PERSPECTIVES ON THE APPLICATION OF BIOCHAR PRODUCED FROM SEWAGE SLUDGE GASIFICATION IN WASTEWATER TREATMENT FOR HEAVY METALS REMOVAL

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Abstract: *Sewage sludge disposal, being a costly and environmentally and socially sensitive process, increasingly burdens utilities and municipalities. Therefore, thermal treatment processes, particularly gasification and pyrolysis, that minimize environmental impacts while simultaneously producing by-products that generate energy, are increasingly gaining importance. However, even in these processes, new by-products are generated and need to be properly disposed. At the same time, increasingly stringent requirements for wastewater treatment are emerging, particularly with anticipated amendments to the EU Directive and the introduction of the fourth level of treatment, primarily aimed at removal of micropollutants.*

This paper links these issues: by using biochar, obtained by sludge gasification, as an adsorbent for the removal of heavy metals from wastewater. As part of the preliminary research, a series of adsorption experiments on synthetic solutions containing selected heavy metals was conducted, resulting in exceptionally high removal efficiencies, mostly over 90%. The ultimate goal of the research is to examine various influencing factors and provide a perspective for the further sustainable disposal of biochar.

Keywords: *sewage sludge, gasification, biochar, adsorbent, heavy metals.*

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1. INTRODUCTION

Water resources management represents one of the key factors for the development of any region. In contemporary times, special attention is devoted to water protection, primarily due to the increasing need to preserve the environment, with an emphasis on biodiversity conservation and public health protection. Wastewater treatment and the disposal of by-products generated in the process have become globally significant issues, particularly over the past three decades. The rising trend in the construction of wastewater treatment plants (WWTPs) has led to the generation of substantial quantities of sewage sludge. In the wastewater treatment process, virtually every technological operation produces certain amounts of sludge as a by-product. As a member of the European Union, the Republic of Croatia is witnessing an increasing number of WWTP construction projects, which are expected to generate significant additional amounts of sewage sludge, making this issue increasingly relevant at the national level. According to available analyses on sewage sludge generation, the total production of sludge in Croatia by the year 2031 is estimated to reach between 78,000 and 100,000 tons of total solids per year (TS/year). Regions with the highest sewage sludge production include northwestern Croatia with the City of Zagreb, eastern Slavonia, Istria and Kvarner, and the Split-Dalmatia County (Nakić et al. 2024).

The complexity of sewage sludge management lies in the fact that the process is costly, environmentally, and socially sensitive, and must align with the principles of sustainable development while minimizing negative environmental impacts under increasingly stringent regulatory guidelines (Nakić et al. 2017). According to Eurostat data, in 2022 approximately 10,200,000 tons of total solids (TS) of sewage sludge were produced in 34 covered European countries, posing a significant environmental challenge. In this context, EU Directive 91/271/EEC explicitly supports the use of sewage sludge, stating in Article 14: "Sludge arising from wastewater treatment shall be re-used whenever appropriate. Disposal routes shall minimize the adverse effects on the environment." There are no universal rules for sludge management at the European level, but two main approaches can be distinguished. In Denmark, Estonia, Slovakia, France, Hungary, and Lithuania, the predominant method of sludge management is land application (on agricultural and non-agricultural land), while thermal treatment is most commonly used in Switzerland, Germany, Austria, Belgium, and Netherlands. Although practice offers various solutions and approaches to sludge management, only some of them are based on the principles of the circular economy and sustainable development, as also supported by Directive 91/271/EEC.

Among currently applied solutions, thermal treatment of sewage sludge stands out as a simple and increasingly used method in developed countries. This approach is gaining growing support due to its practicality and widespread application within the context of sustainable waste management. Particularly notable are relatively recent processes such as pyrolysis and gasification, whose main advantage over conventional incineration is the reduction of environmental impact. These processes generate a new by-product – biochar, a porous carbon material produced through the thermochemical degradation of biomass in the absence or near-absence of oxygen. Biomass can include various types of organic waste such as crop and forest residues, wood chips, algae, sewage sludge, manure, and organic municipal waste (Xiang et al. 2020). Simultaneously, the gasification and pyrolysis of sewage sludge also generate gas that can be utilized for energy production. The yield and composition of this gas, which mainly consists of methane (CH_4), carbon dioxide (CO_2), and hydrogen (H_2), vary depending on the temperature applied and the sludge composition. In general, pyrolysis and gasification processes yield high concentrations of H_2, as mineral components in sludge, such as calcium oxide (CaO), promote the production of H_2-rich syngas (Gopinath et al. 2021).

Biochar represents a stable carbon matrix with a large surface area and an abundance of oxygen-containing functional groups on its surface (Agrafioti et al. 2013). Biochar has gained significant attention for its effectiveness in addressing various environmental challenges, primarily due to its unique physicochemical properties like high specific surface area, microporosity, excellent adsorption capacity, and ion exchange capabilities. These attributes make biochar a versatile material with applications across multiple domains, including catalysis, energy production, soil quality improvement, composting, and adsorption (Rangabhashiyam et al. 2022). Among its most desirable features are its porosity and cost-effectiveness, which contribute to its suitability as a sustainable raw material. Consequently, biochar holds considerable potential as an alternative or complement to conventional activated carbon in adsorption processes (Zhang et al. 2019). Previous studies have shown that biochar can effectively remove certain heavy metals, nutrients (nitrogen/phosphorus), and other pollutants from water. However, removal efficiency depends on the origin of the biochar, pre-treatment methods, and the thermal treatment applied (pyrolysis or gasification). Some studies have reported that additives such as catalysts, metals, surfactants, industrial waste, and agricultural residues were added to raw sewage sludge prior to thermal treatment or mixed with it after carbonization to enhance the adsorption properties of biochar (Leng et al. 2015; Sing et al. 2020). This additional modification of biochar via various physical and chemical processes inevitably increases the costs within its application chain and may also result in additional environmental impacts.

Previous research has focused on the removal of heavy metals and metalloids, including arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), chromium (Cr), and copper (Cu), using various types of biochar (Gopinath et al. 2021; Shen et al. 2018; Xue et al. 2019; Zhang et al. 2019). Wei et al. (2018) used biochar derived from aerobic granular sludge for Cu^{2+} adsorption. Gao et al. (2019) reported effective Cd^{2+} adsorption onto biochar produced by co-pyrolysis of rice straw and sewage sludge, with significantly better performance than biochar made from sewage sludge alone. It was concluded that Cd^{2+} removal (76.1%–80.8%) resulted from cation exchange and precipitation. Fan et al. (2018) used biochar obtained from a mixture of sewage sludge and tea waste to remove cadmium, achieving removal efficiencies of 27.6%–30.8%. Ifthikar et al. (2018) developed magnetic biochar and biochar combined with carboxymethyl chitosan for the removal of Pb^{2+} and Hg^{2+}. Zuo et al. (2017) used $CaCO_3$-modified biochar for Cd^{2+} removal, with a maximum adsorption capacity of 6.5 mg/g. The mechanisms of heavy metal cation removal include physical adsorption, ion exchange, electrostatic attraction, surface complexation, co-precipitation, and physical entrapment (Ifthikar et al. 2017). All these studies demonstrate that biochar can effectively remove heavy metals through various mechanisms, often enhanced by specific physical or chemical modifications to improve its adsorption properties.

The industry has a significant impact on heavy metal concentrations in sewage sludge, as does the pre-treatment of industrial wastewater before discharge into the public sewage systems. The potentially most toxic heavy metals include arsenic, lead, mercury, and cadmium. Unlike organic pollutants, heavy metals are not biodegradable, contributing to their accumulation potential. They can dissolve and contaminate the environment even at low concentrations, indicating a strong need for safe disposal of waste materials containing them, including wastewater (Bubalo et al. 2022).

The fundamental premise of this study is the feasibility and justification of using biochar obtained from the gasification of sewage sludge in an experimental plant for the highly efficient removal of selected heavy metals (Cd, Cr, Cu, and Pb) from wastewater, using pristine, originally obtained biochar without any further modifications. Still, it should be noted that this study represents only preliminary research intended to serve as a foundation for future, more detailed investigations aimed at gaining a deeper understanding of adsorption mechanisms and conducting experiments with real wastewater samples, in order to identify potential methodological limitations and evaluate the feasibility of potential practical application.

2. MATERIALS AND METHODS

Stabilized and dewatered sewage sludge collected from the Karlovac WWTP, which operates at tertiary treatment level, including the removal of suspended solids, organic pollutants, as well as nitrogen and phosphorus compounds, was used to obtain biochar. The sludge was collected in sealed plastic containers and stored at room temperature until drying in a laboratory oven at 105°C to achieve a TS content exceeding 90%. The dried sludge was subjected to gasification in an experimental plant (Looper), shown in **Figure 1**. Gasification converts solid organic material (in this case, sewage sludge) into clean syngas and an inert solid residue. In subsequent stages, the syngas is cleaned of particulates and pollutants and then cooled. A small portion of the hydrogen-rich syngas (approximately 28–30% of the produced gas volume) is used to heat the superheater and reactor. The remaining syngas (around 70% of the generated volume) can be utilized for energy production or other purposes, such as pure hydrogen generation. This waste-to-syngas technology represents a controlled process with minimal carbon dioxide emissions and elimination of other harmful gaseous emissions, achieved by preventing oxygen ingress into the system and maintaining high process temperatures. It is applicable to all types of organic waste (Nakić et al. 2024). One of the remaining challenges being addressed within the broader scope of this research is the management of the residual by-product - biochar. In this study, the obtained biochar was further analysed and used as an adsorbent for the treatment of synthetic wastewater loaded with heavy metals.

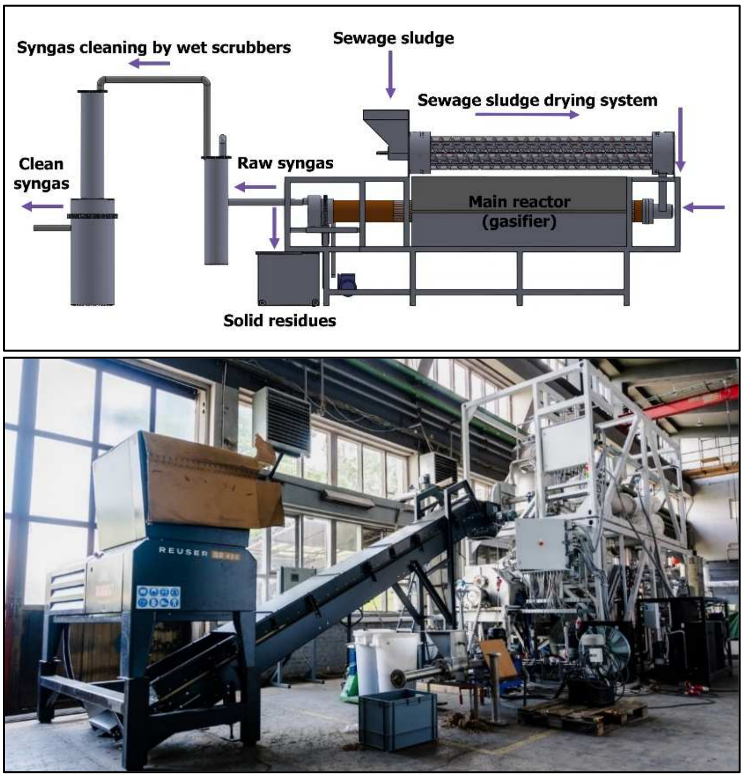

Figure 1. *Schematic diagram (top)* (Bubalo et al. 2022) *and photograph (bottom) of the pilot plant used for sludge gasification (Looper system)*

The chemical composition of the obtained biochar was determined using atomic absorption spectroscopy (instrument: Analyst 200, PerkinElmer, Inc., Waltham, MA, USA). The biochar sample was also analysed by energy-dispersive X-ray fluorescence (ED-XRF), employing a Siemens X-ray tube with a molybdenum (Mo) anode and Mo secondary target in orthogonal geometry. Spectra were analysed using IAEA QXAS software, and the concentrations of elements K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, As, Br, Rb, Sr, Y, Zr, Pb, and Th were determined by direct comparison of count rates with the standard reference material IAEA-SL-1 (Bubalo et al. 2023). Leaching tests were conducted in accordance with the EN 12457-2 standard. Prior to the analysis of heavy metals by atomic absorption spectrometry (PerkinElmer Analyst 800), filtrates were acidified with 1 mL of 65% nitric acid per 100 mL of sample to prevent undesired precipitation during sample storage (Nakić et al. 2017).

The morphology of the biochar samples was examined using scanning electron microscopy (SEM, Tescan Vega 3 instrument). To enhance conductivity for imaging, the samples were coated with chromium for 100 seconds using a Q150T coater (Quorum Technologies, UK). SEM micrographs were captured at various magnifications, providing detailed images with appropriate resolution.

Stock solutions of heavy metals used in the adsorption experiments were prepared by dissolving analytical-grade cadmium nitrate ($Cd(NO_3)_2$), copper (II) nitrate ($Cu(NO_3)_2$), lead (II) nitrate ($Pb(NO_3)_2$), and chromium (III) nitrate ($Cr(NO_3)_3$) in deionized water. Although some of the initial analyses were performed using lower initial concentrations (20 mg/L of each heavy metal), such relatively low concentrations resulted in very high removal efficiencies (approximately 99%) for all four metals under almost all tested conditions (varying pH, contact time, and biochar dosage). Therefore, the majority of the experiments were conducted at significantly higher initial concentrations (200 mg/L) in order to more clearly identify and evaluate the effects of the other investigated parameters (pH, biochar mass and contact time). The pH of each solution was adjusted to the desired values (3, 5, and 7) using 0.1 M HCl or 0.1 M NaOH. pH values were measured using a multiparameter instrument HI98194 (Hanna Instruments, Romania). Adsorption experiments were carried out in sealed 250 mL bottles containing 100 mL of individual heavy metal solutions and a specific amount of biochar (0.25 – 0.75 g). The bottles were placed on a rotary shaker (Reax 2, Heidolph, Germany) and agitated at 45 rpm at room temperature for predetermined contact times (up to 24 hours). After the defined contact time (adsorption period), the samples were filtered using syringe filters with a pore size of 0.45 μm to remove the biochar. Residual concentrations of cadmium, copper, lead, and chromium in the filtrate were determined by inductively coupled plasma optical emission spectrometry (ICP-OES) (Agilent 5900, Agilent Technologies, USA). The adsorption capacity of the biochar for each heavy metal was calculated using the **Equation 1**.

$$q_e = \frac{(C_0 - C_e) \cdot V}{m} \qquad (1)$$

where q_e is the adsorption capacity (mg/g), C_0 the initial concentration of the heavy metal (mg/L), C_e the equilibrium concentration of the heavy metal (mg/L), V the volume of the solution (L), and m the amount (mass) of biochar (g).

3. RESULTS

3.1. Main characteristics of used biochar

The results of the chemical composition analysis of the produced biochar, obtained using absorption spectrometry, indicate that the predominant oxide components are Al_2O_3 (15.6%), CaO (14.7%), and Fe_2O_3 (10.6%). Additionally, 49.1% of the total sample mass remained insoluble, which is attributed to the carbon-based fraction of the biochar.

The heavy metal content analysis of the biochar (**Table 1**) reveals extremely low concentrations of hazardous metals. Moreover, the presence of alkaline compounds, particularly calcium-based components and phosphates in the biochar is expected to further reduce leaching toxicity to levels well below environmental safety thresholds, thus supporting its safe application in various fields (Bubalo et al. 2023).

Table 1. Content of heavy metals and other potentially hazardous elements in the biochar used

CHEMICAL ELEMENT	UNIT	BIOCHAR SAMPLE
Fe	% mass	5
Zn	mg/kg	570
Cu	mg/kg	330
Cr	mg/kg	309
Sr	mg/kg	426
Pb	mg/kg	31
Ni	mg/kg	176
V	mg/kg	118
As	mg/kg	18
Th	mg/kg	< DL
K	% mass	1.22
Ca	% mass	19
Ti	mg/kg	4.921
Mn	mg/kg	606
Ga	mg/kg	7
Br	mg/kg	174
Rb	mg/kg	75
Y	mg/kg	57
Zr	mg/kg	482

**DL – detection limit*

Leaching tests were also conducted to assess the concentrations of elements (primarily heavy metals) that can be mobilized from the solid phase into the aqueous phase over time. These elements are considered potentially hazardous and bioavailable. The objective was to evaluate potential environmental risks and limitations associated with the use of the produced biochar. The obtained leachate concentrations were found to be exceptionally low, with several elements falling below detection limits (**Table 2**), consistent with previous studies (Chen et al. 2014; Hu et al. 2013).

Zinc (Zn) and lead (Pb) exhibited particularly low solubility in the biochar, as did arsenic (As), cadmium (Cd), copper (Cu), and nickel (Ni). Chromium (Cr) showed slightly higher, but still limited, solubility. In contrast, molybdenum (Mo) demonstrated relatively higher leachability; however, due to its very low initial concentration in the biochar, the absolute amount released remains minimal. These findings align with trends observed in earlier research (Nakić et al. 2017). Overall, heavy metals in biochar derived from sewage sludge appear to be stabilized, substantially reducing the risk of environmental contamination during its application (Zielinska et al. 2015). The key conclusion of this investigation is that the use of such biochar as an adsorbent in wastewater treatment appears both feasible and safe, with minimal concern for the release of potentially hazardous substances into the treated water. In other words, significant leaching of heavy metals or other problematic compounds from the biochar is not expected. Nevertheless, this conclusion should be regarded as preliminary, based on initial leaching assessments. Further research is required to confirm these findings, particularly under repeated-use scenarios involving multiple treatment cycles with the same biochar sample.

Table 2. Leaching results of the obtained biochar according to EN 12457 [mg/kg]

CHEMICAL ELEMENT	BIOCHAR SAMPLE
As	< DL
Ba	10,7
Cd	< DL
Co	0,006
Cr	0,36
Cu	< DL
Mo	0,825
Ni	< DL
Pb	0,007
Se	0,004
Zn	< DL

**DL – detection limit*

SEM micrographs (**Figure 2**) of the biochar reveal polydisperse grains and irregularly shaped particles with a coarse surface texture. The particles vary in both size and morphology, are considerably agglomerated, and form a porous, isomorphic mass. The micrographs clearly display a porous structure with numerous small channels and heterogeneous cavities distributed across the surface. This morphology provides a high specific surface area and a large number of active sites. The pores, which differ in size and shape, can influence adsorption efficiency in various ways.

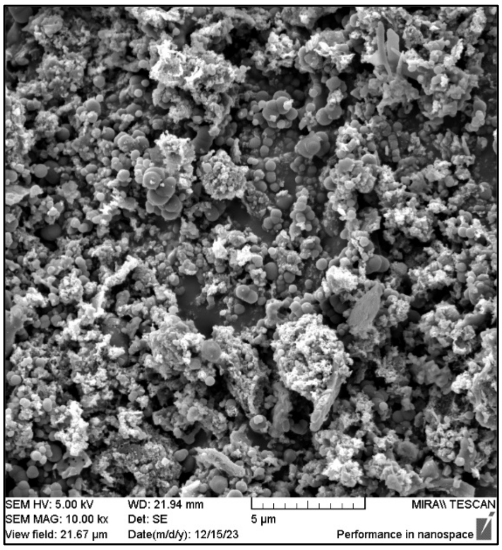

Figure 2. *SEM image of the obtained biochar*

Considering all the observed characteristics of the obtained biochar, it is concluded that this material exhibits promising potential for the adsorption of heavy metals from wastewater.

3.2. Results of the adsorption experiments

The experimental results demonstrated that the lowest removal efficiencies for all four analysed heavy metals were observed at low pH (3.0) and with the smallest amount of biochar used as the adsorbent (0.25 g). In contrast, the highest removal efficiencies were achieved under the following conditions: for cadmium and lead, with 0.5 g of biochar at pH 5; for chromium, with 0.5 g of biochar at pH 7; and for copper, with 0.75 g of biochar at pH 7.

As pH plays a critical role in both metal speciation and surface charge of the adsorbent, variations in pH can significantly affect metal removal performance. It is important to highlight that in all experiments using 0.5 g or 0.75 g of biochar at pH values of 5 or 7, very high removal efficiencies were recorded, exceeding 80% after 15 hours and over 95% after 24 hours. **Figure 3** illustrates the effect of pH on the removal efficiency of various metals, using 0.5 g of biochar and a reaction time of 15 hours.

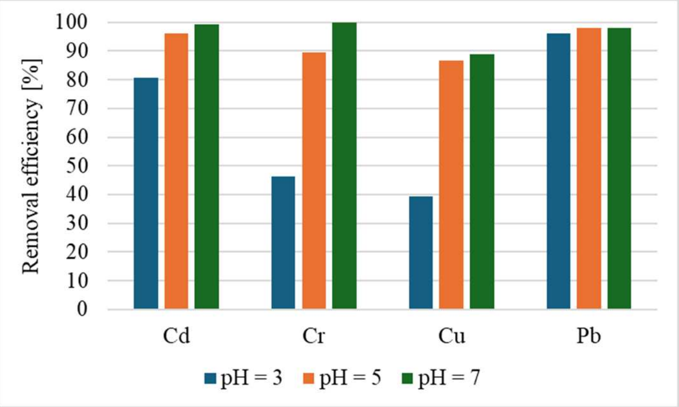

Figure 3. *Removal efficiencies of individual metals at various pH levels*
(Initial solution concentration: 200 mg/L; biochar mass: 0.5 g; reaction time: 15 h)

A clear increasing trend in the removal efficiency of selected metals is observed with increasing amounts of biochar (**Figure 4**), particularly when the dose is raised from 0.25 g to 0.50 g. However, further increases in biochar mass from 0.50 g to 0.75 g result in only marginal improvements, especially in the case of lead and copper.

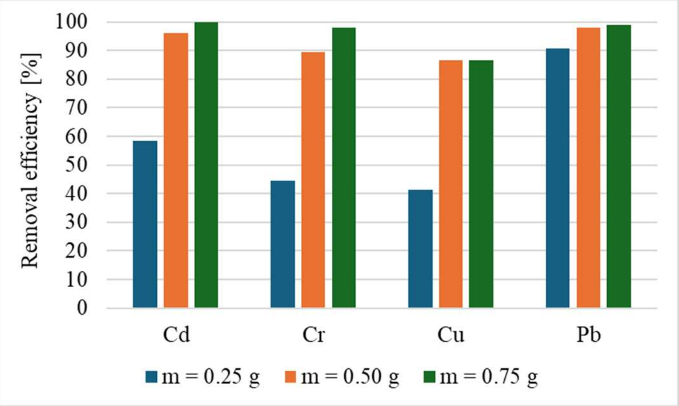

Figure 4. *Removal efficiencies of individual metals at various doses of biochar*
(Initial solution concentration: 200 mg/L; pH 5; reaction time: 15 h)

Figure 5 presents the removal efficiency of the four selected metals over time, for the case with an initial solution concentration of 200 mg/L, pH 5, and 0.5 g of biochar. This scenario clearly illustrates one of the main findings of the experimental series: the majority of contaminants, particularly cadmium and lead, are removed within the first 6 hours. After this initial phase, the removal process slows down, and after 15 hours, the removal rate becomes significantly reduced, virtually negligible for Cd and Pb.

When the results presented in **Figure 5** are expressed indirectly through adsorption capacity (calculated using **Equation 1**), the 24-hour reaction yields the following values: 38.67 mg/g for copper, 39.48 mg/g for lead, 39.79 mg/g for cadmium, and 39.83 mg/g for chromium.

The average adsorption capacities, based on the full set of experiments, were determined as follows: 16.96 mg/g for chromium, 17.40 mg/g for copper, 21.57 mg/g for cadmium, and 23.75 mg/g for lead.

The maximum adsorption capacities were obtained when the lowest amount of biochar (0.25 g) was used, specifically at pH 5 for cadmium (46.64 mg/g) and lead (72.66 mg/g), and at pH 7 for copper (42.42 mg/g) and chromium (43.89 mg/g).

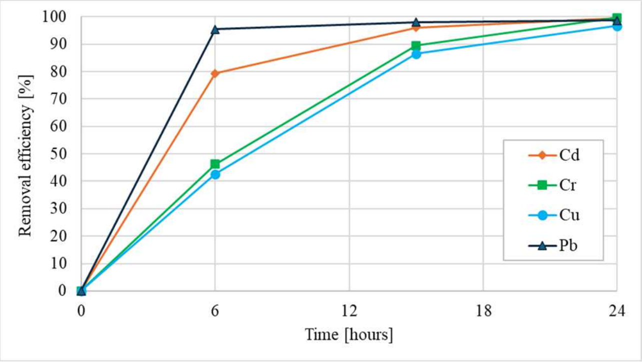

Figure 5. *Removal efficiencies of individual metals over time*
(Initial solution concentration: 200 mg/L; pH 5; biochar mass: 0.5 g)

In general, it was observed that mass transfer increases with higher initial concentrations of heavy metals in solution, i.e., as the initial concentration of metal ions rises, so does their adsorption onto the biochar surface. This clearly indicated that, at the applied biochar doses, particularly with 0.5 and 0.75 g, there were sufficient available adsorption sites on the biochar surface, a finding also reported by Wang et al. 2022. In the present study, it was also observed that, although very high removal efficiencies were achieved at both low (20 mg/L) and high (200 mg/L) initial concentrations of the investigated heavy metals, the utilization efficiency of biochar was significantly higher at the elevated concentrations. Specifically, a much greater adsorption capacity, as calculated using **Equation 1**, was obtained at higher initial concentrations.

On the other hand, an increase in biochar mass does not necessarily result in higher metal adsorption. While larger amounts of biochar positively influence removal efficiency, this effect plateaus beyond a certain point. Specifically, increasing the biochar mass from 0.25 g to 0.5 g led to improved removal efficiency in all cases, whereas further increases beyond 0.5 g showed additional improvements only in some cases.

Thus, although increasing the mass of biochar raises the number of available binding sites, if the number of sites exceeds the number of metal ions in solution, some of these sites remain unoccupied. Consequently, not all active sites are utilized, leading to a decrease in calculated adsorption capacity (Senthilkumar & Mogili Reddy Prasad 2020).

Overall, the adsorption of these heavy metals onto biochar derived from sewage sludge was found to be most favourable under slightly acidic to neutral pH conditions (pH 5–7).

The adsorption capacities of the biochar, as calculated using the results of this study and **Equation 1**, are largely consistent with those reported by Ye et al. (2022), who found values of 40.8 mg/g for Pb and 24.2 mg/g for Cd for biochar derived from different biomass types (e.g., manure and cherry wood).

Unlike most previous studies that focused on the use of modified sewage sludge or chemically modified biochar, this study preliminarily confirms the potential of pristine, unmodified biochar derived from sewage sludge for the efficient removal of selected heavy metals from wastewater. This underscores the economic and environmental benefits of utilizing unmodified biochar, especially when compared to more resource-intensive modification processes.

Considering the results of earlier studies (Nakić et al. 2024) that focused on the removal of heavy metals (Cd and Pb) and nutrients (NH_4^+ and PO_4^{3-}), the current research further confirms the effective removal of Cd, Cr, Cu, and Pb, all of which must be prioritized for removal before discharging due to their harmful effects on aquatic life and the broader ecosystem. In addition, previous investigations (Bubalo et al. 2022; Nakić et al. 2018) have demonstrated the feasibility of using this type of biochar as a substitute construction material, pointing to its broad applicability. This supports the concept of multi-stage reuse: initially as an adsorbent for wastewater treatment, and subsequently, as its adsorption capacity is exhausted, as a construction material. This approach supports multiple sustainable development goals and principles of the circular economy, where a waste product from one industry (wastewater treatment) becomes a valuable resource both within that industry and across others, such as the construction materials sector.

4. CONCLUSION

With the increasing number of WWTPs worldwide, the issue of sewage sludge disposal has become increasingly pressing. Despite a wide range of available technological solutions, most are characterized by high costs and considerable environmental impacts. Current global approaches to sludge disposal aim to align with the core principles of sustainable development. In line with EU directives, use of sewage sludge is encouraged whenever possible, with a strong emphasis on minimizing environmental harm.

Gasification, a high-temperature sludge treatment method, offers significantly lower emissions of harmful gases compared to other thermal processes, making it a promising focus for further research. When considering the biochar produced via gasification of sewage sludge (as in this study), it emerges as a potentially valuable material, readily available, relatively low-cost to produce on an industrial scale, and effective in removing heavy metals from wastewater. These characteristics support the principles of circular economy and sustainable waste management.

The results presented in this study confirm the significant potential of biochar derived from sewage sludge gasification, produced in an experimental pilot plant, for use as an adsorbent in the removal of selected heavy metals from synthetic wastewater at the laboratory scale. Experimental data identified the conditions under which removal efficiencies for cadmium, chromium, copper, and lead exceeded 99%. An optimal treatment duration of 15 hours was determined for all four metals. Additionally, all analysed metals were more effectively adsorbed under neutral to slightly acidic conditions, whereas adsorption efficiency declined under strongly acidic conditions. Increasing the mass of biochar improves heavy metal adsorption up to a certain point; however, if there are more available binding sites than metal ions, the calculated adsorption capacity decreases due to underutilized active sites.

The primary advantage of this study compared to previous ones lies in the achievement of exceptionally high heavy metal removal efficiencies using unmodified, pristine biochar, obtained directly from sewage sludge gasification as a byproduct, without any chemical or physical modifications. This implies a simpler and more cost-effective practical application. A key distinction from biochars used in other global studies lies in the unique production method employed (experimental Looper gasification unit) and the specific composition of the resulting biochar, which is dominated by residual carbon. This carbon acts similarly to activated carbon, functioning as the main adsorbent for heavy metal removal.

Moreover, the potential for multiple applications of this biochar has been highlighted, initially as an adsorbent for wastewater treatment, and subsequently, once its adsorption capacity is exhausted, as a substitute material in the construction industry. Previous studies on the same type of biochar have already confirmed its applicability in such secondary roles.

Overall, biochar produced by sewage sludge gasification demonstrates strong potential as an efficient and economical adsorbent for wastewater treatment. This contributes directly to the circular economy by reducing sludge disposal costs and enabling the reuse of sludge-derived byproducts for heavy metals removal. Although the primary aim of this study was not to evaluate the exact mechanisms underlying the adsorption of selected heavy metals onto biochar, understanding these mechanisms is essential for gaining insight into the interactions between metal ions and the adsorbent surface. Moreover, adsorption mechanisms critically influence the kinetics, thermodynamics, energy profiles, and overall adsorption capacity. Therefore, further studies are needed to deepen the understanding of adsorption mechanisms (containing detailed analysis of adsorption models and a description of kinetics), assess the potential for reusability in multiple treatment cycles, with particular attention to the potential for secondary pollution, by evaluating the possible leaching of other contaminants from the biochar, which is especially important given that the biochar used in this study is derived from waste material. Nonetheless, considering the preliminary leaching assessment of the biochar and the relatively low leaching levels detected, the risk of secondary pollution appears to be minimal. Future work will also involve testing with real wastewater samples and assessing the suitability of spent biochar for applications in the construction materials industry, once its adsorption capacity has been fully exhausted, which would also enable an assessment of cost-effectiveness and provide a more realistic picture of the potential for practical application. This should also include an investigation of the effectiveness of biochar application in continuous flow systems (e.g., flow-through column filters), as these more accurately reflect real-world applications compared to simplified laboratory batch experiments.

5. ACKNOWLEDGMENTS

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