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REVIEW ARTICLE OPEN ACCESS

Harnessing the Power of Bio Adsorbents: A Review on Sustainable Approach to Eliminate Antibiotic Residues in Wastewater for Better Public Health

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Abstract

Antibiotic overuse in animal and human healthcare has led in the accumulation of potentially hazardous antibiotic residues, known as emerging contaminants. These residues contaminate animal products including meat, milk, and eggs, which humans then ingest. Furthermore, antibiotic residues from pharmaceutical firms, hospitals, and households reach wastewater treatment plants, providing an environment conducive to bacterial growth and dissemination. This, in turn, can result in the spread of antibiotic resistance genes (ARGs) among bacterial cells, posing serious threats to both human health and the environment. In the case of ARGs, conventional approaches for eliminating antibiotic residues from wastewater and aquatic habitats have proven ineffective. Recent study, however, has shown that the adsorption technique, particularly when low-cost and environmentally acceptable bioadsorbents such as sawdust, prawn shell waste, algae, and fungi are used, is highly successful in removing antibiotic residues. Bioadsorbents Microalgae, *Terminalia catappa* leaf, and siris seed pods, in particular, have shown outstanding removal efficiency for antibiotics such as tetracycline, dicloxacillin, and nitromidazole, reaching up to 98.74%. These investigations have shed insight on the fundamental principles of the adsorption process, revealing its ability to target ARGs and antibiotic-resistant bacteria as well as remove antibiotic residues. As a result, addressing the issue of antibiotic residues in the environment has become critical in order to protect human health and prevent the spread of antibiotic resistance. Adsorption, particularly when bioadsorbents are used, appears to be a promising and efficient method of combating antibiotic residues and limiting the spread of antibiotic resistance genes and antibiotic-resistant bacteria in aquatic settings.

Keywords: Antibiotic Residues, Aquatic Environment, Bio Adsorbents, Adsorption, Emerging

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INTRODUCTION

Antibiotics play a crucial role in preventing and treating infectious diseases in both humans and animals, while also being widely present in the environment. Their use as growth promoters in livestock is well-documented.[1-4] The most commonly prescribed antibiotic classes, including Beta-lactams, fluoroquinolones, tetracyclines, macrolides, sulfonamides, and cephalosporins, have been identified.[5,6] Notably, there has been a significant 91% increase in antibiotic consumption from 1985 to 2021, with India and China exhibiting the highest consumption rates, primarily involving cephalosporins and tetracyclines[7-10] (Figure 1). This surge can be attributed to population growth, rapid urbanization, and the emergence of infectious diseases.[11] Tetracyclines are particularly prevalent in global animal production.[12,13] Furthermore, the majority of administered antibiotics are excreted, contributing to their release and potential environmental impact. Proper disposal of unused or expired antibiotics is crucial to mitigate the environmental antibiotic burden.[12]

Antibiotic residues are found in various environmental hotspots such as sewage, hospitals, livestock farms, aquaculture farms, and pharmaceutical industries.[14] These residues are detected in municipal waste effluents, surface water, groundwater, drinking water, soil, sediments, and even in sewage sludge and manure-filled soils.[15] Residual antibiotics are also detected in sewage sludge; animal manure and manure-filled soils.[15] The presence of antibiotics in the environment contributes to the development of antibiotic-resistant bacteria and genes, posing risks to human and animal health.[16,17] Antibiotic-resistant strains are increasingly prevalent.[18] Remediation of antibiotic residues in wastewater is crucial, and adsorption processes using specific adsorbents or bioadsorbents have been considered highly efficient for removing antibiotics from aqueous environments.[19,20] Factors like pH, ionic strength, temperature, and organic matter influence the adsorption process, and the structure and functional groups of antibiotics play a significant role.[19,21] Adsorption mechanisms involve intermolecular forces and interactions, making it a simpler and less time-consuming method for remediation.[22,23] While adsorption is widely recognized as an important mechanism for antibiotic removal, further in-depth analysis is needed.[23] Overall, understanding the adsorption of antibiotics and their residues can provide valuable insights into their interactions with adsorbents and bioadsorbents, contributing to effective wastewater treatment and pollutant reduction.

Occurrences of Antibiotic Residues

Pharmaceutical, municipal, and hospital wastewater contain high concentrations of antibiotic residues.[24-26] Antibiotics are essential components of modern medications used to treat infections caused by diverse bacteria.[27] Overuse, improper usage, and discharge of antibiotics contribute to adverse environmental effects by facilitating their release into the environment.

Antibiotic residues, including both mother compounds and metabolites, can accumulate in various cells, tissues, organs, and edible products, posing risks to human and animal health.[28-30] These residues are often detected in wastewater treatment plants (WWTPs) and subsequently discharged into water bodies, contributing to the dissemination of antibiotic-resistant bacteria and genes in the environment Sulfamethoxazole and ciprofloxacin, Diclofenac were the highest resistant antibiotics present in the municipal WWTP. [31,32,33] Environmental risk assessments have indicated that fluoroquinolones and macrolides pose potential risks to the environment and the development of antibiotic resistance.[34] The accumulation of antibiotics and antibiotic-resistant microorganisms in plants, water, and the human gut is a concern associated with WWTPs.[35,36] Antibiotic residues in food and water can lead to various adverse effects, including the transmission of antibiotic-resistant bacteria, autoimmune diseases, cancer, reproductive disorders, and hepatotoxicity.[37,38]

To address these issues, the development of new technologies and techniques for the efficient remediation of antibiotic residues in wastewater is necessary.[36,39] Increased awareness, education, and responsible use of antibiotics are essential in preventing the spread of antibiotic residue pollution.[40]

Rapid screening processes and the utilization of adsorption techniques can aid in monitoring and removing antibiotic residues from wastewater.[41] Overall, comprehensive strategies are needed to mitigate the environmental impact of antibiotic residues and promote safe water and food consumption.

Impact of antibiotic residues on environment, human & animal health

Antibiotics, whether synthetic, natural, or semi-synthetic, possess the ability to kill bacteria or impede their growth.[42] However, the presence of antibiotic residues in the environment, even at low concentrations, has raised concerns about the transmission of antibiotic resistance and adverse health effects, especially for vulnerable populations. [43,44]

Antibiotic residues in wastewater are classified as F-listed and K-listed pollutants, originating from pharmaceutical industries, hospitals, municipalities, and veterinary sources.[17,45] These residues can accumulate in edible plant tissues, as plants lack excretory systems, potentially surpassing maximum residue limits,[45] therefore antibiotic residues accumulate in edible plant tissues and can exceed the normal Maximum Residue Limit (MRL) value.

Research has indicated that antibiotics possess genotoxic properties, as demonstrated by animal and microbial assays such as the SOS chromotest on *Escherichia coli* and the Ames test on *Salmonella* species.[46] Higher plants and animal models like zebrafish have been employed to assess genotoxicity, revealing effects such as chromosomal aberrations, sister chromatid exchange, and micronucleus formation.[34,47] Infact animal models such as zebrafish has also been used to test the genotoxicity of amoxicillin on the model animal zebra fish.[48] Another research study has been conducted to determine the concentration of ceftriaxone antibiotic in raw and pasteurized cow milk and its toxicity on zebrafish model.[49] In genotoxicity of antibiotic test some chromosomal aberrations, sister chromatid exchange, micronucleus formation and many more are clearly observed.[48] For a well evidence, Florfenicol have shown growth inhibition in *Lemna minor* and *Scenedesmus vacuolatus*.[50] Chloramphenicol and Rifampicin have shown delayed cell growth of human stem cell.[51] Ceftriaxone and doxycycline have shown genotoxic as well as cytotoxic effect on human peripheral blood lymphocytes. Penicillin have shown lipid metabolism dysfunction in mice model.[52]

Development of Antibiotic Resistance

Antibiotics are known as the wonder discoveries of the 20th century. The first discovery of wonder antibiotic penicillin has inspired many scientists for further studies and discoveries of more antibiotics for the treatment and prevention of bacterial diseases. But, now we all are wondering about the antibiotic resistance development in hospitals, the environment and in communities. Antibiotic-resistant bacteria are difficult or more precisely they are impossible to prevent and are becoming increasingly more common and thereby causing a global health crisis.[53] New resistance genes are constantly identified and transmitted from one bacterial cell to another by exploiting new resistance mechanisms day by day.[53] In recent studies, some researchers reported that human gut microbiome are the ultimate reservoir for potential dissemination of resistance genes from normal flora to pathogens and are termed as gut resistome.[54] But the question is how this antibiotic resistance problem is rising day by day in the environment. Conventional mechanical and biological wastewater treatment are not able to remediate all pollutants completely, and therefore these pollutants enter into the surface water bodies along with treated wastewater. Consumption of these water contaminated with antibiotic resistance genes (ARGs), antibiotic resistance bacteria (ARB), antibiotic residues are ultimately transmitted within human and animal bodies.[54-56] These ARGs might be diffused extensively by Horizontal gene transfer (HGT)[57] as shown in Figure 2. Transmission of these genes impacts the phenotype of bacteria and leads to the failure of drug treatments, thus threatening human health. Previous studies have revealed several kinds of ARGs in livestock farming such as, tetA, tetM, tetG (tetracycline resistance genes)[58,59] (,sul1 and sul2 (sulfonamide resistance genes),[59] *ermB, ermF* and *mefA* (macrolide resistance genes).[53] These ARGs, are excreted with livestock feces, flow into the WWTP (wastewater treatment plant) and are finally discharged into the environment.[60]

Remediation of different of antibiotic residues by Bioadsorbents

Several adsorbents and bioadsorbents have been studied for the effective removal of harmful antibiotic residues from wastewater. Different antibiotics exhibit varying adsorption mechanisms due to the involvement of distinct intermolecular interactions (Figure 3).

Tetracycline

Tetracycline, a wide-spectrum antibiotic effective against both gram-positive and gram-negative bacteria, poses a significant concern as its residues are frequently detected in various water systems, including surface water, groundwater, drinking water, and wastewater. Due to its incomplete metabolism and absorption in humans and animals, tetracycline residues persist in aquatic environments.

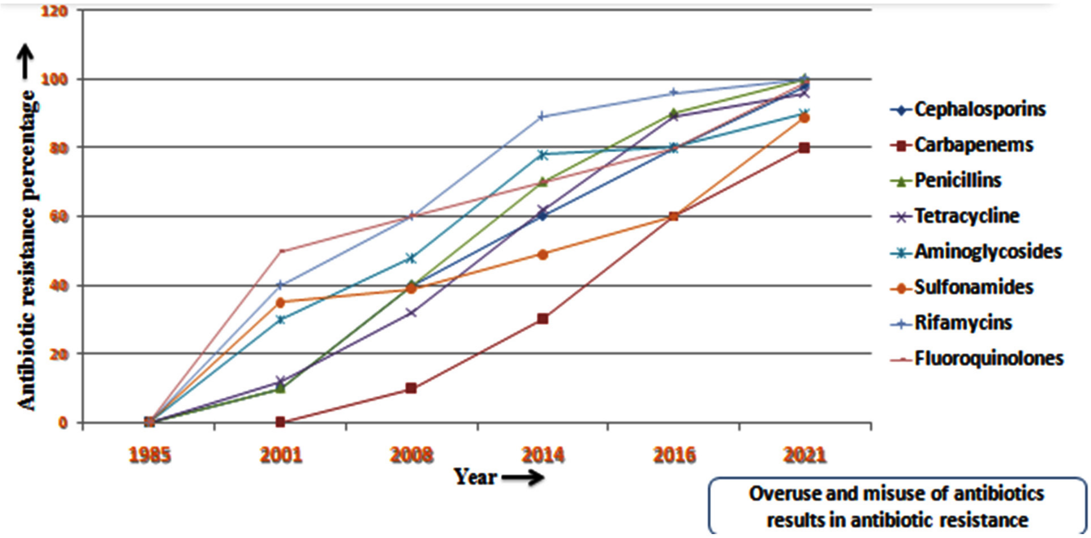

Figure 1. Increase in antibiotic resistance percentage since 1985

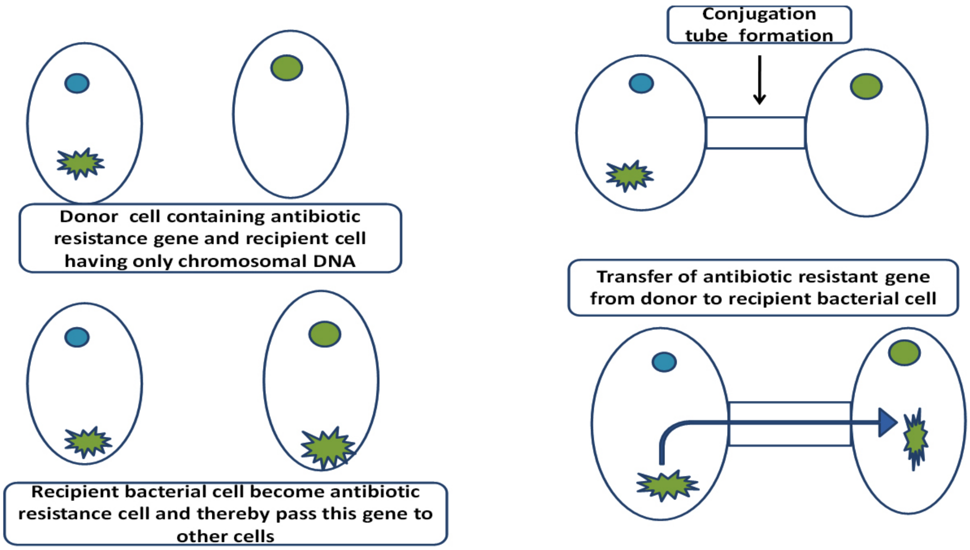

Figure 2. Antibiotic resistance genes transmission mechanism among microorganisms via horizontal gene transfer

Coagulation, flocculation, and biodegradation are not efficient methods for eliminating oxytetracycline (OTC).[61] Pumice stone was found to have a maximum adsorption capacity of 37.09 mg/g at pH 3, with surface complexation and cation exchange identified as the primary adsorption mechanisms.[62] Water hyacinth roots exhibited a removal efficiency of 58.9-84.6%.[63] Ceramsite derived from bentonite, red mud, and pine sawdust demonstrated an adsorption capacity of 2.13 mg/g, attributed to electrostatic interaction, hydrophobic interaction, and hydrogen bonding .[64] Electrostatic interaction, hydrophobic interaction, hydrogen-bonding were the main reasons for the adsorption mechanism in this study.[64] Shrimp shell waste (SSW) as a bioadsorbent exhibited a maximum adsorption capacity of 229.98 mg/g at 55°C, with hydrogen bonds and pi-bonds formed between the antibiotic and SSW bioadsorbent at pH 3.3.[65] Iron (III)-loaded cellulose nanofibers showed a maximum adsorption capacity of 294.12 mg/g at pH 7, with surface complexation and interactions such as hydrogen bonding, electrostatic interactions, and Van der Waals forces.[66] There are many more adsorbents and adsorbents involved in the remediation of tetracycline from the aqueous environment (Figure 4, Table 1).

Dicloxacillin

Dicloxacillin, a beta-lactam antibiotic belonging to the penicillin class, is widely used for treating infections caused by gram-positive bacteria by inhibiting bacterial cell wall synthesis. Tannin, a low-cost and suitable adsorbent, was employed for the adsorption of dicloxacillin from pharmaceutical wastewater. Tannin, a water-soluble polyphenolic compound with a molecular weight range of 500 to several thousands dalton, was isolated from *Terminalia catappa* L. leaf samples[67] as shown in Figure 5. The study focused on the remediation of dicloxacillin residues, and tannin exhibited a maximum adsorption capacity of 17.28 mg/g at pH 6.0 within 24 hours

Table 1. Bioadsorbents for tetracycline remediation

Bioadsorbents/ adsorbents	Maximum adsorption efficiency	Removal efficiency	Desorption efficiency & desorbing agents	Reference
Tectona grandis Linn.	62.5 mg/g	302.27 mg/g	-	104
Zirconium-modified wheat straw	77.2 mg/g	87.7%	92.3% Hydrogen chloride (HCl)	105
Pennisetum sinese Roxb	36.161 mg/g	80%	44.86 mg/g HCl	106
Fe-modified oyster shell	92%	89.9%	HCl	107
Pomelo peel derived biochar	476.19 mg/g	454.56 mg/g	KOH	98
Rice husk ash	8.37 mg/g	60.93%	-	108
Scenedesmus almeriensis microalgae-bacteria consortium	27.09 mg/g	98.7%	89% NaOH	109
Spirulina sp. (microalgae)-derived biochars	147.9mg/g	137.8 mg/g	61%	110
Water hyacinth	202.62 mg/g	210.45 mg/g	-	111
Human-hair derived high surface area porous carbon material	210.18 mg/g	78.94%	-	112

of contact time.[68] Currently, only one study has been conducted on the adsorption of dicloxacillin, indicating the need for further research on the remediation of this antibiotic using other adsorbents(Figure 5, Table 2).[68,69] So there is a need for further research on remediation of dicloxacillin by other adsorbents.

Ciprofloxacin

Ciprofloxacin is a bactericidal antibiotic belonging to the subclass of Fluoroquinolones. It is used for the treatment of urinary tract infections, sexually transmitted diseases, skin infections, and bone infections, as approved by the FDA.[70] These components are present in wastewaters due to the incomplete delivery to the consumer. Everyday, almost 84% of these residues get discharged as incomplete metabolic products in the mentioned wastewaters.[70]

Remediation studies have investigated the use of different chemical and biological adsorbents. For example, activated carbon derived from banana stalk, an environmentally friendly bioadsorbent, exhibited a maximum monolayer adsorption capacity of 49.7 mg/g at pH 4.5 and 323K through a physical adsorption mechanism[71] as shown in (Figure 6, Table 3).

Meropenem

Meropenem is a novel antibiotic used to treat severe infections of the skin, stomach, bacterial meningitis, pneumonia, sepsis, and intra-abdominal infections.[72] Administered via intravenous infusion, meropenem is classified as an intravenous beta-lactam antibiotic and has been approved by the FDA for the prevention and treatment of complicated urinary tract infections.[73,74,75] However, extensive use of meropenem has led to the development of resistance in most bacteria, posing challenges for its complete removal from wastewater treatment plants. As a result, residues find their way into

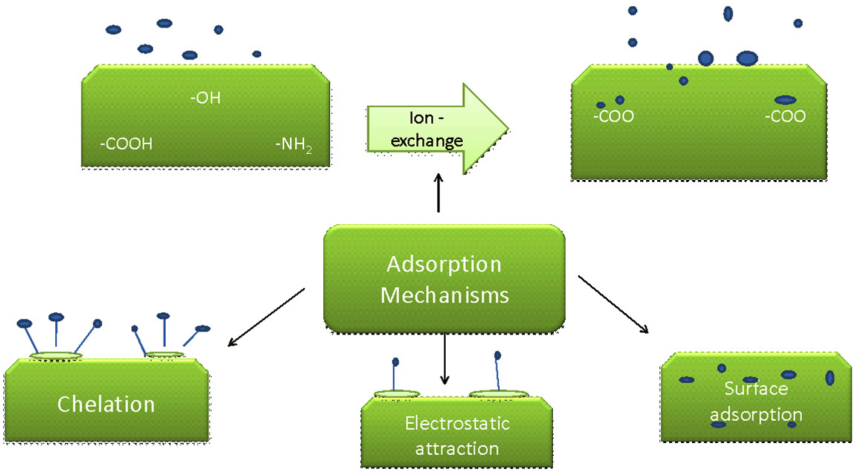

Figure 3. General Mechanism of bioadsorption process for antibiotic residue remediation from aquatic environment

Table 2. Bioadsorbents for dicloxacillin remediation

Bioadsorbents/ adsorbents	Maximum adsorption efficiency	Removal efficiency	Desorption efficiency & desorbing agents	Reference
Natural zeolite	1.072 mg/g	96.7%	-	113
Tannin from *Terminalia catappa* leaf	17.28 mg/g	98.7%	HCl	68

rivers, lakes, seas, and ultimately into drinking water and food sources.[73,76] Another research study found that lignocellulosic bioadsorbents derived from sawdust waste exhibited a 92% removal efficiency for meropenem, which increased to 96% after post-treatment (Figure 7, Table 4).[77] Further research is needed due to the importance of meropenem as the last line of defense for treating severe bacterial infections.

Ceftazidime

Ceftazidime is a broad-spectrum bactericidal antibiotic from the third generation of cephalosporins, effective against many gram-negative and some gram-positive bacteria. The presence of residues of ceftazidime and other antibiotics in aquatic environments has been linked to excessive production and usage, leading to concerns about the persistence and emergence of antibiotic resistance genes. Studies have identified

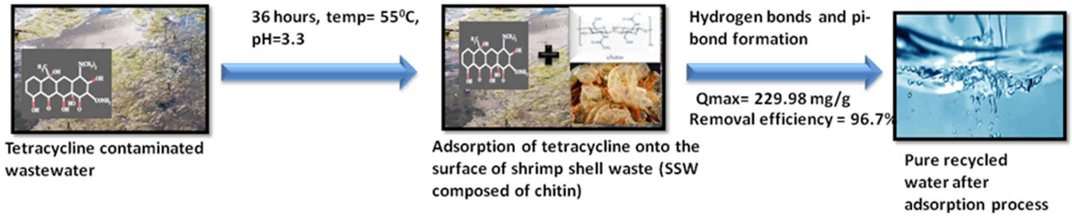

Figure 4. Tetracycline adsorption from wastewater by using shrimp shell waste biomass as bioadsorbent

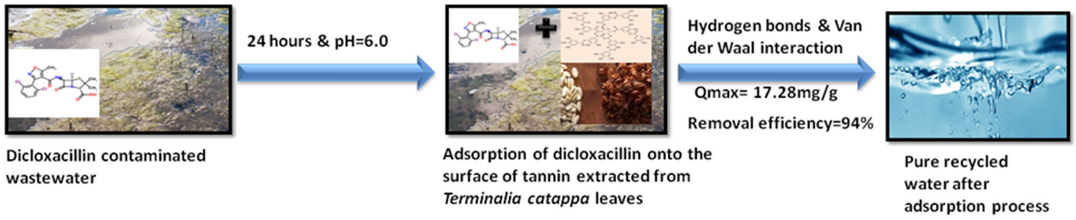

Figure 5. Dicloxacillin adsorption from wastewater by using tannin as bio adsorbent

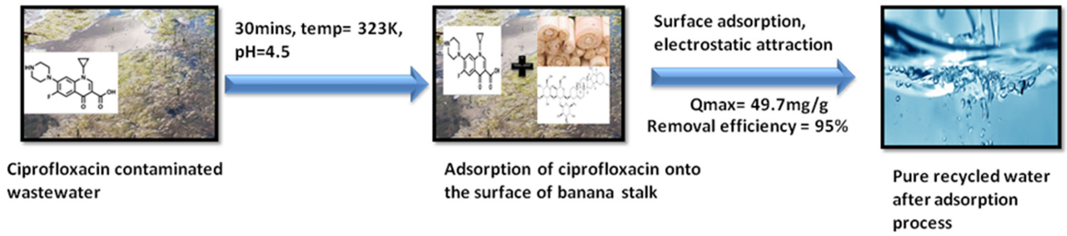

Figure 6. Ciprofloxacin adsorption from wastewater by using banana stalk as bio adsorbent

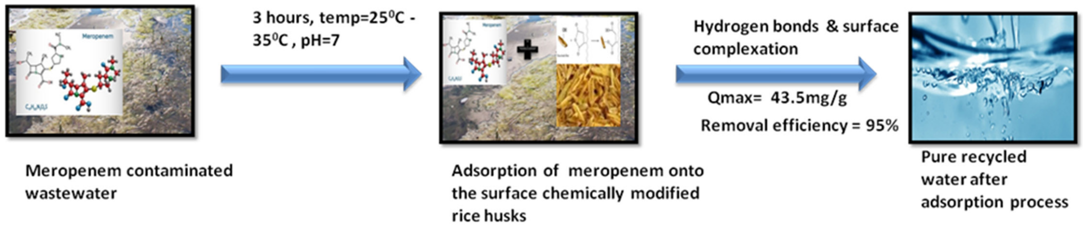

Figure 7. Meropenem adsorption from wastewater by using chemically modified saw dust as bio adsorbent

the presence of ceftazidime in pharmaceutical, hospital, and municipal wastewaters, highlighting the need for effective removal methods. Research has shown that the ceftazidime-tolerant green algae *Chlorella pyrenoidosa* can act as an efficient bioadsorbent, achieving a maximum adsorption capacity of 98.34%.[43,78] The functional groups on the surface of the algal cells, such as amino, hydroxyl, and carboxyl groups, play a role in the adsorption mechanism. The dead algal cells exhibited a high removal efficiency of 99.20%, with electrostatic interactions and hydrogen bonding contributing to the process (Figure 8, Table 5).[78]

Sulfonamide

Sulfonamides are generally the structural analogues of PABA (para-aminobenzoic acid) having distinct solubility level, excretion and absorption features.[79]

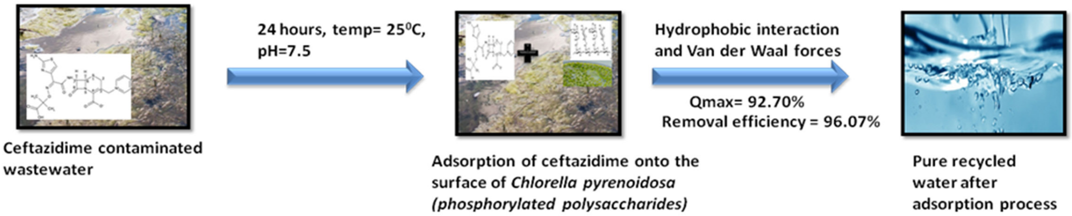

Figure 8. Ceftazidime adsorption from wastewater by using microalgal biomass of *Chlorella pyrenoidosa* as bio adsorbent

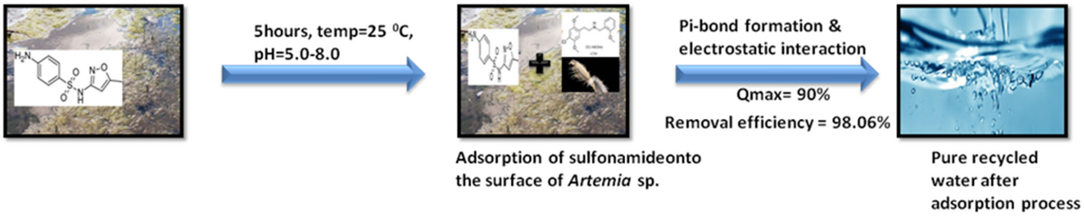

Figure 9. Sulfonamide adsorption from wastewater by using *Artemia* sp. as bio adsorbent

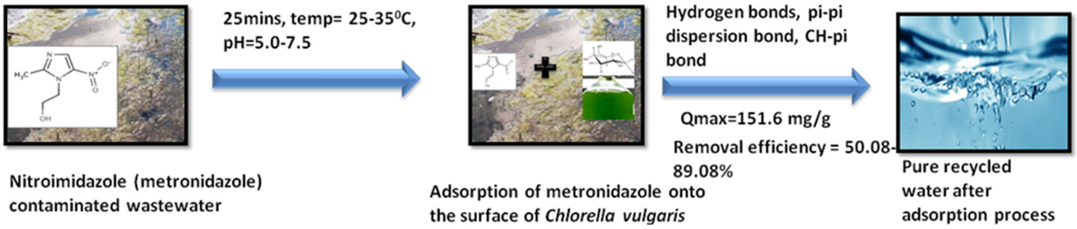

Figure 10. Metronidazole adsorption from wastewater by using *Chlorella vulgaris* microalgal biomass as bio adsorbent

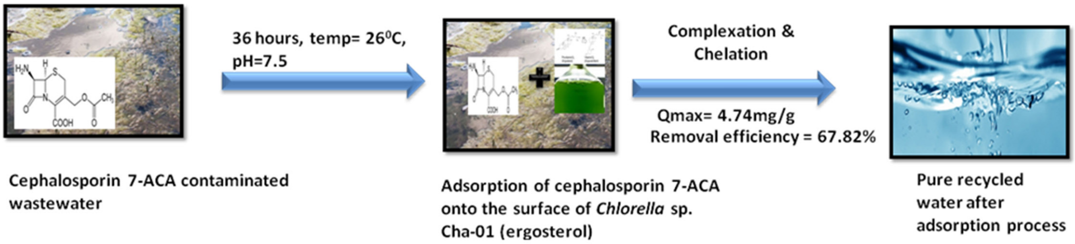

Figure 11. Cephalosporin-7-ACA adsorption from wastewater by using *Chlorella* sp. biomass as bio adsorbent

Chitosan has been identified as a reliable adsorbent for sulfonamide remediation due to its stability in high temperatures and pH ranges.[80] Adsorption mechanisms involve ionic-pi bonding, pi-pi interactions, and hydrogen bonding.[81] Pine bark has shown good affinity for sulfadiazine, sulfamethazine, and sulfachloropyridazine, with up to 95% adsorption within 24 hours.[80] Carbonaceous materials like powdered activated carbon, wood-based granular activated carbon, and graphene exhibit 90-95% adsorption capacity within 5 hours at pH 4.0.[82] Diatom Chaetoceros and arthropod Artemia have demonstrated adsorption of sulfonamides within 24 hours and 5 hours of contact time, respectively, at a temperature of 25°C and pH range of 5.0-8.0[83] as shown in Figure 9. Maximum adsorption capacities were 88% and 90%, respectively. Spent coffee grounds based on biochar and hydrochar showed adsorption capacities of 121.5µg/g and 130.1µg/g for biochar and 82.2µg/g and 85.7µg/g for hydrochar at 25°C.[84] Carboxyl-functionalized biochar derived from walnut shells exhibited 99% removal efficiency for sulfonamide, with involvement of hydrogen bonding and pi-pi interactions.[85] Bioadsorbents demonstrated efficient adsorption of sulfonamide (Figure 9, Table 6).[86]

Nitroimidazole

Nitroimidazole antibiotics are commonly used to treat anaerobic bacterial and protozoan infections, but they are frequently detected in wastewater treatment plants (WWTPs), drinking water, fish-farm waters, and industrial effluents.[87] These antibiotics are challenging to degrade due to their high polarity and are considered potentially carcinogenic and mutagenic.[88] They can contribute to the dissemination and proliferation of antibiotic resistance genes (ARGs) in the environment, posing risks to human and animal health. Consequently,

Table 3. Bioadsorbents for ciprofloxacin remediation

Bioadsorbents/ adsorbents	Maximum adsorption efficiency	Removal efficiency	Desorption efficiency & desorbing agents	Reference
Dialium guineense seed waste	120.34 mg/g	87.6%	-	114
Wheat bran	-	75%	-	115
Corn cob	13.76 mg/g	56.3%	-	116
Rice husk	2.33 mg/g	59.7%	-	117
photocatalytic hydrogel layer supported on alkali modified straw fibers	93.5 mg/g	-	-	118
Enteromorpha prolifera	21.7 mg/g	35.4% at 2.0 g/L bioadsorbent dosage	-	119
Gibberella fujikuroi	39.17 mg/g	53.74%	76.57% NaCl	120

Table 4. Bioadsorbents for meropenem remediation

Bioadsorbents/ adsorbents	Maximum adsorption efficiency	Removal efficiency	Desorption efficiency & desorbing agents	Reference
Lignocellulosic bioadsorbent derived from sawdust waste	231.29 mg/g	96%	92.4%	121
Rice husk functionalized with Mg/Fe-layered double hydroxides	43.5 mg/g	-	-	122

Table 5. Bioadsorbents for ceftazidime remediation

Bioadsorbents/ adsorbents	Maximum adsorption efficiency	Removal efficiency	Desorption efficiency & desorbing agents	Reference
Chlorella pyrenoidosa	98.4%	-	87.6% NaOH	78
Moringa oleifera	121.95 mg/g	87.65%	-	123

Table 6. Bioadsorbents for sulfonamide remediation

Bioadsorbents/ adsorbents	Maximum adsorption efficiency	Removal efficiency	Desorption efficiency & desorbing agents	Reference
Fe_3O_4-assisted extracellular polymeric substances (EPS)	77.93% (SMX) 74.13% (SM1) 65.62% (SM2) 56.64% (SDZ)	67.12%	-	124
Fiber industry wastes	24.06 mg/g	48%	-	125
sulfonated coffee waste	256 mg/g	-	-	126
Pectin derived from orange peel biomass	120 mg/g	92.2%	-	127
Discarded biodiesel waste-derived lignocellulosic biomass	206.2 mg/g	138.8 mg/g	65.5%NaOH	128
Corncobs	-	48%	-	116

the remediation of nitroimidazole antibiotic residues has become a significant concern for researchers. To facilitate practical application and separation, waste biomass-based adsorbents have been found to be more suitable than powdered biochar, as they are easier to recover and regenerate.[89]

The adsorption mechanisms between the adsorbents and nitroimidazole antibiotics involve hydrogen bonding, pi-pi dispersion, and micropore filling[87] as shown in Figure 10. A study assessed the combined use of microorganisms and activated carbon for nitroimidazole adsorption, demonstrating a maximum adsorption capacity of 2.04 mmol/g. However, the researchers observed that the microorganisms used in the biological stage of a wastewater treatment plant did not degrade nitroimidazoles. Nonetheless, the presence of microorganisms during the adsorption process enhanced the adsorption on activated carbon. Pi-pi dispersion interactions between carbon graphene layers and nitroimidazole aromatic rings played a crucial role, while electron-activating groups in both the adsorbent and adsorbate initiated the adsorption process, and pH had no significant effect (Figure 10, Table 7).[90]

Cephalosporin 7 ACA

Cephalosporin antibiotics are commonly used to treat bacterial diseases, but their residues in wastewater pose environmental risks. 7-amino cephalosporanic acid (7-ACA) is an intermediate residue in cephalosporin synthesis, exhibiting antibacterial activity due to its beta-lactam ring.[91]

Guo et al. found that three microalgal strains isolated from Southern Taiwan (Chlorella sp., Chlamydomonas sp., and Mychonastes sp.) had adsorption capacities of 4.74 mg/g, 3.09 mg/g, and 2.95 mg/g, respectively, at pH 7.5 and 26°C.[92,93] The adsorption mechanism involved monolayer and multilayer adsorption on the microalgae's heterogeneous surface. Activated carbon, previously used as an adsorbent, has regeneration issues. Cephalosporin 7-ACA showed

Table 7. Bioadsorbents for nitromidazole remediation

Bioadsorbents/ adsorbents	Maximum adsorption efficiency	Removal efficiency	Desorption efficiency & desorbing agents	Reference
Siris seed pods	180.74 mg/g	98.74%	-	129
Prosopis juliflora	13.55 mg/g	17.45 mg/g	-	130
Rice husk	4.79 mg/g	96.4%	-	131

Table 8. Bioadsorbents for cephalosporin 7-ACA remediation

Bioadsorbents/ adsorbents	Maximum adsorption efficiency	Removal efficiency	Desorption efficiency & desorbing agents	Reference
Lipid-accumulating *Chlorella sp., Chlamydomonassp.,* and *Mychonastes sp*	4.74 mg/g, 3.09 mg/g 2.95 mg/g	-	-	92
Pseudomonas putida	109.5 mg/g	more than 50%	89.7% HCl	132
Activated olive stones	40.71 mg/g	65%	-	133

very good removal efficiency by bio adsorbents (Figure 11 and Table 8).[94]

Mechanism of Bio adsorption

The adsorption process, traditionally considered exothermic, has been found to exhibit both exothermic and endothermic characteristics in recent research articles.[95,96] Adsorption can occur through two types: physisorption (physical adsorption) and chemisorption (chemical adsorption). When bioadsorbents such as microalgae, macroalgae, fungi, bacteria, and medicinal plants are exposed to antibiotic-containing solutions, they exhibit various responses to survive and remediate the harmful antibiotic residues.[95] Among remediation techniques, adsorption is considered a reliable method for removing emerging contaminants from wastewater by binding the antibiotic residues to solid materials, such as adsorbents or bioadsorbents.[65] Antibiotic adsorption by adsorbents like biochar, activated carbon, and nanomaterials primarily occurs through hydrogen bonds, hydrophobic bonds, electrostatic attraction, and Van der Waals forces.[64]

The adsorption mechanism involves ion exchange, pi-pi bond interactions, functional groups and H-bond interactions, electrostatic interactions, pore filling, and intra-particle diffusion.[97] Ion exchange maintains electrical neutrality between liquid and solid phases, while intra-particle diffusion and pore filling depend on specific surface area and pore size of the adsorbent.[98] Surface adsorption, electrostatic interactions, hydrogen bonds, and hydrophobic interactions play significant roles in the adsorption of antibiotics.[99] Various modifications of biochar, bacteria, plants, fungi, algae, and agricultural wastes can enhance their adsorption capabilities. Tetracycline is a extensively studied antibiotic, known for its broad-spectrum feasibility, polar functional groups (carboxyl and acyl-amino), while ciprofloxacin possesses non-polar functional groups.[100]

The adsorption process offers unique advantages for the removal of antibiotic residues from wastewater. Tetracycline has been extensively studied in the research on remediation of antibiotics and their residues using adsorption techniques. The reason for focusing on tetracycline is its favorable response to various types of adsorbents and bioadsorbents. Adsorption technology provides several benefits, including low energy consumption, easy operation, and no production of by-products or secondary pollutants. This process effectively eliminates harmful antibiotic residues, antibiotic resistance genes, and antibiotic-resistant bacteria present in wastewater. Numerous researchers have reported that the use of bioadsorbents makes the adsorption process more eco-friendly and cost-effective.[19,101,102] The adsorption process demonstrates a short remediation period and has been proven to be the most efficient and effective method for removing antibiotic residues from wastewater due to its stability (Figure 4-11, Table 1-8).[22] Bioadsorbents such as banana peel*, Moringa oleifera, Pseudomonas putida, Saccharomyces cerevisiae,* and other agricultural wastes have been identified as suitable options for adsorbing antibiotic residues from wastewater. These bioadsorbents are used in a dried form, eliminating the need for additional nutrients.[96,98,103] Further studies are required to explore additional advantages of using this process for the remediation of antibiotic residues from wastewater.

CONCLUSION

In conclusion, the use of bioadsorbents for removing antibiotic residues from wastewater has shown promising results. Different bioadsorbents, including raw shrimp shell waste, mussel shell, pine bark, oak ash, and tannin from Indian almond leaf, algae, fungi, bacteria have exhibited excellent adsorption capacities for specific antibiotic residues. The interactions between the functional groups of bioadsorbents and antibiotic residues, such as Van der Waals forces and hydrogen bonds, play a crucial role in the adsorption process.

This review highlights the need for further research and evaluation of various bioadsorbents to address antibiotic residues in wastewater. The adoption of eco-friendly adsorption techniques for treating wastewater from pharmaceutical, hospital, and municipal sources is gaining momentum. The development of new adsorbents and bioadsorbents holds significant promise, providing comprehensive, economic, social, and environmental benefits in water pollution control.

Overall, this review serves as a valuable resource for researchers and practitioners engaged in the study and application of adsorption processes for the removal of antibiotic residues from wastewater. Continued exploration and advancement of adsorbent materials and techniques will contribute to more efficient and sustainable solutions in the future.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORS' CONTRIBUTION

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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DATA AVAILABILITY

All datasets generated or analyzed during this study are included in the manuscript.

ETHICS STATEMENT

Not applicable

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