduce the amount of energy required for their construction, operation, and eventual decommissioning. These buildings employ a combination of sustainable construction materials, advanced design techniques, and state-of-the-art energy management systems to minimize energy consumption [6]. As rapid urbanization continues, demand for energy-efficient buildings grows not only for environmental reasons but also for economic and social well-being. In [7], innovative construction materials emphasize that traditional materials contribute to environmental degradation, high energy use, and large maintenance costs; it calls for self-healing concrete, carbon-absorbing bioplastics, and energy-efficient composites that improve durability while reducing carbon footprints and long-term costs. The integration of such materials into construction practices could drastically reduce emissions, energy consumption, and waste.

Alongside the search for novel materials, there is a growing interest in circular construction practices and recycling. The Global Status Report notes that recycled materials accounted for approximately 18 percent of construction inputs in Europe in 2023 [5], yet the embodied carbon of primary materials remains a significant source of emissions. These insights underscore the importance of evaluating innovative materials not only for their performance but also for their broader environmental and social implications.

Cost-benefit analysis (CBA) provides a structured framework for comparing alternative construction solutions. It systematically quantifies and monetizes both the costs (initial investment, operation, and maintenance) and the benefits (e.g., energy savings, reduced carbon emissions, reduced maintenance) of a project over its service life. In construction projects, CBA has long been used to evaluate infrastructure investments and is increasingly applied to assess circular-economy projects, alternative materials, and waste-management strategies [8]. The methodology encompasses both a quantitative assessment of initial and lifecycle costs and a qualitative evaluation of factors such as health, safety, and cultural values [9]. The "ratio of costs and associated benefits" is central to CBA; poor data quality can lead to misleading conclusions.

Beyond traditional financial metrics, CBA can integrate environmental and social impacts. Lifecycle assessment (LCA) and scenario analysis complement CBA by quantifying embodied energy, GHG emissions, and other environmental impacts throughout a building's lifecycle. When combined, these methods enable decision-makers to strike a balance between economic efficiency and sustainability, providing a comprehensive basis for selecting innovative construction materials.

This paper examines the application of cost-benefit analysis as a decision-support tool for evaluating innovative construction materials. After presenting the methodological steps and input parameters needed to apply CBA, the paper synthesizes findings from recent case studies on Compressed Stabilized Earth Blocks, green materials, timber structures, and net-zero-energy buildings (NZEBs). The discussion highlights how CBA can inform material selection by considering cost, performance, and environmental impacts. Therefore, the question arises whether applying a cost-benefit analysis to new materials can show that sustainable construction is not only ecologically but also economically justified, which we will investigate in this paper.

Methodology: Conceptual framework for cost-benefit analysis

This study includes a qualitative analysis of studies on the implementation of cost-benefit analysis. The cost-benefit analysis of construction materials consists of four main steps [10]:

1. Establishing the framework of the analysis.
2. Identifying costs and benefits.
3. Quantifying and monetizing impacts.
4. Interpreting results and performing sensitivity analysis.

1. The baseline is typically a conventional material (e.g., fired clay bricks or reinforced concrete), while the alternative is an innovative material (e.g., Compressed Stabilized Earth Blocks, engineered timber, or advanced insulation). The building or component under study must meet the same functional requirements across alternatives (e.g., structural capacity, thermal performance).
2. Identifying costs and benefits: Costs include initial production and installation, maintenance, replacement, and end-of-life. The cost-benefit methodology for historic housing emphasizes evaluating both initial and lifecycle costs and stresses that qualitative factors, such as health and safety, should also be considered [9]. Benefits consist of energy savings, reduced maintenance, extended service life, improved indoor comfort, and reduced carbon emissions. Environmental benefits can be converted into monetary terms using carbon pricing or by accounting for avoided externalities.
3. Quantifying and monetizing impacts: Both costs and benefits are estimated over the study period, often the building's service life (30–50 years). Costs and benefits are expressed in monetary units to facilitate comparison; the ratio of total benefits to total costs, or the net present value (NPV), is calculated [8]. Input should be based on reliable data; poor data quality undermines the validity of the analysis [8]. Discount rates reflect the time value of money and are tested through sensitivity analysis.
4. Interpreting results and performing sensitivity analysis. A benefit-cost ratio (BCR) greater than 1 or a positive NPV indicates that the benefits outweigh the costs. Sensitivity analyses examine how results change across different discount rates, energy prices, and service-life assumptions. Qualitative factors (e.g., heritage value, health impacts) are assessed alongside quantitative results to inform decision-making [9].

Results

For qualitative analysis, four studies that implemented CBA to analyze new materials or engineering solutions are selected. In [11], a comparative cost–benefit analysis of CSEB and conventional, red-fired bricks in social housing is presented. The analysis emphasizes lifecycle thinking,.as a priority although unit prices can be comparable or marginally higher for CSEB, lower embodied energy during production, and improved thermal performance translate into reduced lifecycle costs. Additional social co-benefits include reliance on local soil resources and low-skilled labor, with a simple three-step production sequence (soil preparation, compression, curing) supporting community uptake. Overall, the study indicates that CSEB can outperform fired bricks on a lifecycle basis when energy and maintenance savings are monetized in CBA.

In [12], the substitution of conventional materials with "green" alternatives (e.g., recycled aggregates, fly-ash concretes, bamboo elements, higher-performing insulation) is evaluated under a cost–benefit lens tied to green-rating improvements. The core finding is that upfront cost premiums are offset over time by operational savings (energy, maintenance) and by benefits that accrue through rating-linked incentives. The authors stress the importance of internalizing environmental externalities (e.g., via carbon pricing) in CBA so that benefit–cost ratios reflect avoided emissions and waste-management costs; where such externalities are recognized, the BCR of sustainable options improves.

In [13], two scenarios for a Romanian social-housing block — deep rehabilitation of the existing building versus construction of a new NZEB — are compared. Under baseline assumptions and a 30-year study horizon, both scenarios yield negative NPVs due to the project's social (non-profit) nature; however, the NZEB performs significantly better (NPV ≈ −2.61 M USD) than rehabilitation (NPV ≈ −3.05 M USD). Operating expenditures are also lower for NZEB over the analysis period, and sensitivity tests (discount rates, energy price paths) preserve NZEB's relative advantage. The study illustrates how CBA helps select the less unfavorable alternative when neither option is strictly profitable, thereby supporting more resilient public investment decisions.

In [14], a combined environmental-economic scenario analysis of a Finnish educational building is conducted, comparing a predominantly wood-framed solution with RC and hybrid alternatives. The wood-based option achieves substantial greenhouse gas reductions across lifecycle stages while remaining cost-competitive in typical configurations; hybrid systems can be tuned to further balance cost and carbon. The results challenge the presumption that low-carbon materials are inherently more expensive and demonstrate that, under reasonable scenarios, timber solutions can meet budget constraints while materially reducing embodied and operational impacts, as captured in LCAs and reflected in CBAs.

Discussion

The qualitative analysis of reviewed studies illustrates that CBA can inform decisions on innovative construction materials by quantifying trade-offs among cost, performance, and environmental impacts. By monetizing energy savings and environmental benefits, CBA often shows that sustainable materials yield long-term economic advantages despite higher up-front costs. For instance, Compressed Stabilized Earth Blocks and timber can reduce lifecycle costs and emissions, and NZEBs can outperform rehabilitation projects in terms of economic resilience.

However, CBA has limitations. Accurate results depend on the quality of input data; "garbage in, garbage out" applies [8]. Estimating future energy prices, discount rates, and service life introduces uncertainty. Some benefits—such as reduced accidents, improved occupant health, or cultural heritage value—are difficult to monetize. Additionally, the selection of discount rates can significantly affect the benefit–cost ratio; sensitivity analyses are essential for robust conclusions. CBA also tends to focus on monetary outcomes and may undervalue social and environmental aspects if they are not properly monetized. Integrating CBA with multicriteria decision-making and stakeholder engagement can address these shortcomings. CBA findings should also be viewed in the light of subsidy policies and regulations, which can further improve the profitability of sustainable materials.

Conclusion

Cost-benefit analysis is a powerful decision-support tool for evaluating innovative construction materials. It combines economic metrics with environmental and social considerations to provide a holistic assessment of alternative materials. The methodology involves defining functional requirements, identifying costs and benefits, monetizing lifecycle impacts, and interpreting results through benefit-cost ratios and sensitivity analyses. When integrated with lifecycle assessment and scenario analysis, CBA enables decision-makers to balance economic efficiency with sustainability.

Recent studies show that sustainable materials can be economically viable. Compressed stabilized earth blocks offer lower lifecycle costs and embodied energy than fired bricks, and wood-based structures reduce carbon emissions while remaining cost-competitive. A lifecycle CBA comparing rehabilitation with new NZEB construction revealed that the NZEB option had a less negative net present value and lower operating costs. Although some projects may not achieve positive NPVs, CBA highlights the relative advantages of higher-performance materials.

The main challenges in applying for CBA include data quality, uncertainty in future parameters, and the difficulty of monetizing non-financial benefits. Future research should focus on developing standardized methodologies for integrating environmental and social impacts into CBA, improving data availability for innovative materials, and combining CBA with multicriteria decision tools. Policymakers and practitioners should use CBA as part of a broader sustainability assessment to ensure that material choices align with economic, environmental, and social objectives.

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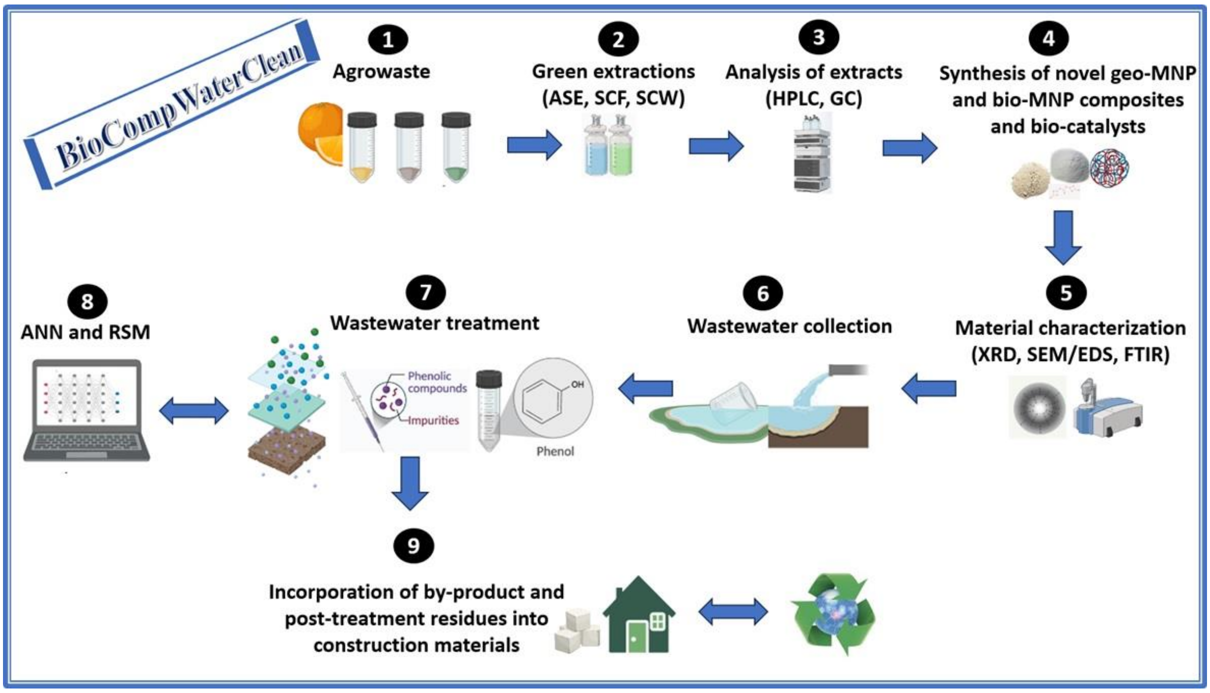
ABOUT

BIOCOMPWATERCLEAN PROJECT

The overall goal of the BioCompWaterClean project is to raise the scientific and innovative excellence in the field of phenolic contaminants removal from wastewater contributing to national and regional scientific and economic growth and well-being. The main objective of the Project implies the utilization of novel bio-functionalized magnetite-geopolymer composites for the removal of phenolic compounds from wastewater. BioCompWaterClean implements smart biowaste management principles in order to synthesize functionalized composites performing as valuable adsorbents/biocatalysts for wastewater treatment. In line with the principles of green and sustainable chemistry, the synthetic routes are being optimized toward minimization of energy and raw materials consumption. An additional element of the implemented smart biowaste management will include the proposed solution for the disposal of solid waste material remained after water treatment processes by its incorporation into the construction material. Therefore, the development of novel adsorbents/biocatalysts for phenolic wastewater treatment by combining the fundamental knowledge with tools of smart biowaste management will provide new opportunities for the development of modern lines for the purification of municipal and industrial wastewater, as well as the improvement of already existing water treatment systems, all in an attempt to reach zero-waste technology. The knowledge gained within this project will strengthen the scientific capacities of individual institutions and their participants, and by its extensive dissemination the collaboration with interested stakeholders will be intensified. This will create excellent starting conditions toward the establishment of circular economy in the wastewater treatment sector.



Full project title: Novel Bio-linked Magnetite/geopolymer Composites in Phenol-containing Wastewater Treatment: Toward Zero-waste Technology

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PI: Prof. Slavica Ražić, PhD

Project leader: University of Belgrade – Faculty of Pharmacy

Partner institutions: University of Novi Sad – Faculty of Technology Novi Sad, University of Novi Sad – Faculty of Sciences, University of Belgrade – Faculty of Civil Engineering, University of Novi Sad – Faculty of Technical Sciences

Website: https://biocompwaterclean.org/