

Bioremediation of carbendazim from contaminated water samples by systemic herbicide-degrading indigenous microbial consortium: A review

Arnab Gon, Roma Roy, Riya Pajiar, Saheli Khan and Jigisha Roy Panda *

Department of Life Science 157/F, Guru Nanak Institute of Pharmaceutical Science and Technology, Nilgunj Road, Sahid Colony, Panihati, Khardaha, Kolkata – 700114, West Bengal, India.

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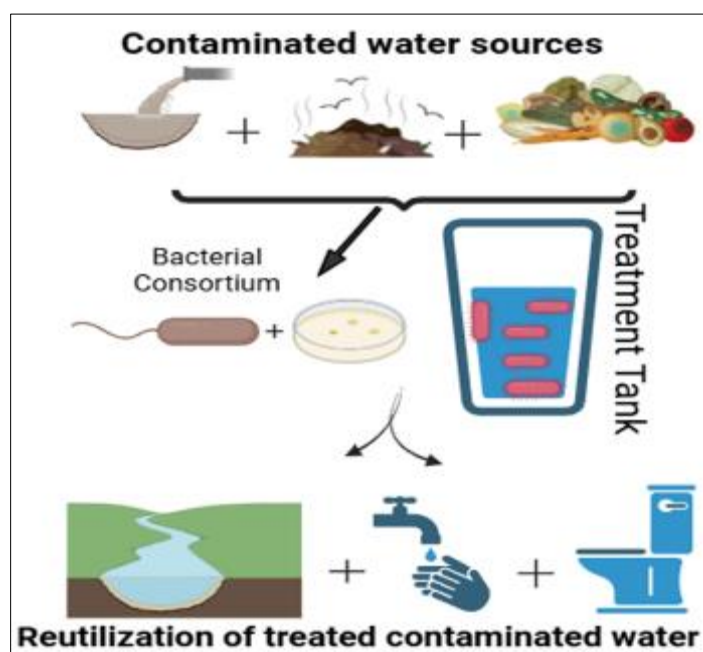
Abstract

The review work examines the bioremediation of carbendazim (CBZ), a widely used systemic fungicide, through the application of bioaugmented microbial consortia. Recent research has demonstrated the effectiveness of using indigenous microbial strains, particularly when combined with fungal species such as *Aspergillus versicolor*, to enhance the degradation of CBZ in contaminated greywater. In a study, a bioaugmented consortium achieved degradation efficiencies of 94.4% for CBZ over a 10-day period, showcasing the potential of this approach in mitigating pesticide residues from environmental matrices. The present work discusses various mechanisms employed by these microbial consortia, focusing on enzymatic pathways that facilitate the breakdown of CBZ into less harmful metabolites. The study highlights the importance of employing toxicity indicators such as the Environmental Potential Risk Indicator for Pesticides (EPRIP) and the Attenuation Factor Index (AFI) to assess the ecological impacts of CBZ in water systems. Notably, CBZ exhibited a higher EPRIP value (42.1) compared to other pesticides, indicating significant environmental risk. By integrating specific bacterial strains like *Pseudomonas* and *Bacillus subtilis* with fungi, researchers have paved the way for more effective bioremediation strategies. This review underscores the promise of bioaugmentation techniques not only for degrading CBZ but also for enhancing overall wastewater treatment processes, thus contributing to sustainable agricultural practices and environmental health.

Keywords: Carbendazim; Biodegradation; Systemic herbicide; Biostimulation; *Rhodococcus* sp.

* Corresponding author: Jigisha Roy Panda

Graphical abstract



1. Introduction

A systemic benzimidazole fungicide, carbendazim (methyl benzimidazol-2-ylcarbamate) is used extensively in horticulture, forestry, agriculture, and associated industries to prevent fungal diseases in crops like cereals, fruits, vegetables, and decorative plants [1]. It works by interfering with the creation of fungal cell walls and the activation of enzymes, which stops fungal growth and reproduction [2]. Because carbendazim is persistent in the environment and has the ability to bioaccumulate through the food chain, it poses serious ecological and human health hazards despite its effectiveness [3].

Table 1 Overview of Carbendazim [4]

ASPECT	DETAILS
Chemical Composition	$C_9H_9N_3O_2$
Primary Applications	Fungicide for crops, fruits, vegetables, and forestry
Half-life	2–25 months (water), 6–12 months (soil)
Health-Hazards	Mutagenicity, carcinogenicity, endocrine disruption, hepatotoxicity
Microbial Degrades	<i>Bacillus</i> sp., <i>Pseudomonas</i> sp., <i>Rhodococcus</i> sp., <i>Aeromonas</i> sp., and others
Key Degradation Pathways	Hydrolysis to 2-aminobenzimidazole (2-AB) and 2-hydroxybenzimidazole (2-HB)

Carbendazim is linked to environmental contamination worldwide, especially in soil, water, and agricultural effluents [5]. Because of its variable half-life, which varies from 2 to 25 months according on environmental factors, it is persistent and removal might be difficult [6]. The mutagenic, carcinogenic, and endocrine-disrupting consequences of carbendazim exposure highlight the need for effective breakdown and elimination [7].

Microbial technology-based bioremediation has become a popular and economical method of treating carbendazim contamination [8]. Through hydrolysis and other enzymatic pathways, several microbial strains, including species of *Bacillus*, *Pseudomonas*, and *Rhodococcus*, have shown the capacity to break down carbendazim into non-toxic compounds [9][10]. These techniques have shown promise in lowering health and environmental risks in both natural and artificial systems [11][12].

1.1. Scope and Objectives

This review paper aims to consolidate and evaluate the existing research on the microbial degradation of carbendazim, with a focus on:

- Carbendazim residues' toxicity and effects on the environment. Microbial degradation processes and mechanisms.
- Technological developments in bioremediation and their useful applications.
- Challenges and opportunities for scaling up bioremediation strategies for environmental cleanup.

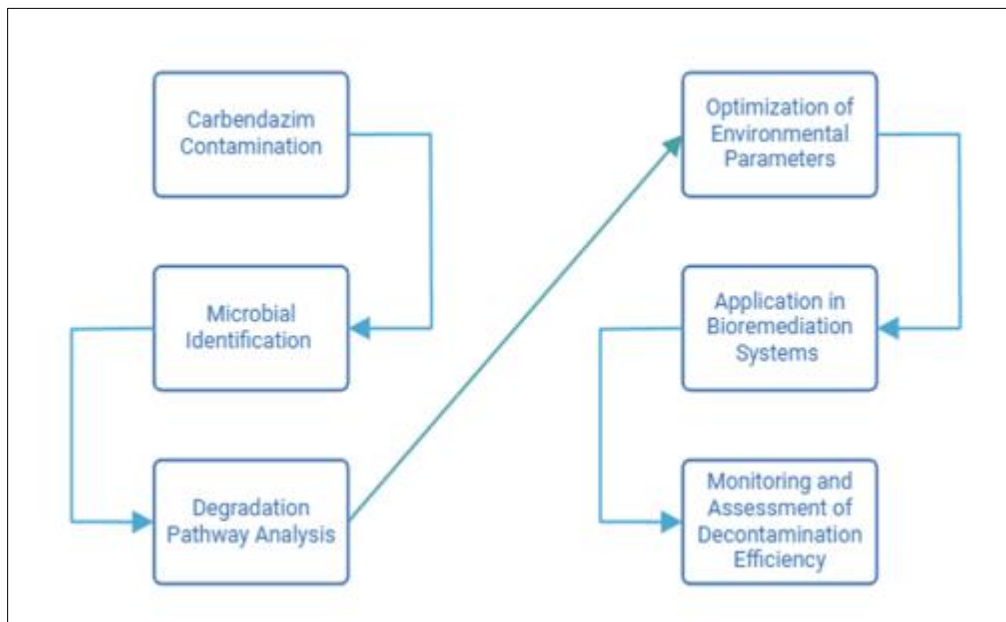


Figure 1 Flowchart of Carbendazim Bioremediation [13]

1.2. Objectives of Review

- To identify the most effective microbial strains and conditions for carbendazim degradation.
- To explore the feasibility of large-scale application of bioremediation strategies.
- To discuss gaps in current research and propose future directions for sustainable solutions.

2. Carbendazim: Properties, Uses, and Environmental Impact

2.1. Chemical structure and properties:

The molecular weight of carbendazim ($C_9H_9N_3O_2$), a member of the benzimidazole carbamate family [14][15], is 191.19 g/mol. A carbamate group is joined to a benzimidazole ring to form its chemical structure, as shown in Figure 2.

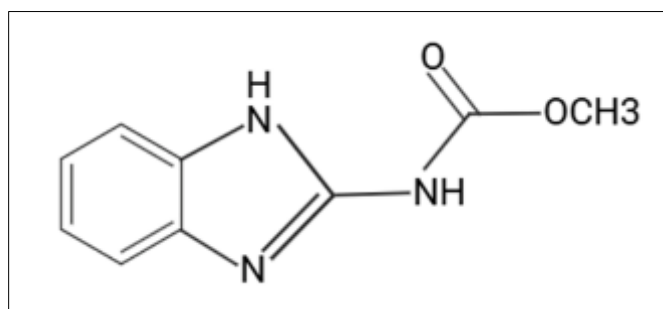


Figure 2 Chemical structure of Carbendazim [16]

With the formula $C_9H_9N_3O_2$, carbendazim is a benzimidazole carbamate fungicide that is distinguished by its stable structure [17][15]. It is persistent in the environment due to its stability in both neutral and acidic environments as well as its lengthy half-life in water (up to 25 months). Widely utilized in agriculture for controlling fungal diseases, such as rice blast and wheat scab, and in forestry for wood preservation [18][12]. Industrial applications include enhancing the durability of textiles, paints, and papers [19][20]. A significant issue is its residue in crops, water, and the food chain, contributing to potential toxicity [21]. Because carbendazim is harmful and persistent, sophisticated cleanup methods are required [22]. Using naturally occurring bacteria to convert carbendazim into non-toxic compounds, microbial degradation has become a viable remedy [23]. The methods, developments, and difficulties in microbial bioremediation will be covered in more detail in the sections that follow [24]. Carbendazim is extremely soluble in water and demonstrates little volatility, rendering it susceptible to leaking into groundwater. Its resistance to microbial and photodegradation breakdown accounts for its longevity in aquatic environments [25][26]. Hepatotoxicity, reproductive toxicity, and endocrine disruption are all part of CBZ's toxicological profile. Research shows that there are measurable levels of CBZ residues in agricultural runoff and urban streams, with concentrations as high as 31 ng/L in urban areas and 214 ng/L in the Brazilian Amazon [27].

3. Bioremediation Techniques

3.1. Overview of Bioremediation

Utilizing biological organisms, mostly fungus and bacteria, to break down or neutralize environmental pollutants and transform them into less harmful or non-toxic substances is known as bioremediation [28]. This method uses microorganisms' inherent metabolic pathways to combat contaminants including hydrocarbons, heavy metals, and pesticides [29][30]. Because some microbial strains may enzymatically break down carbendazim into safer metabolites, bioremediation has showed great promise in this regard [31][32].

Several studies have demonstrated the effectiveness of microbial species like *Bacillus licheniformis*, *Pseudomonas putida*, and *Rhodococcus* sp. in efficiently degrading carbendazim under controlled conditions, making microbial bioremediation particularly beneficial due to its affordability, environmental sustainability, and potential for in-situ applications [33].

3.2. Bioremediation Mechanism:

Enzymatic hydrolysis is the main mechanism by which carbendazim is broken down by microorganisms, producing intermediate compounds such as 2-aminobenzimidazole (2-AB) and 2-hydroxybenzimidazole (2-HB) [34]. After being digested into simpler molecules, these intermediates ultimately decompose into CO_2 and H_2O . Hydrolases and amidases are important enzymes involved in this process because they break the amide and ester bonds in carbendazim molecules [35]. The following is a summary of the degradation pathway:

- **First Hydrolysis:** 2-AB is created when carbendazim undergoes hydrolysis [36].
- **Additional Oxidation:** Oxidative reactions transform 2-AB into 2-HB [36].
- **Ring Cleavage:** CO_2 and H_2O are non-toxic byproducts of the benzimidazole ring cleaving [36].

Microbial technology-based bioremediation has become a popular and economical method of treating carbendazim pollution. Through hydrolysis and other enzymatic processes, several microbial strains, including species of *Bacillus*, *Pseudomonas*, and *Rhodococcus*, have shown the capacity to break down carbendazim into non-toxic metabolites. Exposure to carbendazim can result in mutagenic, carcinogenic, and endocrine-disrupting effects, further emphasizing the necessity for its efficient degradation and removal [37].

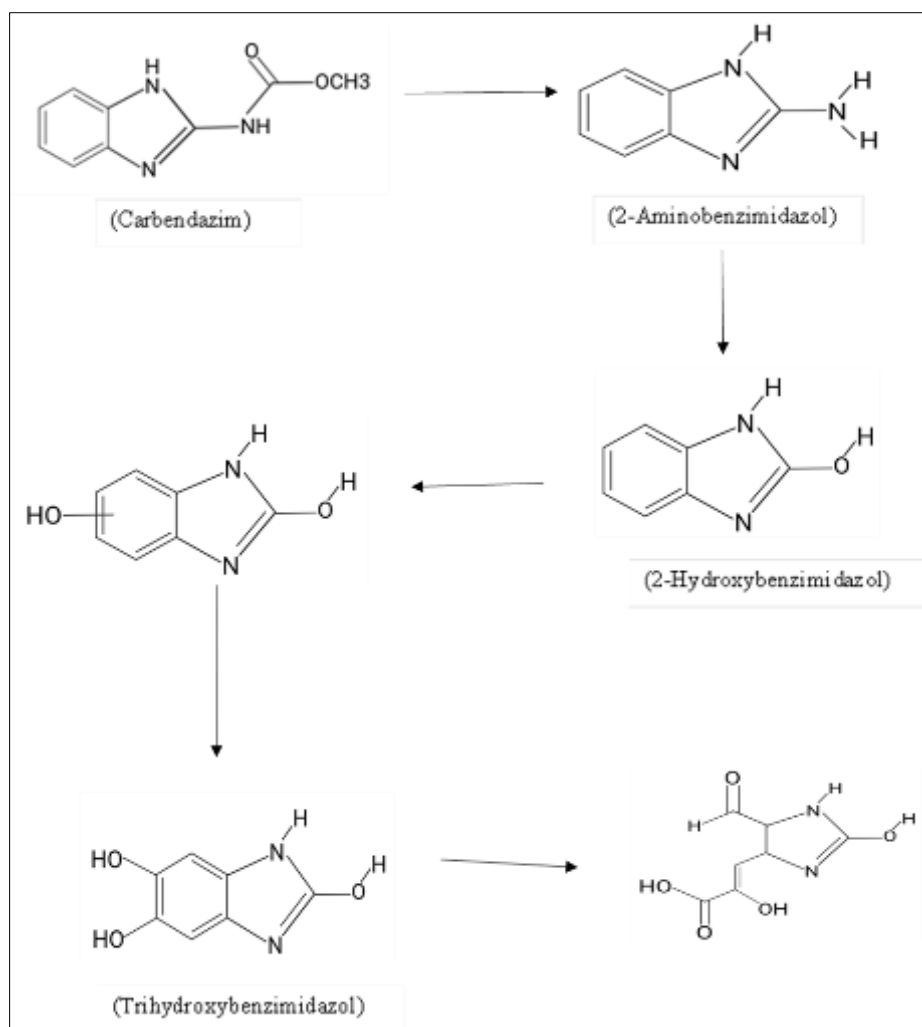


Figure 3 Pathway illustrating carbendazim degradation steps and intermediate products [38]

3.3. Bioremediation Strategies

To maximize the bioremediation of carbendazim, a number of tactics have been devised, including:

- Bioaugmentation is the process of adding certain microbial strains, including *Bacillus* and *Rhodococcus*, to polluted settings in order to accelerate the pace of breakdown. Under ideal circumstances, studies have shown that *Bacillus licheniformis* JTC-3 is capable of degrading more than 70% of carbendazim in a 24-hour period [39].
- Increasing the natural microbial activity by introducing nutrients or growth-promoting substrates is known as biostimulation. For synergistic benefits, this method is frequently used with bioaugmentation [40].
- Consortium-Based Degradation: Making use of diverse microbial consortia to take advantage of each species' complementing metabolic capacities. For instance, the biodegradation of carbendazim has been significantly improved by mixing bacterial consortia with fungus strains such as *Aspergillus versicolor* [38][39].
- Engineered Bioreactors: Creating regulated environments with optimal aeration, temperature, and pH control to promote microbial breakdown. Under similar circumstances, carbendazim has been shown to completely degrade in laboratory-scale bioreactors [41].

Bioremediation offers a sustainable and effective approach to mitigating the environmental impact of carbendazim contamination [42]. By leveraging the natural metabolic pathways of microorganisms, these strategies provide an eco-friendly alternative to conventional methods. Future research should focus on enhancing the scalability of these techniques while addressing challenges like microbial survival and adaptation in real-world scenarios [43].

4. Microbial Consortium in Bioremediation of Carbendazim

4.1. Role of Indigenous Microorganisms

Because of their innate ability to adapt to local environmental circumstances, indigenous microorganisms are essential to the bioremediation of carbendazim. These microorganisms may break down persistent organic contaminants like carbendazim because they frequently have built-in metabolic pathways [44]. It has been demonstrated species of *Pseudomonas* and *Bacillus* use carbendazim as a carbon source in polluted soils, breaking it down into less hazardous intermediates like 2-aminobenzimidazole and 2-hydroxybenzimidazole [45]. Utilizing native microorganisms has the benefit of being ecologically compatible and resilient, which reduces the need for outside modifications or inputs [46]. Research has shown that adding these native strains to microbial consortia greatly increases the rates at which carbendazim degrades [47].

4.2. Selection and Characterization of Consortium

Finding strains with comparable metabolic activity is a necessary step in the selection and characterization of microbial consortia for carbendazim bioremediation. To take advantage of their synergistic interactions, bacterial and fungal species are often combined in a consortium. For example, it has been demonstrated that *Aspergillus versicolor* increases the effectiveness of bacterial consortia by supplying enzymes that hasten the breakdown of complicated substances [48][49]. Analyzing the growth kinetics, substrate usage trends, and enzymatic profiles of possible consortia are common laboratory experiments [50]. To identify important microbial species and track their activity during the degradation process, sophisticated methods such as 16S rRNA sequencing and metabolomics are used [51].

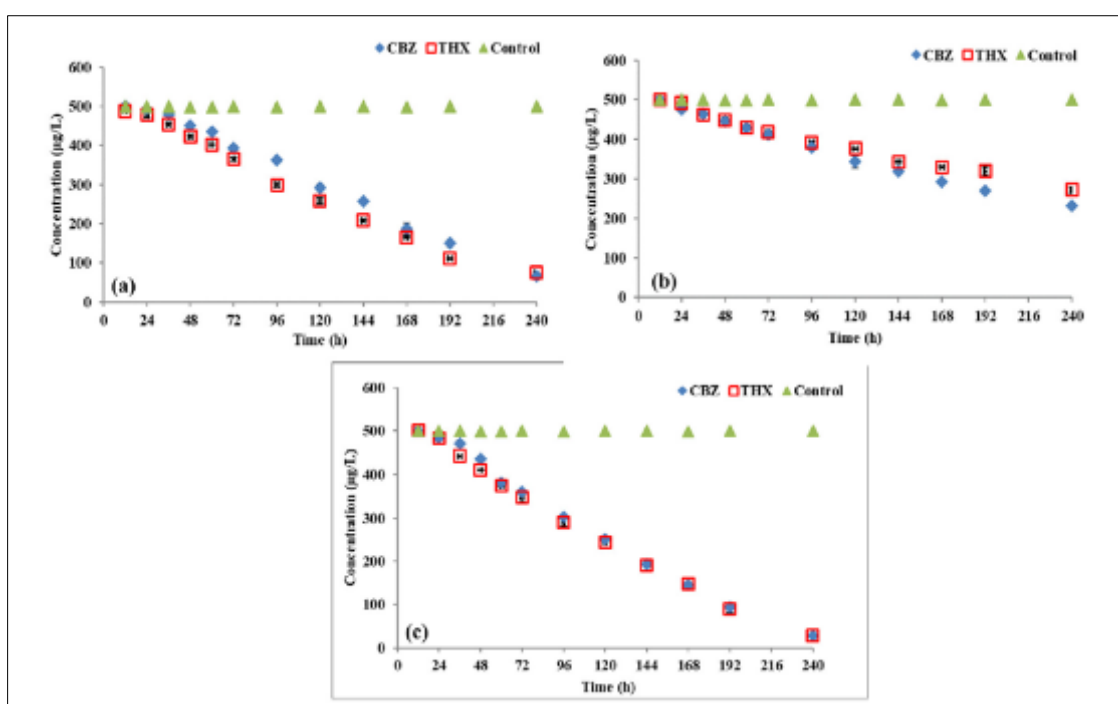


Figure 4 Degradation profiles of pesticides with the tested culture (a) fungus, (b) bacterial consortium, and (c) augmented consortium

According to reports, these consortia have been successfully used in controlled bioreactors, where, under ideal circumstances, degradation rates of over 90% were attained in ten days. This illustrates how microbial consortia may be a useful instrument for extensive bioremediation [51].

5. Carbendazim-Degrading Microorganisms

The breakdown of carbendazim in bacterial and fungal species that can convert this fungicide into less harmful intermediates has been thoroughly investigated. *Sphingomonas paucimobilis*, *Rhodococcus erythropolis*, *Pseudomonas putida*, and *Bacillus licheniformis* are notable bacterial species. These microbes use carbendazim as a source of carbon

and energy [51]. They hydrolyse it to 2-aminobenzimidazole and then oxidize it to 2-hydroxybenzimidazole. By generating extracellular enzymes like laccases and peroxidases that aid in the breakdown of complex carbendazim compounds, *Aspergillus* and *Trichoderma* species have demonstrated a great deal of promise in assisting bacterial degradation [52].

Research has shown that *Rhodococcus* strains have among of the best degradation efficiency; in lab conditions, they can lower carbendazim concentrations by as much as 90%. Because of their tolerance to high contaminant concentrations and capacity to adapt to a variety of environmental circumstances, these bacteria are especially well-suited for bioremediation [53]. The significance of synergistic interactions in bioremediation is further demonstrated by the enhanced results obtained by microbial consortia that incorporate various species with complementary degradative pathways [48].

Utilizing microorganisms that break down carbendazims is a viable way to reduce environmental pollution and provides a long-term substitute for chemical and physical cleanup techniques. The efficiency of these biological solutions can be greatly increased by more investigation into the optimization of microbial strains and their enzymatic pathways [54].

5.1. Isolation and identification

Sampling from polluted soils, water bodies, or agricultural areas subjected to carbendazim application is usually required to isolate carbendazim-degrading bacteria. Microorganisms that can use carbendazim as their only carbon source are carefully grown using enrichment culture methods [55]. Because of their adaptability and metabolic flexibility, microorganisms including *Bacillus*, *Pseudomonas*, *Rhodococcus*, and *Sphingomonas* have been regularly isolated from these settings [56].

Table 2 Carbendazim-degrading strains and degradation efficiency [52]

Strain	Environment	Time	Concentration	Degradation
<i>Bacillus pumilus</i> NY97-1	MSM	24H	300 Mg/L	Degradation rate of 90.07%
<i>Bacillus velezensis</i> HY-3479	M9 minimal medium	36H	100 Mg/L	Degradation rate of 85.25%
<i>Brevibacillus panacihumi</i> C17	MSM	1d	250 Mg/L	Degradation rate of 96.12%
<i>Rhodococcus jialingensis</i> djl-6-2	Soil	14d	200 Mg/L	Degradation rate of 98.32%
<i>Rhodococcus</i> sp. D-1	MSM	24H	100 Mg/L	Degradation rate of 89.35%
<i>Pseudomonas aeruginosa</i> CB3	MSM	48H	400 Mg/L	Degradation rate of 87.96%
<i>Streptomyces</i> CB1	MSM	14d	1000 Mg/L	Degradation rate of 78.64%
<i>Bacillus subtilis</i> CB2	MSM	14d	520 Mg/L	Degradation rate of 78.45%
<i>Rhodococcus erythropolis</i> JAS13	MSM	72H	300 Mg/L	Degradation rate of 79.63%
<i>Rhizobium leguminosum</i> CB4	Soil	-	200 Mg/L	Degradation rate of 97.45%
<i>Brevibacillus borstelensis</i> and <i>Streptomyces albogriseolus</i>	MSM	12H	300 Mg/L	Degradation rate of 75.12%
<i>Mycobacterium</i> sp. SD-4	MSM	14H	250 Mg/L	Degradation rate of 100%
<i>Rhodococcus erythropolis</i> djl-11	MSM	48H	300 Mg/L	Degradation rate of 97%
<i>Rhodococcus</i> sp. CX-1	Soil	14d	200 Mg/L	Degradation rate of 78.63%
<i>Rhodococcus qingshengii</i> djl-6	M9 minimal medium	24H	1000 Mg/L	Degradation rate of 84.12%
<i>Pseudomonas</i> sp. CBW	MSM	48H	300 Mg/L	Degradation rate of 100%
<i>Ralstonia</i> sp. 1-1	Soil	12H	200 Mg/L	Degradation rate of 86.13%
<i>Bacillus subtilis</i> DR-39, CS-126, TL-171, TS-204	Soil	1d	250 Mg/L	Degradation rate of 99.12%

<i>Chryseobacterium</i> sp. JAS14	Soil	24H	300 Mg/L	Degradation rate of 100%
<i>Aeromonas caviae</i> JAS15	MSM	24H	1000 Mg/L	Degradation rate of 98.65%
<i>Trichoderma</i> sp. T2-2	MSM	24H	300 Mg/L	Degradation rate of 73.19%

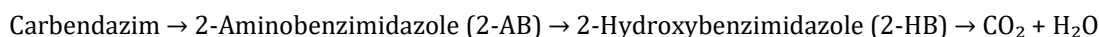
Advanced molecular approaches and phenotypic characterisation are used to identify microorganisms. While ITS sequencing is used to identify fungal strains, techniques such as 16S rRNA sequencing aid in determining the taxonomic identification of bacterial strains. Research has shown that under ideal circumstances, bacteria such as *Rhodococcus erythropolis* and *Pseudomonas putida* may metabolize substantial quantities of carbendazim with high breakdown efficiency [57].

5.2. Metabolic pathways:

Enzymatic hydrolysis, oxidation, and ring cleavage are the processes that break down carbendazim, producing non-toxic end products like CO₂ and H₂O. The primary metabolic pathway starts with the hydrolysis of carbendazim into a less toxic intermediate called 2-aminobenzimidazole (2-AB), which is then oxidized to 2-hydroxybenzimidazole (2-HB), which is further broken down by cleaving the benzimidazole ring structure [56].

Among the important enzymes in these pathways are:

- The first hydrolysis of carbendazim to 2-AB is catalyzed by hydrolases [56].
- The conversion of intermediates such as 2-AB to 2-HB is facilitated by oxidoreductases and amidases [56].
- Ring cleavage is facilitated by dioxygenases, allowing for full mineralization into CO₂ and H₂O [56].



This pathway demonstrates how microbial enzymes work in unison to break down carbendazim's complicated structure, which makes it a viable option for bioremediation applications. Mixed microbial consortia frequently improve these routes by using the many species' complementing enzymatic activity [57].

6. Factors Influencing Bioremediation Efficiency

A number of operational, microbiological, and environmental variables affect the effectiveness of bioremediation for the breakdown of carbendazim. The efficiency of microbial activity and the degradation of the pollutant are determined by these parameters [58].

6.1. Aspects of the Environment

- **Temperature and pH:** Certain temperature and pH ranges are ideal for the activity of microbial enzymes involved in the breakdown of carbendazim. Research shows that moderate temperatures (25–30°C) and a neutral to slightly alkaline pH (6.5–8.5) promote microbial growth and enzymatic activity [59].
- **Moisture Content:** Microbial movement and nutrient availability depend on sufficient soil or substrate moisture levels. Waterlogging or excessive dryness can prevent microbiological activity [58].
- **Oxygen Availability:** By promoting the activity of oxygen-dependent enzymes such as dioxygenases, which are necessary for ring breakage in the carbendazim molecule, aerobic circumstances accelerate the pace of breakdown [58].

6.2. Microbiological Elements

- **Composition of Microbial Consortia:** Degradation efficiency is increased by the cooperative relationships between fungi and bacteria in consortia. For instance, compared to individual strains, *Rhodococcus erythropolis* and *Aspergillus versicolor* have demonstrated greater efficiency [58].
- **Resistance and Adaptation:** Native microorganisms that have evolved to polluted settings are more effective degraders and have a greater tolerance to carbendazim [58].
- **Enzymatic Efficiency:** The pace and degree of carbendazim degradation are directly impacted by the presence of important enzymes such amidases, hydrolases, and oxidoreductases [58].

6.3. Aspects of Operations

- **Availability of Nutrients:** Microbial growth and metabolic activity can be improved by adding nutrients such as phosphorus and nitrogen. However, eutrophication, which can upset microbial communities, can result from high nutrient concentrations [60].
- **Contaminant Concentration:** Microorganisms may be toxically affected by high carbendazim concentrations, which would decrease the effectiveness of bioremediation. This problem can be lessened by taking pre-treatment measures to dilute pollutants [60].
- **Design of a Bioreactor:** The maintenance of ideal conditions for microbial activity in designed systems depends on factors including agitation, aeration, and retention time. Under regulated conditions, bioreactors for the breakdown of carbendazim have demonstrated an efficiency of above 90%.

7. Methods for Assessing Bioremediation Efficacy

Assessing the effectiveness of bioremediation initiatives is essential for determining the degree of pollutant reduction and process optimization. The effectiveness of carbendazim bioremediation is evaluated using a variety of methodologies, which may be divided into chemical, biological, and environmental monitoring approaches [48].

7.1. Chemical Techniques

- **Residual Contaminant Analysis:** To measure the amount of leftover carbendazim and its metabolites in soil, water, and other environmental matrices, high-performance liquid chromatography (HPLC) and gas chromatography-mass spectrometry (GC-MS) are frequently employed. Prior to and during bioremediation, these techniques offer accurate assessments of the amounts of contaminants [47].
- **Profiling Metabolite:** Verifying the biodegradation processes is aided by identifying intermediate and ultimate degradation products, such as 2-aminobenzimidazole and 2-hydroxybenzimidazole. For this, sophisticated spectroscopic methods such as nuclear magnetic resonance (NMR) can be used [46].

7.2. Biological methods

- **Microbial Activity Monitoring:** During bioremediation, evaluating the dynamics of the microbial population and activity levels provide valuable information on the biodegradation process. Commonly employed methods include ATP tests, plate counts, and optical density assessments [32].
- **Enzyme Activity Assays:** Direct proof of metabolic involvement in carbendazim degradation may be obtained by measuring the activity of important enzymes, such as hydrolases and oxidoreductases [32].
- **Molecular Instruments:** Certain microbial populations and degradation-related genes, such as those encoding amidases and dioxygenases, may be found and measured using methods like qPCR and 16S rRNA sequencing [32].

7.3. Environmental monitoring

- **Analysis of Soil and Water Quality:** Tracking variables such as pH, dissolved oxygen content, and nutrient levels aids in assessing how bioremediation has altered the ecosystem. Successful degradation is frequently correlated with improvements in these measures [32].
- **Toxicity Assessments:** To ascertain if bioremediation has decreased toxicity in treated habitats, ecotoxicological studies include assessing changes in the growth or survival of indicator species (e.g., *Vibrio fischeri* or *Daphnia magna*).

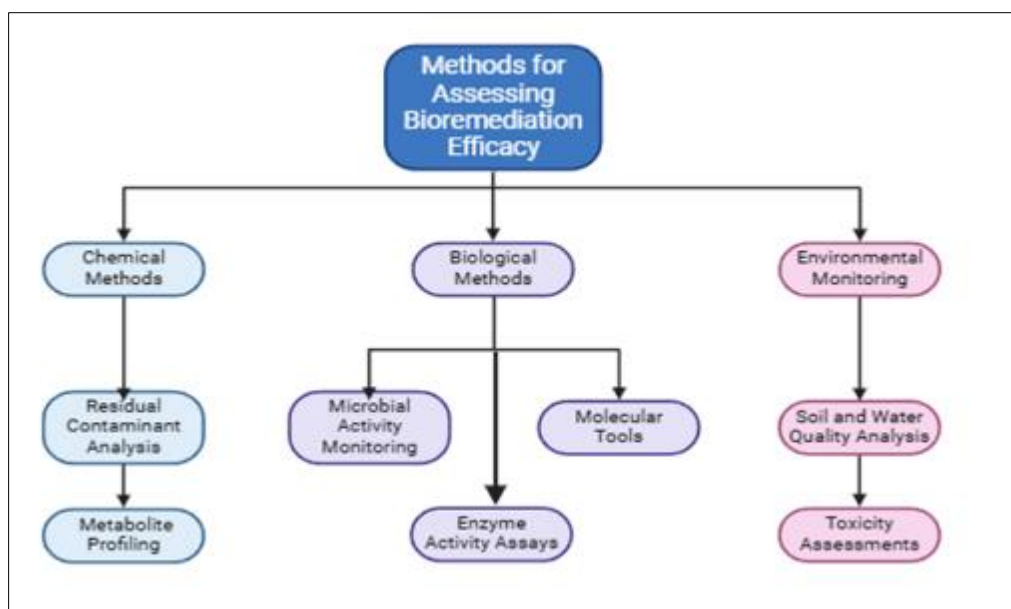


Figure 5 Bioremediation efficacy assessing method

By combining these techniques, the effectiveness of bioremediation may be thoroughly assessed, guaranteeing that degradation processes are both effective and safe for the environment [33].

8. Rationality of the work

This effort makes sense because it addresses the pressing need to reduce the hazards that carbendazim, a persistent fungicide that is often used in agriculture, poses to human health and the environment [45]. The study highlights microbial bioremediation as an economical and sustainable substitute for physical and chemical techniques, which are frequently resource-intensive and detrimental to the environment [36]. The study highlights the promise of environmentally friendly methods for cleaning up carbendazim-contaminated areas by investigating microbial degradation routes, enzymatic processes, and tactics including consortium-based bioremediation.

Table 3 Comparison of biodegradation rates of CBZ with other consortiums [55]

Order	Consortium of microbes	Carbendazim Degradation	Reference
1.	<i>Acinetobacter</i> sp., <i>Enterobacter</i> sp. and <i>Bacillus</i> sp.	91.34%	Hegde et al. (2017)
2.	Consortia of <i>Bacillus</i> sp., <i>Pseudomonas</i> sp., <i>Exiguobacterium</i> sp., <i>Microbacterium</i> sp., <i>Achromobacterium</i> sp., <i>Stenotrophomonas</i> sp.	77.5%	Kanjilal et al. (2018)
3.	Consortia of <i>Bacillus</i> sp. <i>Paracoccus</i> sp. <i>Flavobacterium</i> sp. <i>Pseudomonas</i> sp.	87.25%	Singh et al. (2016)
4.	<i>Brevibacillus borstelensis</i> and <i>Streptomyces albogriseolus</i>	90.86%	Arya and Sharma (2016)
5.	<i>Bacillus subtilis</i> GB03, <i>Bacillus subtilis</i> FZB24, <i>Bacillus amyloliquefaciens</i> IN937a and <i>Bacillus pumilus</i> SE34	79.36%	Bhattacharjee et al. (2020)
6.	Isolated consortium augmented with <i>Aspergillus versicolor</i>	94.56%	Panda et al. (2017)

A roadmap for future research is provided by this work, which also identifies important knowledge gaps, including the ecological impacts of degradation by-products and the difficulties of microbial adaptation. The review also explains the significance of developing scalable technologies, optimizing microbial consortia, and advancing field applications in order to achieve practical and efficient bioremediation [45].

9. Advantages and Challenges

9.1. Advantages of the Review

- **Extensive Coverage:** The review offers a comprehensive overview of the subject by delving deeply into the characteristics of carbendazim, its effects on the environment, microbial degradation mechanisms, and bioremediation techniques [49].
- **Focus on Microbial Solutions:** Highlighting environmentally friendly microbial degrading processes draws attention to long-term substitutes for traditional repair methods [49].
- **Practical Applications:** Practical insights for real-world implementation are provided via the consideration of bioreactor designs, microbial consortia, and field applications. Finding Knowledge Gaps: To help direct future research efforts, the review describes issues such environmental unpredictability, microbial adaptability, and operational optimization [49].

9.2. Disadvantages of the Review

- **Limited Field Data:** The practical validation of suggested solutions is limited because the majority of findings are based on laboratory research and there are fewer real-world applications mentioned [50].
- **Limited Microbial Diversity Scope:** The review may have overlooked less-studied microorganisms that might be efficient degraders because it mostly concentrates on well-known bacterial and fungal strains [50].
- **Implementation Complexity:** Although the review emphasizes cutting-edge methods (such as qPCR and bioreactors), their expense and technical specifications may prevent broad use [50].
- **Insufficient Toxicity Analysis:** There are gaps in our knowledge of environmental safety due to the lack of attention paid to the long-term ecological effects of degradation by-products such as 2-aminobenzimidazole and 2-hydroxybenzimidazole [50].

Assessing the effectiveness of bioremediation initiatives is essential for determining the degree of pollutant reduction and process optimization. The effectiveness of carbendazim bioremediation is evaluated using a variety of methodologies, which may be divided into chemical, biological, and environmental monitoring approaches [50].

10. Conclusion

This analysis concludes by highlighting the serious health and environmental risks that carbendazim poses, as well as the toxicity and persistence of this often used fungicide. The potential for economical, environmentally friendly approaches to lessen its effects is highlighted by the thorough investigation of microbial breakdown routes and bioremediation techniques. High degradation efficiency and the possibility of real-world applications have been demonstrated by microbial consortia and sophisticated biotechnological techniques in lab settings. However, obstacles including microbial adaptability, fluctuating climatic conditions, and the intricacy of operational designs continue to restrict the scalability and field deployment of these solutions.

The review also highlights how crucial it is to comprehend degradation byproducts and the long-term ecological effects they have [29]. This information is necessary to make sure that bioremediation procedures don't unintentionally cause secondary pollution. This work offers a solid basis for developing sustainable remediation methods by pointing out important research gaps and suggesting avenues for further investigation. For carbendazim bioremediation to be successfully implemented globally, ongoing attempts to improve microbiological tactics and include cutting-edge monitoring methods will be essential.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare no conflict of interest with anyone.

References

- [1] Rajpal, N., Sharma, A., and Singh, R. (2023). Bioremediation of carbendazim and thiamethoxam in domestic greywater using a bioaugmented microbial consortium. *Environmental Technology and Innovation*, 30, 103087. <https://doi.org/10.1016/j.eti.2023.103087>
- [2] Zhang, W., and Tripathi, V. (2024). Microbes as carbendazim degraders: Opportunity and challenge. *Frontiers in Microbiology*, 15, 11349639. <https://doi.org/10.3389/fmicb.2024.11349639>
- [3] Kumar, A., and Singh, R. (2024). Environmental detoxification of benzimidazole fungicide carbendazim using microbial hydrolases. *Environmental Technology Reviews*, 13(1), 45–60. <https://doi.org/10.1080/12298093.2024.2416733>
- [4] Mansee, A. (2024). Sustainable indigenous bio-mixture for restoration of soil point source pollution with special reference to chlorpyrifos. *Environmental Monitoring and Assessment*, 196, 363. <https://doi.org/10.1007/s10661-024-12494-5>
- [5] Singh, S., Singh, N., Kumar, V., and Singh, J. (2016). Toxicity, monitoring and biodegradation of the fungicide carbendazim. *Environmental Chemistry Letters*, 14(3), 317–329. <https://doi.org/10.1007/s10311-016-0560-4>
- [6] Mustapha, M. U., Halimoon, N., Wan Johar, W. L., and Abd Shukor, M. Y. (2019). An overview on biodegradation of carbamate pesticides by soil bacteria. *Pertanika Journal of Science and Technology*, 27(2), 547–563.
- [7] Sharma, S., and Sharma, R. (2023). Bioremediation of carbendazim using *Trichoderma* spp.: A sustainable approach. *Indian Journal of Agricultural Sciences*, 93(5), 1123–1128.
- [8] Sarat, N., and Barathi, S. (2013). Enrichment and isolation of endosulfan degrading microorganisms in cashew plantations of Kasargod district, Kerala. *International Journal of ChemTech Research*, 5(1), 6–14.
- [9] Shahgoli, H., and Ahangar, A. G. (2014). Factors controlling degradation of pesticides in the soil environment: A review. *Agriculture Science Developments*, 3, 273–278.
- [10] Perruchon, C., Chatzinotas, A., Omirou, M., and Karpouzas, D. G. (2017). Isolation of a bacterial consortium able to degrade the fungicide thiabendazole: The key role of a *Sphingomonas* phylotype. *Applied Microbiology and Biotechnology*, 101(17), 6581–6593. <https://doi.org/10.1007/s00253-017-8385-2>
- [11] Lin, Z., Pang, S., Zhou, Z., and Chen, S. (2021). Current insights into the microbial degradation for butachlor: Strains, metabolic pathways, and molecular mechanisms. *Environmental Science and Pollution Research*, 28(22), 28078–28091. <https://doi.org/10.1007/s11356-021-12835-4>
- [12] Tomazini, R., Saia, F., van der Zaan, B., and Langenhoff, A. A. M. (2021). Biodegradation of fipronil: Transformation products, microbial characterization, and toxicity assessment. *Science of the Total Environment*, 755, 142572. <https://doi.org/10.1016/j.scitotenv.2020.142572>
- [13] Adamu, M. T., Dahiru, M., and Garba, L. (2020). Microorganisms involved in the bioremediation of pentachlorophenol and lignin discharged by the pulp and paper industry. *Environmental Technology and Innovation*, 20, 101157. <https://doi.org/10.1016/j.eti.2020.101157>
- [14] Elyamine, A. M., and Hu, C. (2020). Earthworms and rice straw enhanced soil bacterial diversity and promoted the degradation of phenanthrene. *Science of the Total Environment*, 738, 140234. <https://doi.org/10.1016/j.scitotenv.2020.140234>
- [15] Liu, X., Hui, N., and Kontro, M. H. (2020). Improved short-term microbial degradation in circulating water reducing high stagnant atrazine concentrations in subsurface sediments. *Water Research*, 184, 116180. <https://doi.org/10.1016/j.watres.2020.116180>
- [16] Yan, X., Jin, W., Wu, G., and Hong, Q. (2018). Hydrolase CehA and monooxygenase CfdC are responsible for the degradation of carbofuran in *Sphingomonas* sp. strain CDS-1. *Applied and Environmental Microbiology*, 84(15), e00835-18. <https://doi.org/10.1128/AEM.00835-18>
- [17] Chaudhary, D. K., and Kim, J. (2017). *Sphingomonas olei* sp. nov., with the ability to degrade aliphatic hydrocarbons, isolated from oil-contaminated soil. *International Journal of Systematic and Evolutionary Microbiology*, 67(8), 2890–2895. <https://doi.org/10.1099/ijsem.0.002053>
- [18] Chen, Y. L. (2017). Microbial degradation of sex steroid hormones: From model organisms to the environmental samples. Thesis, University of California.

- [19] Carvalho, M. F., Alves, C. C. T., Ferreira, M. I. M., and Castro, P. M. L. (2002). Isolation and initial characterization of a bacterial consortium able to mineralize fluorobenzene. *Biodegradation*, 13(5), 289–296. <https://doi.org/10.1023/A:1020501521105>
- [20] Schreiner, G., Wiedmann, T., Schimmel, H., and Ballschmiter, K. (1997). Influence of the substitution pattern on the microbial degradation of mono- to tetrachlorinated dibenzo-p-dioxins and dibenzofurans. *Environmental Science and Technology*, 31(1), 84–90. <https://doi.org/10.1021/es960315f>
- [21] Varun, I. K. Bhat, and R. Prakash, “LCA of renewable energy for electricity generation systems-A review,” *Renewable and Sustainable Energy Reviews*, vol. 13, no. 5, pp. 1067–1073, Jun. 2009, doi: 10.1016/j.rser.2008.08.004.
- [22] N. Rashid, Y. F. Cui, S. U. R. Muhammad, and J. I. Han, “Enhanced electricity generation by using algae biomass and activated sludge in microbial fuel cell,” *Science of the Total Environment*, vol. 456–457, pp. 91–94, Jul. 2013, doi: 10.1016/j.scitotenv.2013.03.067.
- [23] P. P. Rajesh, D. A. Jadhav, and M. M. Ghangrekar, “Improving performance of microbial fuel cell while controlling methanogenesis by *Chaetoceros* pretreatment of anodic inoculum,” *Bioresour Technol*, vol. 180, pp. 66–71, Mar. 2015, doi: 10.1016/j.biortech.2014.12.095.
- [24] K. Nishio, K. Hashimoto, and K. Watanabe, “Light/electricity conversion by defined cocultures of *Chlamydomonas* and *Geobacter*,” *J Biosci Bioeng*, vol. 115, no. 4, pp. 412–417, Apr. 2013, doi: 10.1016/j.jbiosc.2012.10.015.
- [25] M. H. Ravari, A. Sarrafi, and M. Tahmooreesi, “Synthesizing and characterizing the mixed Al,Cu-pillared and copper doped Al-pillared bentonite for electrocatalytic reduction of CO₂,” *S Afr J Chem Eng*, vol. 31, pp. 1–6, Jan. 2020, doi: 10.1016/j.sajce.2019.10.001.
- [26] B. E. Logan and J. M. Regan, “Electricity-producing bacterial communities in microbial fuel cells,” *Trends Microbiol*, vol. 14, no. 12, pp. 512–518, Dec. 2006, doi: 10.1016/j.tim.2006.10.003.
- [27] C. C. Fu, C. H. Su, T. C. Hung, C. H. Hsieh, D. Suryani, and W. T. Wu, “Effects of biomass weight and light intensity on the performance of photosynthetic microbial fuel cells with *Spirulina platensis*,” *Bioresour Technol*, vol. 100, no. 18, pp. 4183–4186, Sep. 2009, doi: 10.1016/j.biortech.2009.03.059.
- [28] Z. Y. Kong, X. J. Melvin Wee, A. Mahmoud, A. Yu, S. Liu, and J. Sunarso, “Development of a techno-economic framework for natural gas dehydration via absorption using tri-ethylene glycol: A comparative study between DRIZO and other dehydration processes,” *S Afr J Chem Eng*, vol. 31, pp. 17–24, Jan. 2020, doi: 10.1016/j.sajce.2019.11.001.
- [29] K. J. Chae et al., “Methanogenesis control by employing various environmental stress conditions in two-chambered microbial fuel cells,” *Bioresour Technol*, vol. 101, no. 14, pp. 5350–5357, Jul. 2010, doi: 10.1016/j.biortech.2010.02.035.
- [30] S. Y. Lee, J. M. Cho, Y. K. Chang, and Y. K. Oh, “Cell disruption and lipid extraction for microalgal biorefineries: A review,” *Bioresour Technol*, vol. 244, pp. 1317–1328, 2017, doi: 10.1016/j.biortech.2017.06.038.
- [31] K. W. Chew et al., “Microalgae biorefinery: High value products perspectives,” *Bioresour Technol*, vol. 229, pp. 53–62, 2017, doi: 10.1016/j.biortech.2017.01.006.
- [32] S. Liu, X. Liu, Y. Wang, and P. Zhang, “Electricity generation from macroalgae *Enteromorpha prolifera* hydrolysates using an alkaline fuel cell,” *Bioresour Technol*, vol. 222, pp. 226–231, Dec. 2016, doi: 10.1016/j.biortech.2016.09.112.
- [33] I. Moreno-Garrido, “Microalgae immobilization: Current techniques and uses,” *Bioresour Technol*, vol. 99, no. 10, pp. 3949–3964, Jul. 2008, doi: 10.1016/j.biortech.2007.05.040.
- [34] A. Khandelwal, A. Vijay, A. Dixit, and M. Chhabra, “Microbial fuel cell powered by lipid extracted algae: A promising system for algal lipids and power generation,” *Bioresour Technol*, vol. 247, pp. 520–527, 2018, doi: 10.1016/j.biortech.2017.09.119.
- [35] K. J. Chae, M. J. Choi, K. Y. Kim, F. F. Ajayi, I. S. Chang, and I. S. Kim, “Selective inhibition of methanogens for the improvement of biohydrogen production in microbial electrolysis cells,” *Int J Hydrogen Energy*, vol. 35, no. 24, pp. 13379–13386, Dec. 2010, doi: 10.1016/j.ijhydene.2009.11.114.
- [36] B. H. H. Goh, H. C. Ong, M. Y. Cheah, W. H. Chen, K. L. Yu, and T. M. I. Mahlia, “Sustainability of direct biodiesel synthesis from microalgae biomass: A critical review,” *Renewable and Sustainable Energy Reviews*, vol. 107, pp. 59–74, Jun. 2019, doi: 10.1016/j.rser.2019.02.012.

- [37] A. T. Hoang et al., "Biofuel production from microalgae: challenges and chances," *Phytochemistry Reviews*, vol. 22, no. 4, pp. 1089–1126, Aug. 2023, doi: 10.1007/S11101-022-09819-Y.
- [38] W. Y. Cheah, P. L. Show, J. S. Chang, T. C. Ling, and J. C. Juan, "Biosequestration of atmospheric CO₂ and flue gas-containing CO₂ by microalgae," *Bioresour Technol*, vol. 184, pp. 190–201, May 2015, doi: 10.1016/j.biortech.2014.11.026.
- [39] S. H. Ho, C. Y. Chen, and J. S. Chang, "Effect of light intensity and nitrogen starvation on CO₂ fixation and lipid/carbohydrate production of an indigenous microalga *Scenedesmus obliquus* CNW-N," *Bioresour Technol*, vol. 113, pp. 244–252, Jun. 2012, doi: 10.1016/j.biortech.2011.11.133.
- [40] D. R. Lovley, "Microbial fuel cells: novel microbial physiologies and engineering approaches," *Curr Opin Biotechnol*, vol. 17, no. 3, pp. 327–332, Jun. 2006, doi: 10.1016/j.copbio.2006.04.006.
- [41] L. E. Doyle and E. Marsili, "Methods for enrichment of novel electrochemically-active microorganisms," *Bioresour Technol*, vol. 195, pp. 273–282, 2015, doi: 10.1016/j.biortech.2015.07.025.
- [42] R. Kakarla and B. Min, "Photoautotrophic microalgae *Scenedesmus obliquus* attached on a cathode as oxygen producers for microbial fuel cell (MFC) operation," *Int J Hydrogen Energy*, vol. 39, no. 19, pp. 10275–10283, Jun. 2014, doi: 10.1016/j.ijhydene.2014.04.158.
- [43] T. Catal, K. L. Lesnik, and H. Liu, "Suppression of methanogenesis for hydrogen production in single-chamber microbial electrolysis cells using various antibiotics," *Bioresour Technol*, vol. 187, pp. 77–83, Jul. 2015, doi: 10.1016/j.biortech.2015.03.099.
- [44] A. S. Vishwanathan, "Microbial fuel cells: a comprehensive review for beginners," *3 Biotech*, vol. 11, no. 5, May 2021, doi: 10.1007/S13205-021-02802-Y.
- [45] D. J. Walker et al., "Electrically conductive pili from pilin genes of phylogenetically diverse microorganisms," *ISME Journal*, vol. 12, no. 1, pp. 48–58, Jan. 2018, doi: 10.1038/ISMEJ.2017.141.
- [46] H. Wang, L. Lu, F. Cui, D. Liu, Z. Zhao, and Y. Xu, "Simultaneous bioelectrochemical degradation of algae sludge and energy recovery in microbial fuel cells," *RSC Adv*, vol. 2, no. 18, pp. 7228–7234, Aug. 2012, doi: 10.1039/C2RA20631E.
- [47] S. B. Velasquez-Orta, T. P. Curtis, and B. E. Logan, "Energy from algae using microbial fuel cells," *Biotechnol Bioeng*, vol. 103, no. 6, pp. 1068–1076, Aug. 2009, doi: 10.1002/BIT.22346.
- [48] G. Reguera, K. D. McCarthy, T. Mehta, J. S. Nicoll, M. T. Tuominen, and D. R. Lovley, "Extracellular electron transfer via microbial nanowires," *Nature*, vol. 435, no. 7045, pp. 1098–1101, Jun. 2005, doi: 10.1038/NATURE03661.
- [49] M. Meinshausen et al., "Greenhouse-gas emission targets for limiting global warming to 2°C," *Nature*, vol. 458, no. 7242, pp. 1158–1162, Apr. 2009, doi: 10.1038/NATURE08017.
- [50] S. B. Velasquez-Orta, I. M. Head, T. P. Curtis, K. Scott, J. R. Lloyd, and H. Von Canstein, "The effect of flavin electron shuttles in microbial fuel cells current production," *Appl Microbiol Biotechnol*, vol. 85, no. 5, pp. 1373–1381, Feb. 2010, doi: 10.1007/S00253-009-2172-8.
- [51] S. E. Oh and B. E. Logan, "Proton exchange membrane and electrode surface areas as factors that affect power generation in microbial fuel cells," *Appl Microbiol Biotechnol*, vol. 70, no. 2, pp. 162–169, Mar. 2006, doi: 10.1007/S00253-005-0066-Y.
- [52] C. McGlade and P. Ekins, "The geographical distribution of fossil fuels unused when limiting global warming to 2°C," *Nature*, vol. 517, no. 7533, pp. 187–190, Jan. 2015, doi: 10.1038/NATURE14016.
- [53] B. H. Lower, M. F. Hochella, and S. K. Lower, "Putative mineral-specific proteins synthesized by a metal reducing bacterium," *Am J Sci*, vol. 305, no. 6-8 SPEC. ISS., pp. 687–710, Jun. 2005, doi: 10.2475/AJS.305.6-8.687.
- [54] B. E. Logan et al., "Microbial fuel cells: Methodology and technology," *Environ Sci Technol*, vol. 40, no. 17, pp. 5181–5192, Sep. 2006, doi: 10.1021/ES0605016.
- [55] H. Jiang, S. Luo, X. Shi, M. Dai, and R. bo Guo, "A novel microbial fuel cell and photobioreactor system for continuous domestic wastewater treatment and bioelectricity generation," *Biotechnol Lett*, vol. 34, no. 7, pp. 1269–1274, Jul. 2012, doi: 10.1007/S10529-012-0899-2.
- [56] B. E. Logan, "Exoelectrogenic bacteria that power microbial fuel cells," *Nat Rev Microbiol*, vol. 7, no. 5, pp. 375–381, 2009, doi: 10.1038/NRMICRO2113.

- [57] Y. Feng, X. Wang, B. E. Logan, and H. Lee, "Brewery wastewater treatment using air-cathode microbial fuel cells," *Appl Microbiol Biotechnol*, vol. 78, no. 5, pp. 873–880, Apr. 2008, doi: 10.1007/S00253-008-1360-2.
- [58] L. Mekuto, A. V. A. Olowolafe, S. Pandit, N. Dyantyi, P. Nomngongo, and R. Huberts, "Microalgae as a biocathode and feedstock in anode chamber for a self-sustainable microbial fuel cell technology: A review," *S Afr J Chem Eng*, vol. 31, pp. 7–16, Jan. 2020, doi: 10.1016/J.SAJCE.2019.10.002.
- [59] K. S. Chew, "What's new in Emergencies, Trauma and Shock?Tackling prehospital delay to reperfusion therapy in ST-elevation myocardial infarction: A global problem, a glocal approach," *J Emerg Trauma Shock*, vol. 10, no. 2, pp. 53–54, Apr. 2017, doi: 10.4103/0974-2700.201587.
- [60] C. Gurikar et al., "Microbial Fuel Cells: An Alternate Approach for Bioelectricity Generation and Waste Management," *J Pure Appl Microbiol*, vol. 15, no. 4, pp. 1833–1845, Dec. 2021, doi:10.22207/JPAM.15.4.74.