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RECENT ADVANCES IN AZITHROMYCIN REMOVAL THROUGH THE BIOCHAR

Nijendra Pratap Singh[1,2], *Shivam Singh*[1], *and Amit Kumar*[*1]

Address(es):
[1] Department of Biotechnology, Sharda School of Engineering and Technology, Sharda University, Greater Noida (UP), India.
[2] Department of Biotechnology, Anand Engineering College, Agra (UP), India.

*Corresponding author: baliyaniitr@gmail.com

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ABSTRACT

Azithromycin contamination is one of the environmental concerns worldwide and it has been included in the EU's watch list for emerging contaminants in the aquatic environment. It is imperative to decrease azithromycin's environmental footprint from the environment in sustainable ways. Azithromycin remediation can be carried out either by adsorption through biochar or microbial degradation. Biochar-based adsorbents are produced using various feedstocks, including waste products. The use of biochar for contaminants removal is an economic and environmentally sustainable approach. Biochar adsorption mechanism involves surface complexation, weak van der Waals' forces, π-π bonding, electrostatic interactions, and H-bonding. Physico-chemical properties of biochar affect the adsorption and removal of azithromycin. Several chemical, thermal, electrochemical, and microwave-aided regeneration methods being used for recycling biochar those are essential for the cost-effectiveness of the process. This also fits with worldwide tendencies toward sustainable development and a circular economy. The latest research on the elimination of azithromycin by using biochars has been discussed in this review.

Keywords: Azithromycin, Adsorption, Engineered biochar, Emerging contaminant, Remediation

INTRODUCTION

Azithromycin is one of the most regularly prescribed medications for bacterial infections. The use of macrolides such as azithromycin is increasing **(Hao *et al.*, 2020)**. Azithromycin contaminant is distributed worldwide. It is reported that the main sources of azithromycin pollutants are hospital wastewater, fish farms, human and animal feces, urine, and pharmaceutical industry. It is now easier to evaluate the risk of contaminants in water that are not yet regulated, with azithromycin included in the EU's watch list for emerging problems in the aquatic environment **(Robert *et al.*, 2018)**. **Velpandian *et al.* (2018)** found that the level of azithromycin in surface water of NCR was70 ± 170 ngL^{-1}. The azithromycin concentration in cow milk samples has been found to be 9708.7 μg kg^{-1} **(Kurjogi *et al.*, 2019)**. Azithromycin was found in municipal wastewater in the city of Zagreb, with concentrations ranging from 0.27 to 22.7μgL^{-1} **(Senta *et al.*, 2019)**.

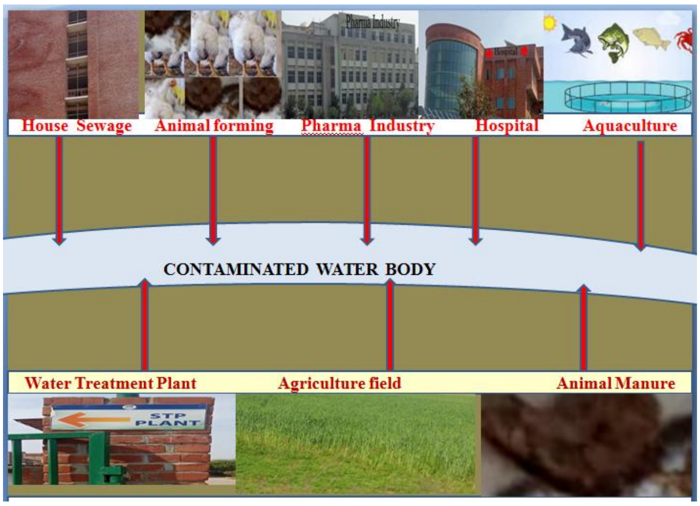

Figure 1 Sources of azithromycin contamination

Azithromycin has even been found across various water bodies, it include wastewater (**Grela *et al.*, 2023**), drinking water (**Ślósarczyk *et al.*, 2021**), surface water (**Guardo *et al.*, 2024; Ilie *et al.*, 2023**), cave water (**Oppeltová *et al.*, 2024**), groundwater (**Arun *et al.*, 2022**), seawater (**Mirzaie *et al.*, 2022**), sediments (**Mirzaie *et al.*, 2022**) and even soil and milk (**Kurjogi *et al.*, 2019**). Azithromycin levels in water and wastewater exceed recommended limits. The availability of azithromycin in the environment has been reported to be 0–500 ng L^{-1} **(Cruz *et al.*, 2021; Mariano *et al.*, 2023)**, but in some cases up to 10000 ng L^{-1} **Figure 1 (Wu *et al.*, 2021).** Azithromycin contaminates water bodies that have adverse effects on aquatic organisms. Fish and other aquatic life may experience toxicity, reproductive problems, and behavioral changes **(Li *et al.*, 2020)**. It can disrupt the balance of microbial communities in water ecosystems, affecting overall ecological health **(Huang *et al.*, 2021b; Pinto *et al.*, 2022)**. Pollution of environmental systems with antibiotics such as azithromycin leads to enrichment of antibiotic resistance genes (ARGs) in bacterial populations **(Konopka *et al.*, 2022)**. The enrichment of ARGs in bacteria is caused by selective pressure of antibiotics on bacterial population. It favors the survival and spreading of antibiotic resistant bacterial strains **(Green, 2022)**. Ammonia-oxidizing bacteria (AOB) are essential for the nitrogen cycle, converting ammonia to nitrite. Exposure to antibiotics affects the abundance and activity of AOB **(Beduk, 2023; Liu *et al.*, 2019; Zhou et al., 2024)**. The enrichment of resistant genes disrupts their ecological function and imbalances nitrogen cycling processes **(Beduk, 2023)**. This has widespread impacts on the ecosystem, affecting plant growth, water quality, and overall ecosystem health **(Sidhu *et al.*, 2019)**. These resistance genes can be transferred horizontally between bacterial species, leading to the spread of antibiotic resistance among microbial communities **Figure 2 (Tao *et al.*, 2022)**. Azithromycin has also been found to accumulate in some plant species. The extent of bioaccumulation azithromycin is depending on factors such as soil composition, plant species, and exposure duration **(Carballo, *et al.*, 2021; Sidhu, *et al.*, 2019; Zhang, *et al.*, 2023)**. The accumulation of azithromycin was reported in both roots and shoots of lettuce (*Lactuca sativa*) **(Almeida *et al.*, 2021)**. Several other studies have reported bioaccumulation of azithromycin in various plant species, including grasses. Bioaccumulation in plants does not directly harm them, it mainly concerns about the potential transfer of azithromycin through the food chain **(Sidhu *et al.*, 2019)**. Azithromycin is an antibiotic that targets bacteria, so it is not inherently toxic to plants. However, like many pharmaceuticals, it has unintended effects on non-target organisms **(Almeida *et al.*, 2021; Mao *et al.*, 2021).** The exposure of azithromycin to plants causes minor stress responses and changes in physiological processes but is unlikely to cause serious toxicity at normal environmental concentrations **(Krupka *et al.*, 2021)**.

Azithromycin, like many drugs, may have effects on human health, particularly during pregnancy and in individuals with certain sensitivities **(Kong *et al.*, 2024; Lu *et al.*, 2023)**. Studies on the teratogenic risk of azithromycin have produced mixed results, with some finding a small increase in the risk of some birth defects, while others found no significant association. While serious toxicity is rare, azithromycin has also been associated with potential hepatic toxicity, cardiovascular effects (such as QT prolongation), and gastrointestinal disturbances **(Almeida,*et al.*, 2021; Choi *et al.*, 2018; Mao *et al.*, 2021; Ribeiro *et al.*, 2024).**

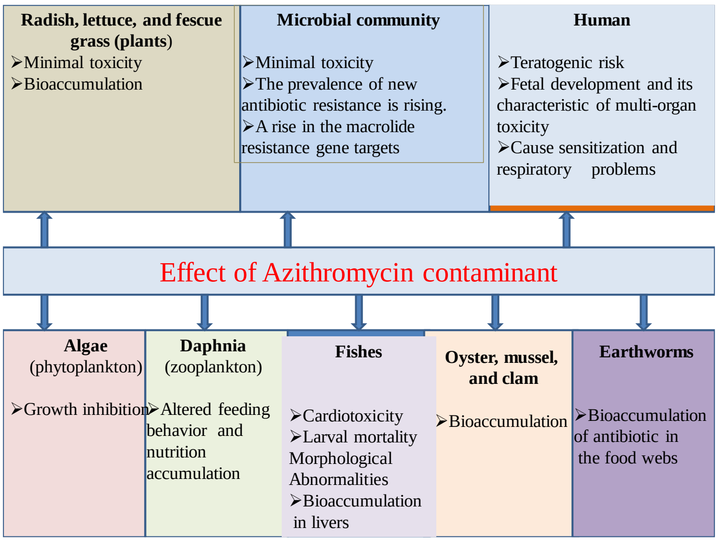

Figure 2 Effect of azithromycin on different biota **(Almeida *et al.*, 2021; Mao *et al.*, 2021; Ribeiro *et al.*, 2024; Shearer *et al.*, 2022)**.

There are lot other methods used for remediation of azithromycin e.g. biodegradation, adsorption, advanced oxidation processes, coagulation and electrocoagulation etc. **(El *et al.*, 2023**; **Imwene *et al.*, 2022; Gopalakrishnan *et al.*, 2023; Hübner *et al.*, 2024; Jalali *et al.*, 2023**; **Mao *et al.*, 2021; Padmaja *et al.*, 2020; Shokri *et al.*, 2019)**. Biodegradation processes are effective against low-concentration of azithromycin. Biodegradation organism are inhibited at higher concentrations of azithromycin **(El *et al.*, 2023**; **Mao *et al.*, 2021).** Advanced oxidation agents have poor solubility in water, require more energy, and produce more toxic products than the parent compounds **(Gopalakrishnan *et al.*, 2023; Hübner *et al.*, 2024)**. Coagulation and electrocoagulation produce a large amount of sludge that needs to be treated and disposed. Electrocoagulation (EC) is a process that involves supplying electric current through sacrificial electrodes to remove pollutants from wastewater **(Padmaja *et al.*, 2020)**. The remediation of azithromycin with biochar can be an environmentally friendly alternative. One of the most obvious reason is its biodegradability, as it usually comes from organic wastes **(Awah and Hendricks, 2024).** The high adsorption capacity of biochar is particularly useful for antibiotics removal (**Ighalo *et al.*, 2022; Lee *et al.*, 2021**). It has a large surface area and a porous structure that significantly improves adsorption capacity (**Mane *et al.* 2024; Satyam and Patra, 2024**). The stable activity of biochar makes it a versatile and effective material for various applications (**Ighalo *et al.*, 2022**). Biochar as a cost-effective and environmental-friendly. The modified biochar obtained at higher pyrolysis temperature have large specific surface area, high pore volume and abundant functional groups favorable for the adsorption process.

Azithromycin is used in humans and animals for skin ulcers, respiratory tract, acute sinus, ear infections, tonsillitis, acute exacerbation of chronic bronchitis, community-acquired pneumonia, throat infections, pelvic floor inflammation, cervical and urinary tract infections **(Firth and Prathapan, 2020; Abruzzo *et al.*, 2022)**. They are often used in combination with other drugs to treat various infectious disorders. Macrolides are natural compounds that contain a large lactone ring containing a deoxy sugar **(Patel and Hashmi, 2023)**. Azithromycin is a macrolide antibiotic that is very effective in treating bacterial infections (**Oliver and Hinks, 2020**). Due to its broad spectrum of immunomodulatory, antibacterial, antiviral, and anti-inflammatory capabilities, it is administered to patients with coronavirus SARS-CoV or MERS-CoV **(Choi *et al.*, 2018; Dejani *et al.*, 2021; Oliver and Hinks, 2020)**.

Challenges associated with azithromycin removal

Azithromycin is often present in environmental matrices at low concentrations, particularly in surface water and wastewater **(Arun *et al.*, 2022; Cela-Dablanca *et al.*, 2022, 2024)**. Sensitive analytical methods and efficient treatment technologies are required to detect and effectively remove azithromycin at these trace levels **(Cestarolli 2021; Guerra and Kabir, 2021; Montone *et al.*, 2024)**. Azithromycin is commonly found in municipal wastewater, hospital effluents, and agricultural runoff, which contain a diverse range of organic and inorganic compounds. The emergence of other contaminants can interfere removal processes as well as affect the efficiency of treatment methods (**Martínez-Polanco *et al.*, 2022; Samal *et al.*, 2022; Cela-Dablanca *et al.*, 2022; Löffler *et al.*, 2023**). Understanding the fate, behavior of azithromycin and its transformation products is valuable to developing effective removal strategies **(Harrower *et al.*, 2021)**. To ensuring effective adsorption on biochar surfaces is challenging due to factors such as competition with other organic and inorganic compounds present in the environment **(Kurniawan *et al.*, 2023)**. Azithromycin is challenging to remove due to its physicochemical properties**.** A molecule is considered sufficiently volatile if its K_H value is greater than 3×10^{-3} mol/δm^{-3}/Pa. Volatility is an important factor determined by this constant. However, antibiotics have very low K_H values making their extraction by evaporation difficult **(Bubonja-Šonje, *et al.*, 2020; Epps and Blaney, 2016; Huang *et al.*, 2021a)**. Excessive amounts of suspended particles in wastewater increase turbidity that prevents sunlight from reaching the upper layer and prevents the photodegradation of azithromycin (Wu et al., 2020). The concentration of azithromycin in wastewater can vary depending on factors such as population demographics, healthcare practices, and seasonal variations in antibiotic use **(Giebultowicz *et al.*, 2020; Mirzaie *et al.*, 2022)**. This variability complicates the design and operation of wastewater treatment systems to effectively target and remove azithromycin **(Al-Wasify *et al.*, 2023; Phoon *et al.*, 2020**).

Table 1 Removal of azithromycin by different biochars

Adsorbent	Azithromycin removal efficiency	Reference
Microalgae-derived nitrogen-doped porous activated carbon	98.5%	**(Ameen *et al.*, 2023)**
Pines Cons	87.8	**(Aziz *et al.*, 2024)**
Rice husk, impregnated with montmorillonite	33.4 mg g^{-1} and 44.73 mgg^{-1}	**(Arif *et al.*, 2023)**
ZIF-8/Zeolite composite	85% in 10 cycles	**(Liu *et al.*, 2023)**
Molecularly imprinted polymer	Over 80%	**(Xie *et al.*, 2023)**
Rice husk	95%	**(Herrera *et al.*, 2022)**
Azolla filiculoides based activatedporous carbon	87% and 98%	**(Balarak *et al.*, 2021)**
Raw saponin-modified nano diatomite	68 mg g^{-1} and 91.7 mg g^{-1}	**(Davoodi *et al.*, 2019)**
Pines Cons based Fe modified	88%	**(Aziz *et al.*, 2024)**
Pines Cons based Fe modified	85 % mixture of Azithromycin and Ciprofloxacin	**(Aziz *et al.*, 2024)**
Oak ash	9600 µmol kg^{-1}, meaning >80% retention	**(Cela-Dablanca *et al.*,2024)**
Pine bark	8280 µmol kg^{-1}, 69%	**Cela-Dablanca *et al.*, 2024)**
Mussel shell	between 3000 and 6000 µmol kg^{-1}, 25–50% retention	**Cela-Dablanca *et al.*, 2024)**

Remediation of azithromycin

Azithromycin contamination can be reduced in the future by using precautionary measures such as reducing the number of prescriptions and preventing excessive use of azithromycin **(Konopka *et al.*, 2022; Pavlinac *et al.*, 2017)**. Removal rates of azithromycin have been less than 55% in conventional wastewater treatment facilities **(Cela-Dablanca *et al.*, 2022; Talaiekhozani *et al.*, 2020).** Existing methods to eliminate azithromycin from aquatic ecosystems have shown no effectiveness, therefore development of new strategies is required **(Amalina *et al.*, 2022a).** Biochar is a type of char produced through the pyrolysis of biomass, such as agricultural waste, wood chips, and manure **(Amalina *et al.*, 2022a; Khater *et al.*, 2024)**. Biochar is produced through a pyrolysis process. In this process, organic materials are heated in the absence of oxygen. Pyrolysis causes the decomposition of the material and produces a solid residue with high carbon content (**Kalina *et***

***al.*, 2022; Yaashikaa *et al.*, 2020).** There are hydroxyl (-OH) and carboxyl (-COOH) groups on the surface of biochar. Because these groups biochar participates in hydrogen bonding and other interactions with azithromycin, its absorption makes it more potent **(Murtaza *et al.*, 2022; Kainth *et al.*, 2024)**.

The use of pine-based biochar to remediate azithromycin contamination is a simple, cost-effective, and beneficial approach to reduce the impact of antibiotic contamination on soil and water **(Ameen *et al.*, 2023; Monisha *et al.*, 2021)**. Rice husk soaked with montmorillonite biochar is an attractive concept for azithromycin treatment **(Song *et al.*, 2020)**. Rice husk biochar impregnating with montmorillonite and activated by carbondioxide was reported as an economical and sustainable adsorbent for the azithromycin removal **(Arif *et al.*, 2023)**. The porous structure of biochar provides a large surface area for azithromycin adsorption. In biochar montmorillonite composite and saponin-modified nanodiatomite provide additional binding sites (**Arif *et al.*, 2023; Davoodi *et al.*, 2019)**. This combination potentially increases the efficiency of removal of azithromycin from water, thereby contributing to environmental cleanup efforts. Rice bran is a renewable and low-cost material for azithromycin removal. Biochar prepared from rice bran has the capability to remediate 33.4 mg g^{-1} and 44.73 mg g^{-1} azithromycin under specific environmental conditions. It showed the azithromycin removal efficiency by 95% **(Herrera *et al.*, 2022; Li *et al.*, 2023; González-Hourcade *et al.*, 2022; Shi *et al.*, 2019)**. Montmorillonite clay has a layered structure with high cation exchange capacity, which enables it to remediate azithromycin through various interactions such as electrostatic forces, hydrogen bonding, and van der Waals forces **(Perelomov *et al.*, 2021; Uddin 2018)**. Thus this enhances adsorption capacity of the composite material. *Azolla filiculoides* based biochar is another interesting material that could be applied in various fields **(Kimani *et al.*, 2020)**. *Azolla filiculoides* biomass as feedstock for biochar production provides a sustainable and environmentally friendly approach to remediate azithromycin. **(Olugbenga *et al.*, 2024).**

Process optimization

It is important to optimize parametric conditions for effective removal of higher concentrations of azithromycin from a sample solution, (**Mojahedimotlagh *et al.*, 2024)**. Several variables including temperature, pH, initial concentration, dosage of biochar, and contact time determine the maximum amount of azithromycin adsorbed (**Balarak *et al.*, 2021)**. It is necessary to predict the ideal parameters for the efficient removal of azithromycin using biochar in batch condition. Using a central composite design to maximize the efficiency of azithromycin release from mesoporous silica is more effectual approach than performing exhaustive 'one-at-a-time' optimization for each process variable affecting the SBA-15 adsorption process **(Shen *et al.*, 2021)**. This method allows more streamlined optimization process for azithromycin removal (**Ibham *et al.*, 2023)**. Azithromycin remediation is most effective in acidic pH, when the pH increases to the alkaline range, effectiveness declines. Response Surface Methodology (RSM) is a statistical technique that combines modeling to optimize variables. RMS is using for reducing costs, saving time, minimizing errors, and reducing the number of runs required **(Ibham *et al.*, 2023; Stylianou *et al.*, 2021)**. This methodology has proven to be very effective in various sectors. It can be applied to raise the standard of research, development, and production processes **(Gholamian *et al.*, 2021)**. The use of RSM offers significant benefits, particularly in identifying variables critical to a process in a single activity. RSM is using for reducing the number of trials required for optimization. However, RSM is not commonly used for macrolides such as azithromycin, for which further work is required in the field to improve the capacity (mg/g) and adsorption effectiveness. RSM was employed for optimization of parameters such as temperature, concentration, and duration to remove macrolides **(Madondo *et al.*, 2022)**.

Mechanisms of azithromycin removal by biochar

Azithromycin remediation by biochar is mainly driven by adsorption on biochar surface, with contributions from surface complexation, pore entrapment, and potential ion exchange processes **(Sen *et al.*, 2023).** Mechanisms of biochar and azithromycin interactions is essential to optimize the performance of biochar-based treatment systems for azithromycin removal. It has been reported that H-bonding, O=C, –OH, and –NH2 functional groups reside on the biochar and azithromycin surface **(Arif *et al.*, 2023; Gholamian *et al.*, 2021; Ribeiro *et al.*, 2024; Upoma *et al.*, 2022).** Azithromycin is primarily absorbed through π–π, electron donor acceptor interactions, involving the lactam ring on the macrolide and the ring on the adsorbent **(Shearer *et al.*, 2022)**. The absorption process involves ion exchange, hydrogen bonding, electrostatic interactions, and π–π electron-donor-acceptor interactions (**Hassan et al., 2020**). Electrostatic interactions occur between the cationic form of the macrolide and anionic surface of the adsorbent **(Jia *et al.*, 2024; Upoma *et al.*, 2022)**. **Figure 3** shows that a carbon dioxide-activated biochar montmorillonite composite is an effective, long-lasting, and reasonably priced adsorbent for removing azithromycin from contaminated water. Rice husk-based biochar, with its highly porous structure and large surface area, provides sufficient space for the physical adsorption of azithromycin molecules **(Herrera *et al.*, 2022; Shi & Liu 2021).** Azithromycin has been adsorbed on the surface of rice husk biochar through weak van der Waals forces and other physical interactions. Surface complexation involves the formation of adsorbents on the surface of rice husk biochar depending on the number of chemical complexes between azithromycin molecules and specific functional groups **(Kanth *et al.*, 2024)**. The mechanism involves the exchange of ions between the biochar surface and the azithromycin molecules in solution. All biochars generally follow similar mechanisms for the removal of azithromycin pollutants **(Arif *et al.*, 2023; Kainth *et al.*, 2024)**

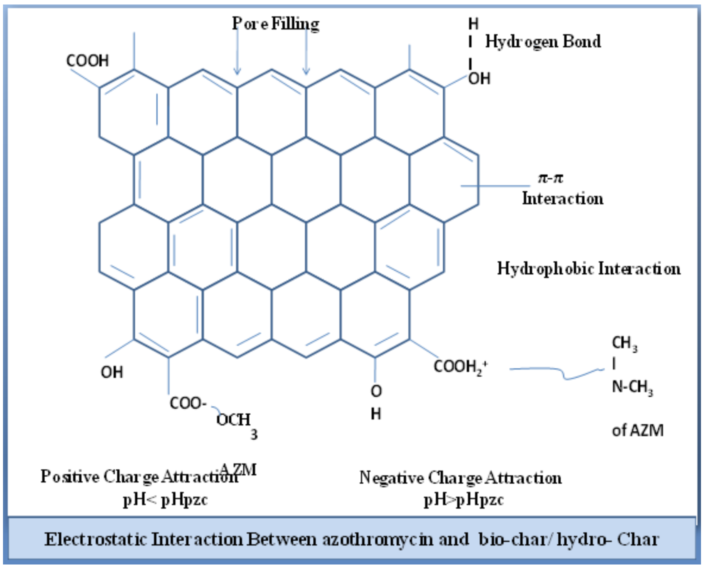

Figure 3 Mechanism of azithromycin adsorption on biochar

Physico-chemical properties of medium affecting the adsorption of azithromycin

The physicochemical properties of the medium play an important role in influencing the adsorption of azithromycin on adsorbents such as biochar. The batch experiment focused on the removal of azithromycin from liquid systems via adsorption on the surface of granular activated carbon prepared with non-reactive adsorbent **(Stylianou *et al.*, 2021; Upoma *et al.*, 2022)**. The adsorption process involves the adsorption of azithromycin on activated carbon, and is highly dependent on various physical parameters. The treatment of pharmaceuticals involves several operational factors such as azithromycin using agarose-based adsorbents. Effect of pH, initial pharmaceutical concentration, adsorbent dose, temperature and contact time are some of these variables shown in **Figure 4 (Arif *et al.*, 2023; Davoodi *et al.*, 2019; Dong *et al.*, 2024; Ribeiro *et al.*, 2024;Wahab *et al.*, 2021).**

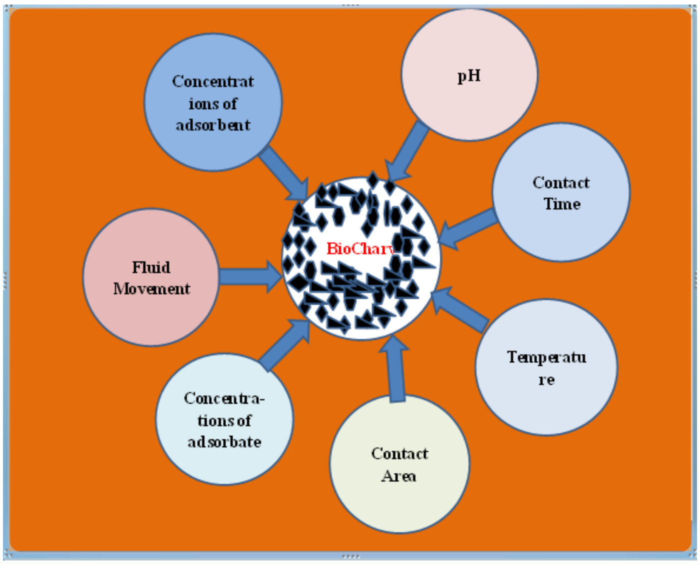

Figure 4 Physico-chemical properties affect adsorption

The results of the adsorption process showed that the R-ND and M-ND methods achieved maximum elimination of azithromycin at a concentration of 20 ppm and a contact time of 60 min. The removal percentages are 99.5% and 98.5% respectively **(Davoodi *et al.*, 2019)**. The removal of azithromycin by α-HNPs had a significant effect on the adsorbent mass effect, which showed that increasing the dosage of adsorbent α-HNPs to 150 mg increases the azithromycin adsorption capacity. This results in an increase in αHNPs. The removal efficiency increased to some extent with each mass increase of adsorbent **(Amin *et al.*, 2023)**. The findings indicate that increasing the dosage of adsorbent enhances azithromycin removal. As the biochar penetrates and the total surface area expands, the elimination of azithromycin also increases **(Arif *et al.*, 2023)**. *Azolla filiculoides* based biochar has been used to study the effects of adsorption time and temperature. *Azolla filiculoides* based biochar has high capacity and efficiency to eliminate azithromycin. The adsorption procedure proceeds rapidly in the initial stage due to the large pore volume and high surface area of the adsorbent. This first stage is followed by a slower stage. The final stage is an equilibrium stage **(Balark *et al.*, 2021)**. The solubility of the adsorbent in water and the degree of dissociation are directly and indirectly affected by temperature, which has a significant impact on the adsorption process **(Al-Ghouti & Al-Absi 2020; Wahab *et al.*, 2021)**.

The efficiency of azithromycin removal is affected by pH level of the solution due to the inherent characteristics of azithromycin **(Upoma *et al.*, 2022; Saita *et al.*, 2018)**. The azithromycin molecule assumes different conformations depending on the pH of the solution. As a result of the antibiotic and dissociation constant, changes in pH level can affect the electrostatic interactions between the sludge and azithromycin, which in turn affects the removal efficiency of azithromycin **(Petropoulos, *et al.*, 2009; Saita, *et al.*, 2018)**. The pH value exceeds 9.0 and ranges up to 11.0. It is also confirmed that azithromycin has a pKa of 8.7, which has higher adsorption capacity than the unmodified saponin molecule. It may be important to note that this change may also result in the addition of more hydroxyl groups which may further increase the adsorption capacity. Diatomite has a pH of about 2.5 and its surface is negatively charged above that point. Azithromycin and diatomite have opposite charge at the pH range of 2.5 to 8.7, resultant that the electrostatic attraction take place. A pH of 11 is considered an ideal pH due to high electrostatic interactions that enhance the interaction between raw diatomite and azithromycin molecules **(Shearer *et al.*, 2022)**. Mechanisms such as H-bonding may also be responsible for the increased negative surface charge of the adsorbent, since pH 11 is higher than the pKa of azithromycin **(Davoodi *et al.*, 2019)**. According to de Sousa, electrostatic interactions and H-bonding generate negative charges on the zeolite surface at acidic pH levels. While it was previously believed that adsorption occurred mostly along the surface groups of the zeolite, the azithromycin molecules may be blocked by acidic sites present in the internal channels of the zeolite due to steric hindrance. However, the ideal pH for azithromycin adsorption is 6.5 if it becomes prorogated **(Aguiar *et al.*, 2018)**.The main mechanism of action appears to be electrostatic attraction, as seen from reduced adsorption at pH 7. Therefore, pH plays an important role in electrostatic interactions and adsorption. The surface charges of the composites revealed how pH affected the adsorption loading **(Liu *et al.*, 2019, 2023)**. Maximum adsorption occurred at a neutral pH of 8. The adsorption capacity is reduced when both the contaminant and adsorbent surfaces have the same positive charge at pH values below 7. Azithromycin surface charge and dissociation constant (pKa) explain, how pH of the solution affects the adsorption capacity of AFAC (*Azolla filiculoides* activated carbon) **(Balarak *et al.*, 2021)**. The pH of the solution is affected by the oxygen functional groups which are available on the surface of the adsorbent that affect the ability of the adsorbent to remove antibiotics from the solution. The surface charge of the adsorbent changes as a result of the presence of H$^+$ or OH$^-$ ions in the solution, which ultimately affects its effectiveness in removing antibiotics **(Zhang *et al.*, 2023)**. The presence of OH$^-$ ions in solution causes deprotonation of surface functional groups at pH values lower than pH 7. The functional groups will be precipitated when the pH value becomes higher than the pHpzc of the point of zero charge, due to the presence of H$^+$ ions in the solution **(Balarak *et al.*, 2021)**. The surface of AFAC is more positively charged than pHpzc at a lower pH, i.e. 8.45 **(Balarak, *et al.*, 2021; Zhang, *et al.*, 2023)**.

The pH level also affects the solubility and dissociation of the adsorbent, leading to better interaction with the adsorbent. The pKa value of azithromycin is approximately 8.5, which means that at pH 8.543, 50% of azithromycin is unionized (not charged) and 50% ionized **(Herrera *et al.*, 2022)**.When it comes to the removal of azithromycin through adsorption, this process is less effective in solutions with lower pH levels (2.0-4.0). Starting at 20.8%, the removal rate of azithromycin increases only marginally to 22.2%. It was observed that the surface electrostatic attraction force between the drug azithromycin and α-HNPs (hematite nanoparticles) gradually increases up to pH adsorption levels higher than 8.0 **(Al-Hakkani *et al.*, 2022)**. This behavior is particularly noticeable at pH 10.0, where the elimination percentage reaches approximately 79% **(Ameen *et al.*, 2023)**. The effect of pH on the degradation ability of phytate-modified biochar depends on the pyrolysis temperature of the biochar; However, it had no obvious effect on non-amended biochar **(Hua *et al.*, 2022)**. The solubility of the adsorptive in water and the degree of dissociation are both directly and indirectly affected by temperature, which usually has a significant effect on the adsorption process **(Robinson *et al.*, 2022)**.

Regeneration of biochar

Regeneration of biochar involves restoring its adsorption capacity and effectiveness after it has been used to remove contaminants from water or other media **(Alsawy *et al.*, 2022; Jagadeesh and Sundaram, 2023**). One of the key factors in assessing the feasibility and cost-benefit ratio of a material is its regeneration capacity. Operating, purchasing, and preparation costs of adsorbent are reduced through the reuse process. The percentage of regeneration varies for deionized water, NaOH, HCl, and ethyl alcohol **(Januario *et al.*, 2021)**. The ideal regeneration conditions not only created excellent structure effect relationships between physical and chemical properties but also successfully controlled the competition. There is a close connection between the deep carbonization process and the adsorption/oxidation site repair process **(Jay *et al.*, 2023)**. Direct thermal regeneration involves heating biochar to high temperatures, typically between 400°C and 800°C, in an inert atmosphere such as nitrogen or argon **(Zhan *et al.*, 2023)**. Steam regeneration involves heating biochar in the presence of steam at temperatures ranging from 300°C to 700°C. Biochar derived from rice husk and subjected to thermal treatment at temperatures between 450°C and 600°C has shown significant removal efficiencies for azithromycin, achieving over 95% removal from pharmaceutical effluents **(Ajala *et al.*, 2023; Kang, *et al.*, 2022)**.

The electrochemical regeneration of biochar impregnated with azithromycin is an innovative approach that combines the principles of electrochemistry and sustainable remediation. This method involves using an electric current to induce redox reaction. It can regenerate the adsorption capacity of biochar. It allow reutilization of the biochar-azithromycin composite **(Li *et al.*, 2019; Zhou *et al.*, 2021)**. A new technology is used for recycling spent activated biochar based on hydrothermal treatment at a temperature of 160–320 °C. Treatment at 280°C is sufficient to completely decompose azithromycin **(Nouioua *et al.*, 2023; Wurzer *et al.*, 2023)**. Biological regeneration of biochar impregnated with azithromycin involves utilizing microbial activity. Microbes having capability to degrade or metabolize the adsorbed antibiotic on the biochar surface.

This process harnesses the natural capabilities of microorganisms and enzymes to break down organic compounds, such as azithromycin, into simpler, less harmful substances **(Amalina *et al.*, 2022b; Jayakumar *et al.*, 2021).** Magnetically active biochar-zeolite composites are washed with methanol, ultrasonicated in distilled water, and coated with polymers for their regeneration. Biochar and hydrochar are regenerated using different techniques. Each regeneration technique has some advantages and disadvantages as shown in **Table 2 (Amalina *et al.*, 2022b; Hassan *et al.*, 2020; Mishra *et al.*, 2023; Nouioua *et al.*, 2023; Wurzer *et al.*, 2023)**.

Table 2 Advantage and disadvantage of different regeneration methods

Type of method	**Advantages**	**Disadvantages**
Biological	-Natural and Sustainable -Low cost -Long effectiveness	-Slow Treatment rates -Site specific requirement -Risk of incomplete remediation
Hydrothermal	-Mild condition -Effective desorption -Environmental friendly -Versatile	-Energy intensive -Long treatment time -Complex operation -Limited effectiveness
Chemical	-Easy - Reduction of carbon loss - Higher recovery of the adsorbents & regeneration	- Referring to both the effectiveness of regeneration and the structural characteristics. - Less recoveries
Electrochemical	- In-situ operation - Lowe energy consumption - Moderate temperatures - Chemicals are not use	Generation of strongly bound compounds - At low pollutant concentrations, the efficiency of current for organic decomposition is diminished
Microwave-aided Regeneration	-Short treatment time - Energy consumption Lower - High restoration of carbon porosity	-The effectiveness of the regenerated samples in adsorbing various pollutants cannot be assured
Thermal	- Easy -Widely used	-Harmful products generation - High carbon loss

Effect of biochar properties on azithromycin adsorption

Biochars undergo an extensive characterization process to determine their adsorption capacity **(Muhammad *et al.*, 2024)**. The assessment takes into account several important elements, including surface area, micropore volume, total number, and total pore volume. The properties of biochar significantly influence its adsorption capacity and the plant's ability to remove azithromycin **(Castiglioni *et al.*, 2021; Jagadeesh and Sundaram, 2023)**. As the temperature in the pyrolysis increases, the surface area and structure of the char improves. Much attention has been paid to the creation of engineered biochar with a large porous structure and large surface area. Chemical activation is most popular and efficient means to increase the surface area and porosity of biochar **(Alsawy *et al.*, 2022; Li *et al.*, 2022)**.The functional groups including -C=O and -C-O are generally associated with organic agricultural products that cover a significant part of the total pore volume **(Yuan *et al.*, 2021)**. It contains several surface functional groups for adsorption, including amino (−NH2), hydroxyl (−OH), and carboxyl (−COOH) **(Hassaan *et al.*, 2023)**.

Azithromycin bio-adsorption and sustainability

Azithromycin removal using biochar technology under line with several sustainability goals. It addresses the environmental impact of azithromycin, promotes clean water, supports responsible production practices and contributes to climate action. Biochar technology is an important step toward achieving a more sustainable and healthy future. It effectively removing azithromycin from water supplies, this way it prevents the spread of azithromycin-resistant bacteria and protects human health thereby contributing to UN Sustainability Goal 3. Biochar also improves water quality by removing azithromycin contaminants thereby contributing to safe and clean drinking water and meets UN Sustainability Goal 6. Producing biochar from agricultural waste promotes responsible resource use and reduces waste and meets UN Sustainability Goal 12. Biochar production and its use would achieve carbon sequestration leading into a possible contribution to climate change mitigation and meets UN sustainability Goal-13.

FUTURE PERSPECTIVE AND CHALLENGES

The future of biochar-based extradition of azithromycin holds great promise as a sustainable and effective solution. It holds the capability to address pharmaceuticals pollutants in wastewater. Optimized biochar materials may have the potential to extradicate azithromycin from complex water matrices by providing improved selectivity, efficiency, and recyclability. The overall removal efficiency can be raised by integrating biochar-based adsorption with other technologies on treatment, such as membrane filtration, advanced oxidation processes, and biological treatment. The challenges linked to azithromycin removal, such as recurrent contaminants and low concentration values, can be approached easily by biochar. Moreover, it will allow tracking and control of the total biochar-based adsorption process in real time during removal of azithromycin. However, non-conventional pyrolysis processes produce numerous by-products that include polycyclic aromatic hydrocarbons and volatile organic compounds; these may threaten the growth of microbes **(Bus *et al.*, 2022; Jose *et al.*, 2019; Yemele *et al.*, 2024)**. Biochar is difficult to recycle and leads to secondary pollution and increase costs **(Kosar *et al.*, 2024; Sarougi and Routray, 2024)**. The release of azithromycin from biochar depends on the type of biochar, the interaction between biochar and azithromycin, and the conditions **(Ngigi *et al.*, 2020; Patel *et al.*, 2022)**. Biochar's low density and small particle size make it challenging to remove from water after dissolving. Biochar may not be effective at immobilizing metals, hazardous substances and it might allow them to migrate through the soil **(Bus *et al.*, 2022)**. Biochar stability affects the mobility of metals and metalloids in contaminated soils. The production and application of nano-biochar is costly, and there is little information on its widespread use. In some cases it has been reported that nano-biochar has toxic effects on plants, mammals and soil microflora **(Rajput *et al.*, 2022)**. Interaction of nano-biochar with pollutants in the rhizosphere and their effect on plant-soil dynamics **(Sarma *et al.*, 2024)**.

CONCLUSION

Ecosystems are in a great risk because of widespread presence of azithromycin contaminants in the environment. Microbial communities, bioaccumulation in food chains are disrupted by these contaminants and contribute to increasing antibiotic resistance. To address this issue strict regulations are necessary. Biochars are innovative solutions that are needed for improved waste management, protection of health and minimizing environmental impact. Selection of appropriate biomass feedstock, thermal treatment methods where biomass is treated at high temperatures are the steps for the preparation and activation of biochar. Carbon content, stability and porosity are properties of the resulting biochar influenced by factors such as feedstock type, particle size, residence time and post-treatment processes of biochar. Biochar is an environmentally and sustainable resource for removal of antibiotics because of high surface area and adsorption capacity. Adsorbents based on biochar have varying adsorption and removal capacities for organic pollutants such as azithromycin, depending on the biomass source and the amendments applied. While common biochars achieve moderate to high efficiencies. Engineered -biochars with tailored properties exhibit improved adsorption, which is essential for achieving high removal rates. Therefore, biochar is a promising material for wastewater treatment, particularly for the removal of pharmaceuticals and other organic contaminants because this versatility.

REFERENCES

Abruzzo, A., Parolin, C., Rossi, M., Vitali, B., Cappadone, C., & Bigucci, F. (2022). Development and characterization of azithromycin-loaded microemulsions: A promising tool for the treatment of bacterial skin infections. *Antibiotics*, *11*(8), 1040. https://doi.org/10.3390/antibiotics11081040

Aguiar, D., Insa, S., Mozeto, A. A., Petrovic, M., Thiago Pereira Chaves, & Pedro Sergio F. (2018). Equilibrium and kinetic studies of the adsorption of antibiotics from aqueous solutions onto powdered zeolites. *Chemosphere 205*, 137–146. https://doi.org/10.1016/j.chemosphere.2018.04.085

Ajala, O. A., Akinnawo, S. O., Bamisaye, A., Adedipe, D. T., Adesina, M. O., Okon-Akan, O. A., Adebusuyi, T. A., Ojedokun, A. T., Adegoke, K. A., & Bello, O. S. (2023). Adsorptive removal of antibiotic pollutants from wastewater using biomass/biochar-based adsorbents. *RSC Advances*, *13*(7), 4678–4712. https://doi.org/10.1039/d2ra06436g

Al-Ghouti, M. A., & Al-Absi, R. S. (2020). Mechanistic understanding of the adsorption and thermodynamic aspects of cationic methylene blue dye onto cellulosic olive stones biomass from wastewater. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-72996-3

Al-Hakkani, M. F., Gouda, G. A., Hassan, S. H. A., Mohamed, M. M. A., & Nagiub, A. M. (2022). Environmentally azithromycin pharmaceutical wastewater management and synergetic biocompatible approaches of loaded azithromycin@hematite nanoparticles. *Scientific Reports*, *12*(1), 10970. https://doi.org/10.1038/s41598-022-14997-y

Al-Wasify, R. S., Alruwaili, M. M., Aljohani, F. S., Hamed, S. R., & Ragab, S. (2023). The efficiency of wastewater treatment plants for the removal of antibiotics. *IntechOpen EBooks*. https://doi.org/10.5772/intechopen.111999

Alsawy, T., Rashad, E., El-Qelish, M., & Mohammed, R. H. (2022). A comprehensive review on the chemical regeneration of biochar adsorbent for sustainable wastewater treatment. *Npj Clean Water*, *5*(1). https://doi.org/10.1038/s41545-022-00172-3

Amalina, F., Razak, A. S. A., Krishnan, S., Sulaiman, H., Zularisam, A. W., & Nasrullah, M. (2022). Biochar production techniques utilizing biomass waste-derived materials and environmental applications – A review. *Journal of Hazardous Materials Advances*, *7*, 100134. https://doi.org/10.1016/j.hazadv.2022.100134

Amalina, F., Razak, A. S. A., Krishnan, S., Zularisam, A. W., & Nasrullah, M. (2022). A comprehensive assessment of the method for producing biochar, its characterization, stability, and potential applications in regenerative economic sustainability – A review. *Cleaner Materials*, *3*, 100045. https://doi.org/10.1016/j.clema.2022.100045

Ameen, F., Reza Mostafazadeh, Yasamin Hamidian, Erk, N., Sanati, A. L., Karaman, C., & Ayati, A. (2023). Modeling of adsorptive removal of azithromycin from aquatic media by CoFe2O4/NiO anchored microalgae-derived nitrogen-doped porous activated carbon adsorbent and colorimetric quantifying of azithromycin in pharmaceutical products. *Chemosphere*, *329*, 138635. https://doi.org/10.1016/j.chemosphere.2023.138635

Ana Catarina Almeida, Gomes, T., Antonio, J., & Lillicrap, A. (2021). Specific toxicity of azithromycin to the freshwater microalga *Raphidocelis subcapitata*. *Ecotoxicology and Environmental Safety*, *222*, 112553–112553. https://doi.org/10.1016/j.ecoenv.2021.112553

Arif, M., Liu, G., Muhammad, Mian, M., Ashraf, A., Yousaf, B., Muhammad Saqib Rashid, Ahmed, R., Imran, M., & Mujtaba, A. (2023). Impregnation of biochar with montmorillonite and its activation for the removal of azithromycin from aqueous media. *Environmental Science and Pollution Research*, *30*(32), 78279–78293. https://doi.org/10.1007/s11356-023-27908-z

Arun, S., Xin, L., Gaonkar, O., Neppolian, B., Zhang, G., & Chakraborty, P. (2022). Antibiotics in sewage treatment plants, receiving water bodies and groundwater of Chennai city and the suburb, South India: Occurrence, removal efficiencies, and risk assessment. *Science of the Total Environment*, *851*, 158195. https://doi.org/10.1016/j.scitotenv.2022.158195

Asheghmoalla, M., & Mehrab Mehrvar. (2024). Integrated and hybrid processes for the treatment of actual wastewaters containing micropollutants: A review on recent advances. *Processes*, *12*(2), 339. https://doi.org/10.3390/pr12020339

Awah, C., Heynderickx, P.M. (2024). Hydrothermal carbonization of plastic waste: a review of its potential in alternative energy applications.*Fuel Communications*, 18, 100103–100103.https://doi.org/10.1016/j.jfueco.2023.100103

Aziz, S., Sundus Anbreen, Iftikhar, I., Fatima, T., Iftikhar, A., & Ali, L. (2024). Green technology: synthesis of iron-modified biochar derived from pine cones to remove azithromycin and ciprofloxacin from water. *Frontiers in Environmental Science*, *12*. https://doi.org/10.3389/fenvs.2024.1353267

Balarak, D., Mahvi, A. H., Shahbaksh, S., Wahab, M. A., & Abdala, A. (2021). Adsorptive removal of azithromycin antibiotic from aqueous solution by *Azolla filiculoides*-based activated porous carbon. *Nanomaterials*, *11*(12), 3281. https://doi.org/10.3390/nano11123281

Bubonja-Šonje, M., Knežević, S., & Abram, M. (2020). Challenges to antimicrobial susceptibility testing of plant-derived polyphenolic compounds. *Archives of Industrial Hygiene and Toxicology*, *71*(4), 300–311. https://doi.org/10.2478/aiht-2020-71-3396

Buss, W., Hilber, I., Graham, M. C., & Mašek, O. (2022). Composition of PAHs in biochar and implications for biochar production. *ACS Sustainable Chemistry & Engineering*, *10*(20), 6755. https://doi.org/10.1021/acssuschemeng.2c00952

Carballo, M., Rodríguez, A., & de la Torre, A. (2021). Phytotoxic effects of antibiotics on terrestrial crop plants and wild plants: A systematic review. *Archives of Environmental Contamination and Toxicology*, *82*(1), 48–61. https://doi.org/10.1007/s00244-021-00893-5

Castiglioni, M., Rivoira, L., Ingrando, I., Del Bubba, M., & Bruzzoniti, M. C. (2021). Characterization techniques as supporting tools for the interpretation of biochar adsorption efficiency in water treatment: A critical review. *Molecules*, *26*(16), 5063. https://doi.org/10.3390/molecules26165063

Cela-Dablanca, R., Barreiro, A., Lucía Rodríguez-López, Arias-Estévez, M., María Fernández-Sanjurjo, Álvarez-Rodríguez, E., & Avelino Núñez-Delgado. (2024). Azithromycin removal using pine bark, oak ash and mussel shell. *Environmental Research*, 119048–119048. https://doi.org/10.1016/j.envres.2024.119048

Cela-Dablanca, R., Barreiro, A., Rodríguez-López, L., Pérez-Rodríguez, P., Arias-Estévez, M., Fernández-Sanjurjo, M. J., Álvarez-Rodríguez, E., & Núñez-Delgado, A. (2022). Azithromycin adsorption onto different soils. *Processes*, *10*(12), 2565. https://doi.org/10.3390/pr10122565

Chan, J. F., Chan, K.H., Kao, R. Y., To, K. K. W., Zheng, B.-J., Li, C. P. Y., Li, P. T., Dai, J., Mok, F. K., Chen, H., & Hayden, F. G. (2013). Broad-spectrum antivirals for the emerging Middle East respiratory syndrome coronavirus. *Journal of Infection*, *67*(6), 606–616. https://doi.org/10.1016/j.jinf.2013.09.029

Choi, Y., Lim, H.-S., Chung, D., Choi, J., & Yoon, D. (2018). Risk evaluation of azithromycin-induced QT prolongation in real-world practice. *BioMed Research International*, 2018, 1–8. https://doi.org/10.1155/2018/1574806

Cruz, Pariente, M. I., R. Alfaro Molina, & Martinez, F. J. (2021). Advanced bio-oxidation of fungal mixed cultures immobilized on rotating biological contactors for the removal of pharmaceutical micropollutants in a real hospital wastewater.***Journal of Hazardous Materials***, *425*, 128002. https://doi.org/10.1016/j.jhazmat.2021.128002

Dai, Y., Zhang, N., Xing, C., Cui, Q., & Sun, Q. (2019). The adsorption, regeneration and engineering applications of biochar for removal organic pollutants: A review. *Chemosphere*, *223*, 12–27. https://doi.org/10.1016/j.chemosphere.2019.01.161

Davoodi, S., Dahrazma, B., Goudarzi, N., & Gorji, H. G. (2019). Adsorptive removal of azithromycin from aqueous solutions using raw and saponin-modified nano diatomite. *Water Science and Technology*, *80*(5), 939–949. https://doi.org/10.2166/wst.2019.337

Dejani N. N., Elshabrawy, H. A., Carlos, & de, P. (2021). Anticoronavirus and immunomodulatory phenolic compounds: opportunities and pharmacotherapeutic perspectives. *Biomolecules*, *11*(8), 1254–1254. https://doi.org/10.3390/biom11081254

Dong, X., Chu, Y., Tong, Z., Sun, M., Meng, D., Yi, X., Gao, T., Wang, M., & Duan, J. (2024). Mechanisms of adsorption and functionalization of biochar for pesticides: A review. *Ecotoxicology and Environmental Safety*, *272*, 116019. https://doi.org/10.1016/j.ecoenv.2024.116019

El, A., El-Bialy, H. A., & Gomaa, O. M. (2023). Biodegradation of COVID19 antibiotic; azithromycin and its impact on soil microbial community in the presence of phenolic waste and with temperature variation. *World Journal of Microbiology & Biotechnology*, 39(6). https://doi.org/10.1007/s11274-023-03591-7

Fatemeh M., Nasab E. A., Foroutan, R., Vakilabadi D. R., Dobaradaran, S., Azamateslamtalab, E. & Bahman R. (2024). Azithromycin decomposition from simple and complex waters by H_2O_2 activation over a recyclable catalyst of clay modified with nanofiltration process brine. *Environmental Technology & Innovation*, *33*, 103512. https://doi.org/10.1016/j.eti.2023.103512

Fatma Beduk. (2023). Combined effects of cadmium and azithromycin on soil nitrification Process. *Water*, *15*(5), 881–881. https://doi.org/10.3390/w15050881

Firth, A., & Prathapan, P. (2020). Azithromycin: The first broad-spectrum therapeutic. *European Journal of Medicinal Chemistry*, *207*, 112739. https://doi.org/10.1016/j.ejmech.2020.112739

Gholamian, S., Hamzehloo, M., Farrokhnia, A., & Mahdavifar, Z. (2021). Response surface methodology optimizing the adsorptive removal of azithromycin using mesoporous silica SBA-15: Mechanism, thermodynamic, equilibrium, and kinetics modeling studies. *Journal of Environmental Science and Health, Part A*, *56*(10), 1145–1164. https://doi.org/10.1080/10934529.2021.1974267

Gholamiyan, S., Hamzehloo, M., & Farrokhnia, A. (2020). RSM optimized adsorptive removal of erythromycin using magnetic activated carbon: Adsorption isotherm, kinetic modeling and thermodynamic studies. *Sustainable Chemistry and Pharmacy*, *17*,100309.https://doi.org/10.1016/j.scp.2020.100309

Gopalakrishnan, G., Jeyakumar, R. B., & Somanathan, A. (2023). Challenges and emerging trends in advanced oxidation technologies and integration of advanced oxidation processes with biological processes for wastewater treatment. *Sustainability*, *15*(5), 4235. https://doi.org/10.3390/su15054235

Giebułtowicz, J., Nałęcz-Jawecki, G., Harnisz, M., Kucharski, D., Korzeniewska, E., & Płaza, G. (2020). Environmental risk and risk of resistance selection due to antimicrobials' Occurrence in two Polish wastewater treatment plants and receiving surface water. *Molecules*, *25*(6), 1470. https://doi.org/10.3390/molecules25061470

Gracia-Marín, E., Rico, A., Fabregat-Safont, D., López, F. J., Félix Hernández, Pitarch, E., & Bijlsma, L. (2024). Comprehensive study on the potential environmental risk of temporal antibiotic usage through wastewater discharges. *Chemosphere*, *346*, 140587. https://doi.org/10.1016/j.chemosphere.2023.140587

Grela, A., Kuc, J., Klimek, A., Matusik, J., Pamuła, J., Franus, W., Urbański, K., &Bajda, T. (2023). Erythromycin scavenging from aqueous solutions by zeolitic materials derived from fly ash. *Molecules*, *28*(2), 798. https://doi.org/10.3390/molecules28020798

Grenni, P. (2022). Antimicrobial resistance in rivers: A review of the genes detected and new challenges. *Environmental Toxicology and Chemistry*, *41*(3), 687–714. https://doi.org/10.1002/etc.5289

González-Hourcade, M., dos-Reis, S., Grimm, A., Van Duong Dinh, Lima, E. C., Larsson, S. H., & Gentili, F. (2022). Microalgae biomass as a sustainable precursor to produce nitrogen-doped biochar for efficient removal of emerging pollutants fromaqueous media. ***Journal of Cleaner Production***,*348*, 131280. https://doi.org/10.1016/j.jclepro.2022.131280

Guardo, A. D., Castiglioni, S., Gambino, I., Alessia Sailis, Giulia Salmoiraghi, Schiarea, S., Vighi, M., & Terzaghi, E. (2024). Modelling micropollutant cycle in Lake Como in a winter scenario: Implications for water use and reuse, ecosystem services, and the EU zero pollution action plan. *Science of the Total Environment*, *906*, 167594–167594. https://doi.org/10.1016/j.scitotenv.2023.167594

Guerra, E. M., & D.T. Cestarolli. (2021). Azithromycin electrochemical detection using a VO2 thin film. *Journal of Alloys and Compounds*, *885*, 160997. https://doi.org/10.1016/j.jallcom.2021.160997

Guo, S., Zou, Z., Chen, Y., Long, X., Liu, M., Li, X., Tan, J., & Chen, R. (2023). Synergistic effect of hydrogen bonding and π-π interaction for enhanced adsorption of rhodamine B from water using corn straw biochar. *Environmental Pollution*, *320*, 121060. https://doi.org/10.1016/j.envpol.2023.121060

Hao, F., Tan, W., Jiang, L., Zhang, L., Zhao, X., Zou, Y., Hu, Y., Luo, X., Jiang, X., McIntyre, R. S., Tran, B., Sun, J., Zhang, Z., Ho, R., Ho, C., & Tam, W. (2020). Do psychiatric patients experience more psychiatric symptoms during COVID-19 pandemic and lockdown? A case-control study with service and research implications for immunopsychiatry. *Brain, Behavior, and Immunity*, *87*. https://doi.org/10.1016/j.bbi.2020.04.069

Harrower, J., McNaughtan, M., Hunter, C., Hough, R., Zhang, Z.,& Helwig, K. (2021). Chemical fate and partitioning behavior of antibiotics in the aquatic environment—A review. *Environmental Toxicology and Chemistry*, *40*(12), 3275–3298. https://doi.org/10.1002/etc.5191

Hassaan, M. A., Murat Yılmaz, Mohamed M.I. Helal, ElNemr, M. A., Ragab, S., & Ahmed El Nemr. (2023). Improved methylene blue adsorption from an aqueous medium by ozone-triethylenetetramine modification of sawdust-based biochar. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-39495-7

Hassan, M., Naidu, R., Du, J., Liu, Y., & Qi, F. (2020). Critical review of magnetic biosorbents: Their preparation, application, and regeneration for wastewater treatment. *Science of the Total Environment*, *702*, 134893. https://doi.org/10.1016/j.scitotenv.2019.134893

Herrera, K., Morales, L. F., Tarazona, N. A., Aguado, R., & Saldarriaga, J. F. (2022). Use of biochar from rice husk pyrolysis: Part A: Recovery as an adsorbent in the removal of emerging compounds. *ACS Omega*, *7*(9), 7625–7637. https://doi.org/10.1021/acsomega.1c06147

Hua, L., Cheng, T., Liang, Z., & Wei, T. (2022). Investigation of the mechanism of phytate-modified biochar-catalyzed persulfate degradation of Ponceau 2R. *Biochar*, *4*(1). https://doi.org/10.1007/s42773-022-00136-3

Huang, A., Yan, M., Lin, J., Xu, L., Gong, H., & Gong, H. (2021). A review of processes for removing antibiotics from breeding wastewater. *International Journal of Environmental Research and Public Health*, *18*(9), 4909. https://doi.org/10.3390/ijerph18094909

Huang, H., Zhou, Z, X, C., Wei, D., Deng, X., Yu, L., Wang, H., Deng, Z., Weng, S., Ning, D., Xiao, C., Yan, Q., Zhou, J., He, Z., & He, J. (2021). Environmental water and sediment microbial communities shape intestine microbiota for ost health: The central dogma in an anthropogenic aquaculture ecosystem. *Frontiers in Microbiology*, *12*. https://doi.org/10.3389/fmicb.2021.772149

Hübner, U., Spahr, S., Lutze, H., Wieland, A., Rüting, S., Gernjak, W., Wenk, J. (2024). Advanced oxidation processes for water and wastewater treatment – guidance for systematic future research. *Heliyon*, e30402–e30402. https://doi.org/10.1016/j.heliyon.2024.e30402

Ibham , Spraggon, M., I.M. Rizwanul Fattah, & Idris, M. (2023). Response surface methodology (RSM) for optimizing engine performance and emissions fueled with biofuel*: Review of RSM for sustainability energy transition*. *18*, 101213. https://doi.org/10.1016/j.rineng.2023.101213

Jalali, F.J., Chahkandi, B., Gheibi, M., Eftekhari, M., Behzadian, K., Campos, L. C. (2023). Developing a smart and clean technology for bioremediation of antibiotic contamination in arable lands. *Sustainable Chemistry and Pharmacy*, *33*, 101127–101127. https://doi.org/10.1016/j.scp.2023.101127

Ibrahim, A., Ismail, A., Juahir, H., Ihsan, Y. N., Sudianto, S., Ovinis, M., Kassim, A. M., Hanapi, N. H. M., & Hafizi, A. D. (2023). Preparation and characterization of activated carbon obtained from Melaleuca cajuputi leaves. *Carbon Trends*, *13*, 100301. https://doi.org/10.1016/j.cartre.2023.100301

Ilie, M., Marinescu, F., Ghita, G., Savin, I., Tudor, G., Lucian Luminaroiu, Gheorghe, P.-I., Dumitrescu, G., & Norazian Mohamed Noor. (2023). Evaluation of the Ecological Risk and the Development of Antimicrobial Resistance due to the Presence of the Macrolide Antibiotics Azithromycin and Clarithromycin in Romanian Aquatic Environment. *IOP Conference Series. Earth and Environmental Science*, *1216*(1), 012009. https://doi.org/10.1088/1755-1315/1216/1/012009

Jagadeesh, N., & Sundaram, B. (2023). Adsorption of pollutants from wastewater by biochar: A review. *Journal of Hazardous Materials Advances*, *9*, 100226. https://doi.org/10.1016/j.hazadv.2022.100226

Jayakumar, A., Wurzer, C., Soldatou, S., Edwards, C., Lawton, L. A., & Mašek, O. (2021). New directions and challenges in engineering biologically-enhanced biochar for biological water treatment. *Science of the Total Environment*, *796*, 148977. https://doi.org/10.1016/j.scitotenv.2021.148977

Jia, Y., Ou, Y., Khanal, S. K., Sun, L., Shu, W., & Lu, H. (2024). Biochar-based strategies for antibiotics removal: mechanisms, factors, and application. *ACS ES&T Engineering*. https://doi.org/10.1021/acsestengg.3c00605

Kabir Mh, S, Y., Sa, M., Upoma Bp, S, A., Azam G, Jahan T, Islam Ms, & Moniruzzaman M. (2021). An LLE Based LC- ESI MS/MS Analytical method development to detect azithromycin residue in water to monitor contamination level of river and fish farm of Bangladesh. *Research Square*. https://doi.org/10.21203/rs.3.rs-588090/v1

Kadadou, D., Tizani, L., Alsafar, H. & Hasan, S. W. (2024). Analytical methods for determining environmental contaminants of concern in water and wastewater. *MethodsX*, 102582. https://doi.org/10.1016/j.mex.2024.102582

Kalina, M., Sarka Sovova, Svec, J., Trudicova, M., Hajzler, J., Kubikova, L., & Vojtech Enev. (2022). The effect of pyrolysis temperature and the source biomass on the properties of biochar produced for the agronomical applications as the soil conditioner. *Materials*, *15*(24), 8855. https://doi.org/10.3390/ma15248855

Kang, Z., Jia, X., Zhang, Y., Kang, X., Ge, M., Liu, D., Wang, C., & He, Z. (2022). A review on application of biochar in the removal of pharmaceutical pollutants through adsorption and persulfate-based AOPs. *Sustainability*, *14*(16), 10128. https://doi.org/10.3390/su141610128

Kainth, S., Sharma, P., & Pandey, O. P. (2024). Green sorbents from agricultural wastes: A review of sustainable adsorption materials. *Applied Surface Science Advances*, *19*, 100562. https://doi.org/10.1016/j.apsadv.2023.100562

Katiyar, R., Chen, C.-W., Singhania, R. R., Tsai, M.-L., Saratale, G. D., Pandey, A., Dong, C.-D., & Patel, A. K. (2022). Efficient remediation of antibiotic pollutants from the environment by innovative biochar: current updates and prospects. *Bioengineered*, *13*(6), 14730–14748. https://doi.org/10.1080/21655979.2022.2108564

Khater, E.-S., - Bahnasawy, A., Hamouda, R., Amr Sabahy, Abbas, W., & Morsy, O. M. (2024). Biochar production under different pyrolysis temperatures with different types of agricultural wastes. *Scientific Reports*, *14*(1). https://doi.org/10.1038/s41598-024-52336-5

Khezri, M. R., Zolbanin, N. M., Ghasemnejad-berenji, M., & Jafari, R. (2021). Azithromycin: Immunomodulatory and antiviral properties for SARS-CoV-2 infection. *European Journal of Pharmacology*, *905*, 174191. https://doi.org/10.1016/j.ejphar.2021.174191

Kimani, S. M., Bimantara, P. O., Hattori, S., Tawaraya, K., Sudo, S., Xu, X., & Cheng, W. (2020). Co-application of poultry-litter biochar with Azolla has synergistic effects on CH4 and N2O emissions from rice paddy soils. *Heliyon*, *6*(9), e05042. https://doi.org/10.1016/j.heliyon.2020.e05042

Kong, Z., Zhu, L., Liu, Y., Liu, Y., Chen, G., Jiang, T., & Wang, H. (2024). Effects of azithromycin exposure during pregnancy at different stages, doses and courses on testicular development in fetal mice. *Biomedicine & Pharmacotherapy*, *170*, 116063. https://doi.org/10.1016/j.biopha.2023.116063

Konopka, J. K., Chatterjee, P., LaMontagne, C., & Brown, J. (2022). Environmental impacts of mass drug administration programs: exposures, risks, and mitigation of antimicrobial resistance. *Infectious Diseases of Poverty*, *11*(1). https://doi.org/10.1186/s40249-022-01000-z

Kosar, F., & Muhammad, K. T. (2024). Advancements in application of modified biochar as a green and low-cost adsorbent for wastewater remediation from organic dyes. *Royal Society Open Science*, *11*(5). https://doi.org/10.1098/rsos.232033

Krupka, M., Piotrowicz-Cieślak, A. I., & Michalczyk, D. J. (2021). Effects of antibiotics on the photosynthetic apparatus of plants. *Journal of Plant Interactions*, *17*(1), 96–104. https://doi.org/10.1080/17429145.2021.2014579

Kurjogi, M., Issa Mohammad, Y. H., Alghamdi, S., Abdelrahman, M., Satapute, P., & Jogaiah, S. (2019). Detection and determination of stability of the antibiotic residues in cow's milk. *PLOS ONE*, *14*(10), e0223475. https://doi.org/10.1371/journal.pone.0223475

Kurniawan, T. A., Othman, M. H. D., Liang, X., Goh, H. H., Gikas, P., Chong, K.-K., & Chew, K. W. (2023). Challenges and opportunities for biochar to promote circular economy and carbon neutrality. *Journal of Environmental Management*, *332*, 117429. https://doi.org/10.1016/j.jenvman.2023.117429

Ighalo, J.O., Rangabhashiyam, S., Dulta, K., Umeh, C.T., Iwuozor, K.O., Aniagor, C.O., Eshiemogie, S.O., Iwuchukwu, F.U., Igwegbe, C.A., (2022). Recent advances in hydrochar application for the adsorptive removal of wastewater pollutants. *Chemical Engineering Research and Design*, 184, 419–456. https://doi.org/10.1016/j.cherd.2022.06.028

Imwene, K. O., Ngumba, E., & Kairigo, P. K. (2022). Emerging technologies for enhanced removal of residual antibiotics from source-separated urine and wastewaters: A review. *Journal of Environmental Management*, *322*, 116065. https://doi.org/10.1016/j.jenvman.2022.116065

Lee, S.C., Jang, H.Y., Kim, S.B., (2023).Characterization of ibuprofen removal by calcined spherical hydrochar through adsorption experiments, molecular modeling, and artificial neural network predictions.*Chemosphere*, 311,137074. https://doi.org/10.1016/j.chemosphere.2022.137074

Li, G., Huang, Z., Chen, C., Cui, H., Su, Y., Yang, Y., & Cui, L. (2019). Simultaneous adsorption of trace sulfamethoxazole and hexavalent chromium by biochar/MgAl layered double hydroxide composites. *Environmental Chemistry*, *16*(1), 68. https://doi.org/10.1071/en18132

Li, H., Lin, Y., Qin, X., Song, L., Fan, F., Liu, Y., & Li, S. (2024). An updated review on how biochar may possess potential in soil ARGs control on aspects of source, fate and elimination. *Biochar*, *6*(1). https://doi.org/10.1007/s42773-024-00319-0

Li, S., Tan, X., Li, H.,Gao, Y., Wang, Q., Xu, C., & Guo, M. (2022). Investigation on pore structure regulation of activated carbon derived from sargassum and its application in supercapacitor. *Scientific report*, *12*(1), 10106. https://doi.org/10.1038/s41598-022-14214-w

Li, Y., Ma, Y., Yang, L., Duan, S., Zhou, F., Chen, J., Liu, Y., & Zhang, B. (2020). Effects of azithromycin on feeding behavior and nutrition accumulation of Daphnia magna under the different exposure pathways. *Ecotoxicology and Environmental Safety*, *197*, 110573. https://doi.org/10.1016/j.ecoenv.2020.110573

Li, Z., Zheng, Z., Li, H., Xu, D., Li, X., Xiang, L., & Tu, S. (2023). Review on rice husk biochar as an adsorbent for soil and water remediation. *Plants*, *12*(7), 1524. https://doi.org/10.3390/plants12071524

Liu, G., Dai, Z., Liu, X., Dahlgren, R. A., & Xu, J. (2022). Modification of agricultural wastes to improve sorption capacities for pollutant removal from water – a review. *Carbon Research1*(1), 1-24. https://doi.org/10.1007/s44246-022-00025-1

Liu, L., Li, S., Han, J., Lin, W., & Luo, J. (2019). A two-step strategy for the rapid enrichment of nitrosocosmicus-like ammonia-oxidizing thaumarchaea. *Frontiers in Microbiology*, 10. https://doi.org/10.3389/fmicb.2019.00875

Liu, X., Bahadoran, A., Alizadeh, A., Emami, N., Al-Musawi, T. J., Ahmed Hussien Alawadi, Aljeboree, A. M., Mahmoud Shamsborhan, Iman Najafipour, Seyed Erfan Mousavi, Milad Mosallanezhad, & Davood Toghraie. (2023). Sonocrystallization of a novel ZIF/zeolite composite adsorbent with high chemical stability for removal of the pharmaceutical pollutant azithromycin from contaminated water. *Ultrasonics Sonochemistry*, *97*, 106463. https://doi.org/10.1016/j.ultsonch.2023.106463

Löffler, P., Escher, B. I., Baduel, C., Virta, M., & Foon Yin Lai. (2023). Antimicrobial Transformation Products in the Aquatic Environment: Global Occurrence, Ecotoxicological Risks, and Potential of Antibiotic Resistance.*Environmental Science & Technology* , *57* (26), 9474-9494 https://DOI: 10.1021/acs.est.2c09854

Lopez, F. J., Pitarch, E., Botero-Coy, A. M., Fabregat-Safont, D., Ibáñez, M., Marin, J. M., Peruga, A., Ontañón, N., Martínez-Morcillo, S., Olalla, A., Valcárcel, Y., Varó, I., & Hernández, F. (2022). Removal efficiency for emerging contaminants in a WWTP from Madrid (Spain) after secondary and tertiary treatment and environmental impact on the Manzanares River. *Science of the Total Environment*, *812*, 152567. https://doi.org/10.1016/j.scitotenv.2021.152567

Lu, X., Mao, T., Dai, Y., Zhu, L., Li, X., Ao, Y., & Wang, H. (2023). Azithromycin exposure during pregnancy disturbs the fetal development and its characteristic of multi-organ toxicity. *Life Sciences*, *329*, 121985. https://doi.org/10.1016/j.lfs.2023.121985

Maddamsetti, R., Yao, Y., Wang, T., Gao, J., Huang, V. T., Hamrick, G. S., Son, H.-I., & You, L. (2024). Duplicated antibiotic resistance genes reveal ongoing selection and horizontal gene transfer in bacteria. *Nature Communications*, *15*(1), 1449. https://doi.org/10.1038/s41467-024-456389

Madondo, N. I., Rathilal, S., & Bakare, B. F. (2022). Utilization of response surface methodology in optimization and modelling of a microbial electrolysis cell for wastewater treatment using Box–Behnken design method. *Catalysts*, *12*(9), 1052. https://doi.org/10.3390/catal12091052

Mane, P.V., Rego, R.M., Losic P. L., D., Kurkuri, M.D., (2024).Unveiling cutting-edge advances in high surface area porous materials for the efficient removal of toxic metal ions from water. *Progress in Materials Science*, 101314.https://doi.org/10.1016/j.pmatsci.2024.10131

Mao, Y., Yu, Y., Ma, Z., Li, H., Yu, W., Cao, L., & He, Q. (2021). Azithromycin induces dual effects on microalgae: Roles of photosynthetic damage and oxidative stress. *Ecotoxicology and Environmental Safety*, *222*, 112496. https://doi.org/10.1016/j.ecoenv.2021.112496

Mariano, M. F., Angeles, L. F., Aga, D. S., Villanoy, C. L., & Caroline M.B. Jaraula. (2023). Emerging pharmaceutical contaminants in key aquatic environments of the Philippines. *Frontiers in Earth Science*, 11, 124313. https://doi.org/10.3389/feart.2023.1124313

Martínez-Polanco, M. P., Valderrama-Rincón, J. A., Martínez-Rojas, A. J., Luna-Wandurraga, H. J., Díaz-Báez, M. C., Bustos-López, M. C., & Valderrama-Rincon, J. D. (2022). Degradation of high concentrations of azithromycin when present in a high organic content wastewater by using a continuously fed laboratory-scale UASB bioreactor. *Chemosphere*, *287*, 132191. https://doi.org/10.1016/j.chemosphere.2021.132191

Michaelis, C., & Grohmann, E. (2023). Horizontal gene transfer of antibiotic resistance genes in biofilms. *Antibiotics*, *12*(2), 328. https://doi.org/10.3390/antibiotics12020328

Miklasińska-Majdanik, M. (2021). Mechanisms of resistance to macrolide antibiotics among Staphylococcus aureus. *Antibiotics*, *10*(11), 1406. https://doi.org/10.3390/antibiotics10111406

Milaković, M., Vestergaard, G., González-Plaza, J. J., Petrić, I., Šimatović, A., Senta, I., Kublik, S., Schloter, M., Smalla, K., & Udiković-Kolić, N. (2019). Pollution from azithromycin-manufacturing promotes macrolide-resistance gene propagation and induces spatial and seasonal bacterial community shifts in receiving river sediments. *Environment International*, *123*, 501–511. https://doi.org/10.1016/j.envint.2018.12.050

Mirzaie, F., Teymori F., Shahcheragh, S., Dobaradarn, S., Arfaeinia, H., Kafaei, F., Sahebi, S., Farjadfard, S., & Ramavandi. B., (2022). Occurrence and distribution of azithromycin in wastewater treatment plants, seawater, and sediments of the northern part of the Persian Gulf around Bushehr port: A comparison with Pre-COVID 19 pandemic. *Chemosphere 307*,135996. https://doi.org/10.1016/j.chemosphere.2022.135996

Mishra, E., Shruti Kapse, &Jain, S. (2023). Consideration about regeneration, reactivity, toxicity, and challenges of biochar-based nanocomposites. *Advances in Science, Technology & Innovation/Advances in Science, Technology & Innovation*, 107–118. https://doi.org/10.1007/978-3-031-28873-9_9

Monisha, R. S., Mani, R. L., Sivaprakash, B., Rajamohan, N., & Vo, D.-V. N. (2021). Green remediation of pharmaceutical wastes using biochar: a review. *Environmental Chemistry Letters*, *20*(1), 681–704. https://doi.org/10.1007/s10311-021-01348-y

Montone, C. M., Giannelli Moneta, B., Laganà, A., Piovesana, S., Taglioni, E., & Cavaliere, C. (2024). Transformation products of antibacterial drugs in environmental water: Identification approaches based on liquid chromatography-high resolution mass spectrometry. *Journal of Pharmaceutical and Biomedical Analysis*, *238*, 115818. https://doi.org/10.1016/j.jpba.2023.115818

Muhammad Z Y., Salman R. N., Juchelková, D., & Muhammad. (2024). Harnessing the power of functionalized biochar: progress, challenges, and future perspectives in energy, water treatment, and environmental sustainability. *Biochar*, *6*(1). https://doi.org/10.1007/s42773-024-00316-3

Murtaza, G., Ahmed, Z., Dai, D.-Q., Iqbal, R., Bawazeer, S., Usman, M., Rizwan, M., Iqbal, J., Akram, M. I., Althubiani, A. S., Tariq, A., & Ali, I. (2022). A review of mechanism and adsorption capacities of biochar-based engineered composites for removing aquatic pollutants from contaminated water. *Frontiers in Environmental Science*, 10, 1035865. https://doi.org/10.3389/fenvs.2022.1035865

Ngigi, A. N., Ok, Y. S., & Thiele-Bruhn, S. (2020). Biochar affects the dissipation of antibiotics and abundance of antibiotic resistance genes in pig manure. *Bioresource Technology*, *315*, 123782. https://doi.org/10.1016/j.biortech.2020.123782

Nouioua, A., Salem, D. B., Ouakouak, A., Rouahna, N., Baigenzhenov, & Hosseini-Bandegharaei, A. (2023). Production of biochar from *Melia azedarach* seeds for the crystal violet dye removal from water: combining of hydrothermal carbonization and pyrolysis. *Bioengineered*, *14*(1), 290–306. https://doi.org/10.1080/21655979.2023.2236843

Oliver, M. E., & Hinks, T. S. C. (2020). Azithromycin in viral infections. *Reviews in Medical Virology*, *31*(2). https://doi.org/10.1002/rmv.2163

Olugbenga S., O., Goodness Adeleye, P., Blessing Oladipupo, S., Timothy Adeleye, A., & Igenepo John, K. (2024). Biomass-derived biochar in wastewater treatment- a circular economy approach. *Waste Management Bulletin*, *1*(4), 1–14. https://doi.org/10.1016/j.wmb.2023.07.007

Oppeltová, P., Vítězslav, V. G., M., Pavel, C., Ulrich, O., Jozef Sedláček, V., H., Kristýna Kohoutková, R. Klepárník, & Šimečková, J. (2024). Occurrence and path pollution of emerging organic contaminants in mineral water of Hranice hypogenic Karst. *Frontiers in Environmental Science*, *12*, 1339818. https://doi.org/10.3389/fenvs.2024.1339818

Padmaja, K., Cherukuri, J., & Anji Reddy, M. (2020). A comparative study of the efficiency of chemical coagulation and electrocoagulation methods in the treatment of pharmaceutical effluent. *Journal of Water Process Engineering*, *34*, 101153. https://doi.org/10.1016/j.jwpe.2020.101153

Patel, P. H., & Hashmi, M. F. (2023, May 16). *Macrolides*. PubMed; StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK551495/

Patel, A. K., Katiyar, R., Chen, C.-W., Singhania, R. R., Awasthi, M. K., Bhatia, S., Bhaskar, T., Dong, C.D. (2022). Antibiotic bioremediation by new generation biochar: Recent updates. *Bioresource Technology*, *358*, 127384. https://doi.org/10.1016/j.biortech.2022.127384

Pavlinac, P. B., Singa, B. O., John-Stewart, G. C., Richardson, B. A., Brander, R. L., McGrath, C. J., Tickell, K. D., Amondi, M., Rwigi, D., Babigumira, J. B., Kariuki, S., Nduati, R., & Walson, J. L. (2017). Azithromycin to prevent post-discharge morbidity and mortality in Kenyan children: a protocol for a randomised, double-blind, placebo-controlled trial (the Toto Bora trial). *BMJ Open*, *7*(12), e019170. https://doi.org/10.1136/bmjopen-2017-019170

Perelomov, L., Mandzhieva, S., Minkina, T., Yury Atroshchenko, Perelomova, I., Bauer, T., Pinsky, D., & Anatoly Barakhov. (2021). The synthesis of organoclays based on clay minerals with different structural expansion capacities. *Minerals*, *11*(7), 707. https://doi.org/10.3390/min11070707

Petropoulos, A. D., Kouvela, E. C., Starosta, A. L., Wilson, D. N., Dinos, G. P., & Kalpaxis, D. L. (2009). Time-resolved binding of Azithromycin to *Escherichia coli* ribosomes. *Journal of Molecular Biology*, *385*(4), 1179–1192. https://doi.org/10.1016/j.jmb.2008.11.042

Phoon, B. L., Ong, C. C., Mohamed Saheed, M. S., Show, P.-L., Chang, J.-S., Ling, T. C., Lam, S. S., & Juan, J. C. (2020). Conventional and emerging technologies for removal of antibiotics from wastewater. *Journal of Hazardous Materials*, *400*, 122961. https://doi.org/10.1016/j.jhazmat.2020.122961

Pinto, I., Simões, M., & Gomes, I. B. (2022). An overview of the impact of pharmaceuticals on aquatic microbial communities.*Antibiotics*, *11*(12), 1700.https://doi.org/10.3390/antibiotics11121700

Pyrolysis - an overview | ScienceDirect Topics. (n.d.). Www.sciencedirect.com. https://www.sciencedirect.com/topics/chemical-engineering/pyrolysis

Rajput, P., Kumar, P., A.K. Priya, Kumari, S., Seyede Roghie Ghadirnezhad Shiade, Rajput, V. D., Fathi, A., Pradhan, A., Sarfraz, R., Sushkova, S., Saglara Mandzhieva, Minkina, T., Soldatov, A., Ming Hung Wong, & Rensing, C. (2024). Nanomaterials and biochar mediated remediation of emerging contaminants. *Science of the Total Environment*, *916*, 170064. https://doi.org/10.1016/j.scitotenv.2024.170064

Rajput, V. D., Minkina, T., Ahmed, B., Singh, V. K., Mandzhieva, S., Sushkova, S., Bauer, T., Verma, K. K., Shan, S., van Hullebusch, E. D., & Wang, B. (2022). Nano-biochar: A novel solution for sustainable agriculture and environmental remediation. *Environmental Research*, *210*, 112891. https://doi.org/10.1016/j.envres.2022.112891

Ribeiro, A. C., Freitas, E., Vidovix, T. B., Salcedo, M., Bergamasco, R. (2024). Synthesis of a novel functionalized biosorbent from mango stone and its application in the pharmaceutical's removal from water and a synthetic mixture. *Chemosphere*, *346*, 140520. https://doi.org/10.1016/j.chemosphere.2023.140520

Robert, L., Marinov D., Isabella, S., Teresa, L. (2018). Review of the 1st watch list under the water Framework Directive and recommendations for the 2nd Watch List. *JRC PublicationsRepository*. 1831-9424. https://doi.org/10.2760/614367

Robinson, R., Brabie, L., Pettersson, M., Amovic, M., & Ljunggren, R. (2022). An empirical comparative study of renewable biochar and fossil carbon as carburizer in steelmaking. *ISIJ International*, *62*(12), 2522–2528. https://doi.org/10.2355/isijinternational.isijint-2020-135

Saita, M. G., Aleo, D., Melilli, B., Mangiafico, S., Cro, M., Sanfilippo, C., & Patti, A. (2018). pH-Dependent stability of azithromycin in aqueous solution and structure identification of two new degradation products. *Journal of Pharmaceutical and Biomedical Analysis*, *158*, 47–53. https://doi.org/10.1016/j.jpba.2018.05.042

Samal, K., Mahapatra, S., & Ali, Md. H. (2022). Pharmaceutical wastewater as Emerging Contaminants (EC): treatment technologies, impact on environment and human health. *Energy Nexus*, *6*, 100076. https://doi.org/10.1016/j.nexus.2022.100076

Sánchez-Martín, J. A., Campos, P., & Miller, A. Z. (2019). Effect of pyrolysis conditions on the total contents of polycyclic aromatic hydrocarbons in biochars produced from organic residues: Assessment of their hazard potentia*l*. *667*, 578–585. https://doi.org/10.1016/j.scitotenv.2019.02.421

Saraugi, S. S., & Routray, W. (2024). Advances in sustainable production and applications of nano-biochar. *Science of the Total Environment*, *955*, 176883. https://doi.org/10.1016/j.scitotenv.2024.176883

Sarma, H., Shyam, S., Zhang, M., & Guerriero, G. (2024). Nano-biochar interactions with contaminants in the rhizosphere and their implications for plant-soil dynamics. *Soil & Environmental Health*, *2*(3), 100095. https://doi.org/10.1016/j.seh.2024.100095

Satyam, S., Patra, S., (2024). Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review. *Heliyon*,10,9, 29573, https://doi.org/10.1016/j.heliyon.2024.e29573

Sen, U., Esteves, B., Aguiar, T., & Pereira, H. (2023). Removal of Antibiotics by Biochars: A Critical Review. *Applied Sciences*, *13*(21), 11963–. https://doi.org/10.3390/app132111963

Senta, I., Kostanjevecki, P., Krizman-Matasic, I., Terzic, S., & Ahel, M. (2019). Occurrence and behavior of macrolide antibiotics in municipal wastewater treatment: possible importance of metabolites, synthesis byproducts, and transformation products. *Environmental Science & Technology*, *53*(13), 7463–7472. https://doi.org/10.1021/acs.est.9b01420

Shearer, L., Pap, S., & Gibb, S. W. (2022). Removal of pharmaceuticals from wastewater: A review of adsorptive approaches, modelling and mechanisms for metformin and macrolides. ***Journal of Environmental Chemical Engineering****10*(4), 108106. https://doi.org/10.1016/j.jece.2022.108106

Shen, Y., Li, H., Ryser, E. T., & Zhang, W. (2021). Comparing root concentration factors of antibiotics for lettuce (Lactuca sativa) measured in rhizosphere and bulk soils. *Chemosphere*, *262*, 127677. https://doi.org/10.1016/j.chemosphere.2020.127677

Shi, J., Fan, X., Tsang, D. C. W., Wang, F., Shen, Z., Hou, D., & Alessi, D. S. (2019). Removal of lead by rice husk biochars produced at different temperatures and implications for their environmental utilizations. *Chemosphere*, *235*, 825–831. https://doi.org/10.1016/j.chemosphere.2019.06.237

Shi, S., & Liu, Y. (2021). Nitrogen-doped activated carbons derived from microalgae pyrolysis by-products by microwave/KOH activation for CO2 adsorption. *Fuel*, *306*, 121762. https://doi.org/10.1016/j.fuel.2021.121762

Sidhu, H., O'Connor, G., & Kruse, J. (2019). Plant toxicity and accumulation of biosolids-borne ciprofloxacin and azithromycin. *Science of the Total Environment*, *648*, 1219–1226. https://doi.org/10.1016/j.scitotenv.2018.08.218

Ślósarczyk, K., Jakóbczyk-Karpierz, S., Różkowski, J., & Witkowski, A. J. (2021). Occurrence of pharmaceuticals and personal care products in the water environment of poland: a review. *Water*, *13*(16), 2283. https://doi.org/10.3390/w13162283

Song, J., Zhang, S., Li, G., Du, Q., & Yang, F. (2020). Preparation of montmorillonite modified biochar with various temperatures and their mechanism for Zn ion removal. *Journal of Hazardous Materials*, *391*, 121692. https://doi.org/10.1016/j.jhazmat.2019.121692

Stylianou, M., Christou, A., Michael, C., Agapiou, A., Papanastasiou, P., & Fatta-Kassinos, D. (2021). Adsorption and removal of seven antibiotic compounds present in water with the use of biochar derived from the pyrolysis of organic waste feedstocks. *Journal of Environmental Chemical Engineering*, *9*(5), 105868. https://doi.org/10.1016/j.jece.2021.105868

Talaiekhozani, A., Joudaki, S., Banisharif, F., Eskandari, Z., Cho, J., Moghadam, G., & Rezania, S. (2020). Comparison of azithromycin removal from water using UV radiation, fe (vi) oxidation process and ZnO nanoparticles. *International Journal of Environmental Research and Public Health*, *17*(5), 1758. https://doi.org/10.3390/ijerph17051758

Tao, S., Chen, H., Li, N., Wang, T., & Liang, W. (2022). The spread of antibiotic resistance genes in vivo model. *The Canadian Journal of Infectious Diseases & Medical Microbiology*, 3348695. https://doi.org/10.1155/2022/3348695

Uddin, F. (2018). Montmorillonite: an introduction to properties and utilization. *Current Topics in the Utilization of Clay in Industrial and Medical Applications*. https://doi.org/10.5772/intechopen.77987

Upoma, B. P., Yasmin, S., Ali Shaikh, Md. A., Jahan, T., Haque, Md. A., Moniruzzaman, M., & Kabir, M. H. (2022). a fast adsorption of azithromycin on waste-product-derived graphene oxide induced by h-bonding and electrostatic interactions. *ACS Omega*, *7*(34), 29655. https://doi.org/10.1021/acsomega.2c01919

Van Epps, A., & Blaney, L. (2016). Antibiotic residues in animal waste: occurrence and degradation in conventional agricultural waste management practices. *Current Pollution Reports*, *2*(3), 135–155. https://doi.org/10.1007/s40726-016-0037-1

Velpandian, T., Halder, N., Nath, M., Das, U., Moksha, L., Gowtham, L., & Batta, S. P. (2018). Un-segregated waste disposal: an alarming threat of antimicrobials in surface and ground water sources in Delhi. *Environmental Science and Pollution Research*, *25*(29), 29518–29528. https://doi.org/10.1007/s11356-018-2927-9

Wahab, M., Zahoor, M., Muhammad Salman, S., Kamran, A. W., Naz, S., Burlakovs, J., Kallistova, A., Pimenov, N., & Zekker, I. (2021). Adsorption-membrane hybrid approach for the removal of azithromycin from water: an attempt to minimize drug resistance problem. *Water*, *13*(14), 1969. https://doi.org/10.3390/w13141969

Wijitkosum, S. (2021). Biochar derived from agricultural wastes and wood residues for sustainable agricultural and environmental applications. *International Soil and Water Conservation Research*.10, (2), 335-341. https://doi.org/10.1016/j.iswcr.2021.09.006

Wu, D., Sui, Q., Yu, X., Zhao, W., Li, Q., Fatta-Kassinos, D., & Lyu, S. (2021). Identification of indicator PPCPs in landfill leachates and livestock wastewaters using multi-residue analysis of 70 PPCPs: Analytical method development and application in Yangtze River Delta, China. *Science of the Total Environment*, *753*, 141653. https://doi.org/10.1016/j.scitotenv.2020.141653

Wu, H., Lu, W., Chen, Y., Zhang, P., & Cheng, X. (2020). Application of boehm titration for the quantitative measurement of soot oxygen functional groups. *Energy & Fuels*, *34*(6), 7363–7372. https://doi.org/10.1021/acs.energyfuels.0c00904

Wurzer, C., Oesterle, P., Jansson, S., & Ondřej Mašek. (2023). Hydrothermal recycling of carbon absorbents loaded with emerging wastewater contaminants. *Environmental Pollution*, *316*, 120532. https://doi.org/10.1016/j.envpol.2022.120532

Xie, W.-M., Wu, Y., Yan, W.-Y., Ma, Y., Meng, H., Wang, G.-X., Zhang, L.-M., Jia, G.-Z., Li, W.-H., Xiao, Y., & Fang, F. (2023). The erythromycin sorption removal at environmentally relevant concentration based on molecular imprinted polymer: Performance and mechanism. *Environmental Pollution*, *336*, 122425. https://doi.org/10.1016/j.envpol.2023.122425

Xue H., Deng L., Kang D., (2024). Advanced biochar-based materials for specific antibiotics removal from hospital wastewater via adsorption and oxidative degradation. *Journal of Environmental Chemical Engineering* 114275. https://doi.org/10.1016/j.jece.2024.114275

Yaashikaa, P.R., Kumar, P.S., Varjani, S. and Saravanan, A.J.B.R.(2020) A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. *Biotechnology Reports*, *28*, e00570.https://doi.org/10.1016/j.btre.2020.e00570

Yemele, O. M., Zhao, Z., Nkoh, J. N., Ervice Ymele, & Usman, M. (2024). A systematic review of polycyclic aromatic hydrocarbon pollution: A combined bibliometric and mechanistic analysis of research trend toward an environmentally friendly solution. *The Science of the Total Environment*, *926*, 171577. https://doi.org/10.1016/j.scitotenv.2024.171577

Yuan, D., Yuan, H., He, X., Hu, H., Qin, S., Clough, T., Wrage-Mönnig, N., Luo, J., He, X., Chen, M., & Zhou, S. (2021). Identification and verification of key functional groups of biochar influencing soil N2O emission. *Biology and Fertility of Soils*, *57*(4), 447–456. https://doi.org/10.1007/s00374-021-01541-9

Zhan, D., Ye, A., & Hou, T. (2023). Research progress on biochar-based material adsorption and removal of ibuprofen. *Frontiers in Environmental Science*, *11*. https://doi.org/10.3389/fenvs.2023.1327000

Zhang, H., Du, M., Jiang, H., Zhang, D., Lin, L., Ye, H., & Zhang, X. (2015). Occurrence, seasonal variation and removal efficiency of antibiotics and their metabolites in wastewater treatment plants, Jiulongjiang River Basin, South China. *Environmental Science: Processes & Impacts*, *17*(1), 225–234. https://doi.org/10.1039/c4em00457d

Zhang, H., Wang, T., Sui, Z., Zhang, Y., Norris, P., Sun, B., & Pan, W.-P. (2019). Plasma induced addition of active functional groups to biochar for elemental mercury removal. *Plasma Chemistry and Plasma Processing*, *39*(6), 1449–1468. https://doi.org/10.1007/s11090-019-10019-4

Zhang, W., Miao, H., Liu, J., Wu, H., Wang, Y., Gu, P., Lei, N., Yang, K., Zheng, Z., & Li, Q. (2023). Response of submerged macrophytes and biofilms to coexisting azithromycin and tetracycline: Antibiotic resistance genes removal, toxicity assessment and microbial properties. *Aquatic Toxicology*, *256*, 106410. https://doi.org/10.1016/j.aquatox.2023.106410

Zhou, W., Meng, X., Gao, J., Zhao, H., Zhao, G., & Ma, J. (2021). Electrochemical regeneration of carbon-based adsorbents: a review of regeneration mechanisms, reactors, and future prospects. *Chemical Engineering Journal Advances*, *5*, 100083. https://doi.org/10.1016/j.ceja.2020.100083

Zhou, Z., Huang, F., Chen, L., Liu, F., Wang, B., & Tang, J. (2024). Effects of antibiotics on microbial nitrogen cycling and N_2O emissions: a review. *Chemosphere*, 142034. https://doi.org/10.1016/j.chemosphere.2024.142034