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MITIGATING AQUATIC CARBAMAZEPINE POLLUTION: A SYSTEMATIC REVIEW OF BIOREMEDIATION STRATEGIES

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Abstract

Pharmaceutical pollution in aquatic environments causes significant ecological and public health challenges. Carbamazepine is one of the major pharmaceutical pollutants, and bioremediation is considered a suitable method for removing pharmaceutical pollutants. Thus, this study aimed to systematically review the published literature on biological approaches, specifically microbial and algal bioremediation, for the removal of the pharmaceutical pollutant carbamazepine from aquatic systems. A systematic review of the published literature was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) approach. A comprehensive literature search was conducted using Google Scholar, PubMed, and ResearchGate for studies published between 2015 and April 2025. The keywords 'carbamazepine', 'bioremediation', 'aquatic environments' and 'pharmaceutical pollution' were included in the search. The search identified a total of 1,148 articles (ResearchGate: 100, PubMed: 18, Google Scholar: 1,030). After following the exclusion and inclusion criteria, four full papers were selected to review. According to the findings, the bacterial strain *Rhodococcus zopfii* exhibited the highest carbamazepine removal (99.92–99.98%) at a pH of 7 and 40°C. However, the elevated temperature requirement limits the practical applicability. *Gordonia polyisoprenivorans* achieves over 50% carbamazepine removal at pH 7 and 32 °C. Among microalgae, *Ankistrodesmus braunii* is utilised due to its high removal efficiency (up to 87.6% at 10 mg/L Carbamazepine) and robust tolerance, making it the most suitable choice for a range of Carbamazepine concentrations. In contrast, *Chlamydomonas mexicana* and *Scenedesmus obliquus* exhibit lower efficiencies at higher Carbamazepine concentrations. To further elucidate the absolute effects of these approaches, a meta-analysis of existing literature is recommended. Future research should investigate hybrid systems that combine bacterial and algal consortia to improve removal efficiency and mitigate potential environmental challenges.

Keywords: Aquatic Environments, Bioremediation, Carbamazepine, Pharmaceutical Pollution

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Introduction

Pharmaceuticals play a significant role in enhancing the quality of life. However, the manufacturing of pharmaceutical products has given rise to significant environmental challenges due to massive production, irresponsible use, improper disposal, and inefficient treatment processes (Ashiwaju et al., 2023). Significant amounts, ranging from microgram to milligram levels, of active pharmaceutical compounds are detected in groundwater, topsoil, drinking water, and even in the atmosphere (Srinivasan et al., 2025).

Pharmaceutical pollution has raised concerns with the increased occurrence of active pharmaceutical compounds and is considered an "emerging contaminant" in global aquatic ecosystems. Conventional treatment plants are not always capable of removing specific pharmaceutical compounds from wastewater before it is discharged. As a result, pharmaceuticals are frequently and consistently detected in aquatic environments. Examples of highly detected pharmaceutical compounds found in aquatic environments are carbamazepine, acetaminophen, diclofenac and ibuprofen (Tay et al., 2023a).

The psychotropic drug carbamazepine ($C_{15}H_{12}N_2O$) is one of the most frequently detected drugs in global surface waters with a detection frequency of 61.4 % worldwide. Carbamazepine is an antiepileptic drug that is not only used to treat epileptic seizures but also to treat pain from trigeminal neuralgia and bipolar disorder (Ayano, 2016). Due to poor removal from sewage and slow dissipation, carbamazepine is frequently detected in freshwater environments (Emily et al., 2022).

As a result of its abundant presence in surface waters, carbamazepine has been the focus of numerous toxicity studies on its hazard to human health and the environment, such as abnormal human endocrine system function, interference with human fetal development and affecting the larvae growth of aquatic animals (Yang et al., 2023).

For the removal of carbamazepine, traditional physical and chemical methods, including adsorption, membrane filtration, and electrochemical treatments such as ozonation, chlorination, and Fenton reactions, are used. However, conventional approaches are often costly, generate toxic by-products, and are not always suitable for addressing the complexity of pharmaceutical contaminants. In contrast, bioremediation, which uses microbial communities to break down pollutants, offers a promising alternative and cost-effective method when applied effectively (Tay et al., 2023b).

Bioremediation, utilising native microbial monocultures or consortia or bioaugmentation, has been used for decades as a sustainable technology to manage anthropogenic pollution. The advantages of bioremediation include reduced input of hazardous chemicals, energy, and time, and it is relatively inexpensive compared to physicochemical technologies (Azubuike et al., 2016). The primary benefit of bioremediation is that the pollutant is chemically transformed, rather than simply being shifted from one environment to another. However, a notable drawback of this method is that the remediation speed does not meet the treatment capacity requirements. Nevertheless, considering the benefits of this approach, efforts are being made to optimise efficiency and reduce retention times. Therefore, selecting an appropriate microbial community and optimising the biodegradation process play a crucial role in enhancing the biodegradation performance of carbamazepine.

However, the effectiveness, degradation efficiency and practical applicability of various bioremediation strategies remain scattered across the literature. This systematic review aims to systematically evaluate current research on microbial and algal-based removal of carbamazepine in aquatic systems, providing a comprehensive assessment of existing methods, their comparative efficiencies, and future directions for sustainable water treatment solutions.

In a systematic review, existing research studies are evaluated against previously defined study criteria and further sorted by thoroughly analysing their content. In the sorting process, the validity and suitability of the research question are highly assessed. The further systematic review assesses the methodological quality of the studies included, ensuring a rigorous and objective evaluation of the research conducted in this field. Finally, a qualitatively synthesised conclusion is extracted using the previously set inclusion and exclusion criteria. Furthermore, this study will help identify the most effective microbial and algal-based methods for removing carbamazepine in aquatic systems, as well as their comparative efficiencies, and provide future directions for sustainable aquatic ecosystems.

Methodology:

Search Strategy

A systematic review of published studies on the bioremediation strategies for carbamazepine removal from aquatic environments follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach. A PRISMA analysis was conducted through four sequential steps: identification, screening, eligibility assessment, and inclusion. For the "Identification" process, a comprehensive search was conducted using ResearchGate, PubMed (US National Library of Medicine, USA), and Google Scholar for peer-reviewed articles published from 2015 to 2025. The keywords were 'carbamazepine', 'bioremediation', 'aquatic environments', and 'pharmaceutical pollution'. Then, articles were screened by removing duplicates. The remaining articles were initially selected by reading abstracts. Full texts of the shortlisted articles were then thoroughly reviewed for eligibility. Studies that failed to meet the inclusion criteria or were excluded for any reason were systematically excluded. Most qualitatively suitable and eligible articles were included for analysis. Only peer-reviewed articles published in English were considered for the final analysis, while conference proceedings, commentaries, and other non-peer-reviewed literature were excluded. This selection strategy ensured the analysis remained focused and scientifically rigorous, allowing for a thorough examination of the chosen parameters.

The papers obtained from the database search using the specified criteria were pooled, and duplicate entries were removed. Next, the articles were first assessed by reviewing their titles and then by examining their abstracts. Studies that did not meet the inclusion criteria were excluded during the initial screening phases. The remaining articles were examined through a final screening by reading their full texts, and those that did not meet the inclusion criteria were excluded.

Inclusion / Exclusion Criteria.

The following inclusion criteria were applied when selecting articles:

(a) Studies about carbamazepine, (b) Studies conducted on biological remediation methods only, (c) only in aquatic systems, (d) Used microbial (bacteria, fungi) or algae-based bioremediation, (e) Studies that discuss the pharmaceutical degradation efficiency of the method.

The following exclusion criteria were applied in removing the articles:

(a) Duplicate articles, (b) Studies focused on non-aquatic environments, (c) Studies about general pollution without pharmaceutical focus, (d) Errors with experimental design and results presentation (no replicates, no average or standard errors of mean), (e) Articles published in languages other than English, (f) Systematic reviews, literature reviews and conference proceedings.

Results and discussion:

The literature search yielded several studies in the databases, as follows: PubMed (n = 18), ResearchGate (n = 100), and Google Scholar (n = 1030).

Following the exclusions, only four articles were incorporated into the current review. Fig. 1 illustrates the search strategy employed for article selection. This systematic review aimed to review existing scientific data on the biological approaches for the remediation of carbamazepine in aquatic environments. All four studies included in this review have focused on microbial or algal-based bioremediation, providing data on the efficiency of pharmaceutical degradation.

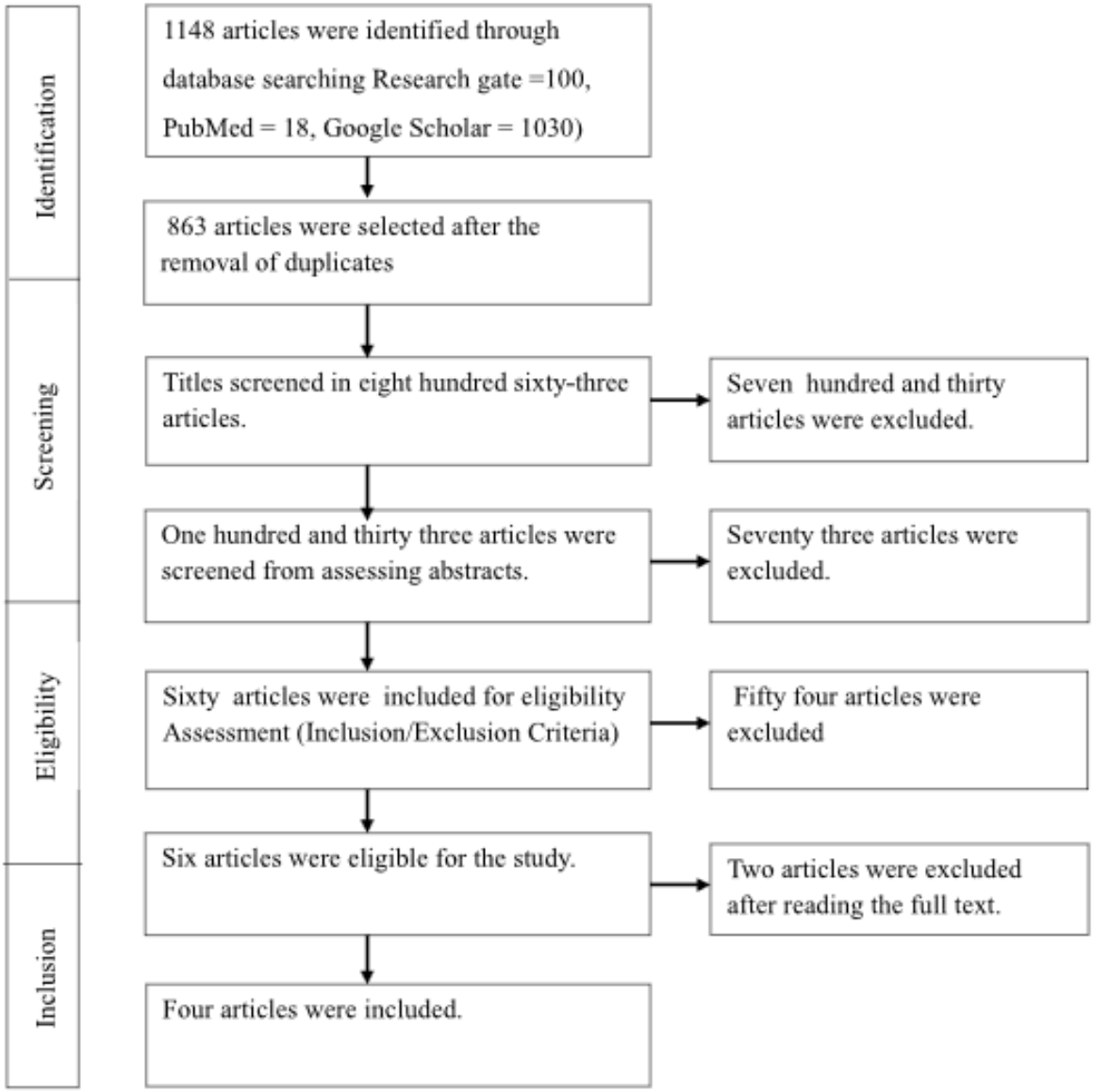

Figure 01: Flow Diagram Explaining the Search Strategy, Inclusion and Exclusion Criteria Used for The Systematic Review of Scientific Literature.

Table 01: Summary of Studies on Microbial and Algal-Based Bioremediation of Carbamazepine in Aquatic Environments.

Research paper	Microbial/algae Type	Carbamazepine Concentration	Degradation Efficiency (%)	Key Conditions (e.g., pH, Temp)
(Kasri et al., 2024)	*Rhodococcus zopfii* (bacteria)	10 mg/L	99.92 ±0.04% to 99.98 ±0.14% within 5 days under optimal conditions.	Temperature: 40°C (optimal) pH: 7 (optimal) Agitation: 150 rpm
(Yehya et al., 2020)	*Ankistrodesmus braunii* (algae)	2.5 and 10 mg/L	87.6% (60 days)	Temperature: 30°C Agitation: 135 rpm
(Wang et al., 2023)	*Gordonia polyisoprenivorans*(bacteria)	10 mg/L	>50%	Temperature: 32°C pH: 7 Agitation: 150 rpm
(Xiong et al., 2016)	*Chlamydomonas Mexicana* (microalgae)	100 mg/L	35% (10 days)	Temperature: ~25–27°C pH: 7.0–7.5 (standard range)
	Scenedesmus obliquus (microalgae)	(100). mg/L	28% (10 days)	

As shown in Table 1, Kasri et al. (2024) have evaluated the biodegradation of carbamazepine by the gram-positive bacterium *Rhodococcus zopfii*, specifically examining the optimum biodegradation conditions and the roles of extracellular enzymes. The biodegradation efficiency of carbamazepine, concentrations of carbamazepine that can be removed by bioremediation, and the optimum pH and temperature conditions for bioremediation were investigated in this study. For the carbamazepine biodegradation, the optimum compound concentration, pH, and temperature were 10 mg/L, pH 7, and 40 ℃, respectively, with carbamazepine biodegradation percentages ranging from 99.92 ± 0.04% to 99.98 ± 0.14%. Bacterial growth and carbamazepine biodegradation occurred sequentially, with bacterial growth promoting the biodegradation of carbamazepine. This study provides vital information on the biodegradation of carbamazepine using the gram-positive bacterium R. *zopfii* as a sustainable technology, thereby mimicking natural processes and benefiting wastewater treatment management and industrial applications.

Yehya et al. (2020 used green microalgae, *Ankistrodesmus braunii* (A. braunii), for the biodegradation of carbamazepine. The respective effects of the culture medium, the initial inoculum, and carbamazepine concentrations on carbamazepine removal were studied. The data presented clearly

demonstrate that the highest percentage of carbamazepine elimination achieved was 87.6% at a temperature of 30 °C.

Wang et al. (2023) utilised a bacterium capable of degrading carbamazepine, isolated from wastewater, and identified the strain as *Gordonia polyophrenivorans*. The concentration of carbamazepine in the bacterial degradation system at different time periods was measured using High-performance liquid chromatography (HPLC) at an initial concentration of 10 mg/L. The resulting strain was able to remove more than 50% of carbamazepine. In summary, this study reported on a new biodegradation pathway of carbamazepine using a novel bacterium.

Xiong et al. (2016*)* used freshwater microalgae *Chlamydomonas mexicana* and *Scenedesmus obliquu*s to evaluate the toxicity and cellular stresses of carbamazepine on these microalgae, as well as its biodegradation by both species. *C. mexicana* and *S. obliquus* could achieve a maximum of 35% and 28% biodegradation of 100 mg L^{-1} carbamazepine, respectively. This study demonstrated that *C. mexicana* was more tolerant to carbamazepine and could be used for the treatment of carbamazepine-contaminated aquatic systems.

Those four studies focus on the removal of carbamazepine from water using bioremediation, particularly through bacterial and algal-based approaches. All the studies have investigated the effect of key parameters (pH, temperature, initial carbamazepine concentration, and degradation efficiency (%) on the removal process.

Kasri et al. (2024) and Wang et al. (2023) both utilised gram-positive bacterial strains to degrade carbamazepine, achieving high removal efficiencies and focusing on the degradation pathways or enzyme roles involved. Kasri et al. (2024) utilised the bacterium *Rhodococcus zopfii*, where**as** Wang et al. (2023) employed the bacterium *Gordonia polyisoprenivorans*. However, Kasri et al. (2024 reported that the highest removal efficiency (~99.9%) was achieved compared to Wang et al. (2023 (>50%), with similar key conditions (pH: 7, Agitation: 150 rpm) but with slightly different temperature change (8 °C). For maximum removal efficiency, *Rhodococcus zopfii* (Kasri et al., 2024) is beneficial to use, achieving near-complete carbamazepine removal in just 5 days under optimal conditions. However, *Rhodococcus zopfii* operates at a higher temperature (40°C), which may not be practical for all wastewater treatment facilities but is highly efficient.

Gordonia polyisoprenivorans is more flexible regarding temperature, making it easier to integrate into existing treatment systems if lower temperatures are preferred.

Yehya et al. (2020 and Xiong et al. (2016 both use microalgae to remove carbamazepine, but with different efficiencies and mechanisms. Yehya et al. (2020 utilised green microalgae, *Ankistrodesmus braunii* (A. braunii), for the biodegradation of carbamazepine at an initial concentration of 10 mg/L, achieving a maximum percentage of carbamazepine elimination of 87.6% at 30°C. Xiong et al. (2016 used freshwater microalgae *Chlamydomonas mexicana* and *Scenedesmus obliquus* species to evaluate the biodegradation of carbamazepine by both microalgal species. *C. mexicana* and *S. obliquus* could achieve a maximum of 35% and 28% biodegradation of 100 mg L^{-1} of carbamazepine, respectively. When comparing the tolerance to carbamazepine, *C. mexicana*, which had only 30% growth inhibition, was more tolerant to carbamazepine than *S. obliquus*, which had 97% growth inhibition due to carbamazepine concentration.

For maximum removal efficiency, *Ankistrodesmus braunii* is the best microalgae for carbamazepine removal due to its high removal efficiency, strong tolerance to carbamazepine, and practical applicability across a range of carbamazepine concentrations. A. *braunii* achieved up to 87.6%

carbamazepine removal even at 10 mg/L, which is much higher than the removal rates reported for C. *mexicana* (35%) and S. *obliquus* (28%) at 100 mg/L, while C. *Mexicana* is more tolerant than S. *obliquus* at high carbamazepine concentrations; however, its removal efficiency is much lower than that of A. braunii at lower, more environmentally relevant or moderately elevated carbamazepine levels. Therefore, A. *braunii* can be suggested as an effective solution for the bioremediation of carbamazepine in aquatic environments.

Conclusions and Recommendations

Bioremediation using microorganisms, specifically bacteria and microalgae, offers a viable and sustainable approach for removing pharmaceutical pollutants, such as carbamazepine, from aquatic environments. All four studies included in the systematic review investigated the influence of key parameters, such as pH, temperature, initial carbamazepine concentration, and microbial or algal inoculum, on removal efficiency and process robustness. When considering bacterial bioremediation, *Rhodococcus zopfii* achieved near-complete carbamazepine removal (99.92–99.98%), outperforming *Gordonia polyisoprenivorans* (removal >50%). However, the higher temperature requirement for *R. zopfii* may limit its practical applicability in some aquatic environments. Microalgae, *including Ankistrodesmus braunii, Chlamydomonas mexicana* and *Scenedesmus obliquus*, have been shown to be effective in removing carbamazepine. However, the removal efficiency of *A. braunii* far surpasses that of other microalgae, making it a superior candidate for practical application. To analyse the absolute effect of different bioremediation strategies on carbamazepine removal, a meta-analysis of existing findings is highly recommended. Future research should investigate hybrid systems that combine bacterial and algal consortia to enhance carbamazepine removal further and address potential challenges related to metabolite toxicity and process scalability.

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