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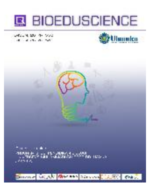

Zooremediation: Utilizing Animals for Environmental Purification and Pollution Mitigation

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Abstract

Background: The global human population continues to grow rapidly, leading to increasing urban waste and environmental contamination. One emerging and promising approach to mitigating this pollution is zooremediation, which utilizes animals as biological agents for environmental cleanup. This review aims to critically assess the effectiveness of various animal species in removing specific classes of pollutants, with particular attention to their mechanisms of action—zooextraction, zootransformation, and zooaccumulation—and the environmental conditions under which they operate. Effectiveness is evaluated based on pollutant removal efficiency, adaptability to contaminated environments, and ecological safety. **Methods:** Through systematic literature analysis, we identified key species, including Geukensia demissa, Daphnia magna, and Anadara granosa, which demonstrated measurable success in the remediation of aquatic environments contaminated with heavy metals and organic pollutants. Additionally, soil-dwelling nematodes such as Caenorhabditis elegans and Cephalobus persegnis play critical roles in hydrocarbon degradation and in enhancing microbial synergy in polluted substrates. These findings highlight the diverse functional capacities of animals in bioremediation efforts. The methodology employed in this study is a comprehensive literature review, focusing on peer-reviewed articles published over the last two decades. **Results:** This review synthesizes findings related to pollutant types, animal species used in zooremediation, remediation outcomes, and ecological impacts. By critically examining existing studies, the evaluation identifies trends, gaps, and challenges in the application of zooremediation. **Conclusion:** Future research should focus on understanding the long-term impacts, optimizing protocols, and safeguarding both ecological and animal health to fully realize the potential of zooremediation in managing environmental pollution on a global scale.

Keywords: Zooremediation; Environmental Purification; Pollution Mitigation.

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Introduction

The global human population continues to grow rapidly, leading to an increase in urban waste (Ditta & Arshad, 2016; Kaur et al., 2023; Junior et al., 2021). Without effective waste management, this surge in waste can result in severe and lasting environmental pollution (Junior et al., 2021). Waste from residential areas, when collected in landfills, undergoes decomposition. Rainwater percolating through these landfills can carry pollutants, forming leachate. This hazardous leachate poses a significant risk of contaminating groundwater (Jóźwiak et al., 2019; Junior et al., 2021).

The growing human population drives increased food demands and agricultural development. The effectiveness of agriculture in meeting these demands often relies on the use of pesticides and herbicides (Pahalvi et al., 2021; Sarwar et al., 2020; Workineh, 2020). However, residues from these chemicals negatively impact the biological and chemical properties of soil microflora and fauna. When these residues contaminate groundwater and are consumed by humans, they can act as toxins (Thakar et al., 2024). In particular, organochlorine residues are highly toxic and notoriously difficult to control (Martínez-burgos et al., 2024).

The development of human industries has facilitated easier living. However, industrial growth near agricultural lands and residential areas accelerates waste flow, negatively impacting human health and well-being. Common issues in waste treatment include septic system failures and discharge from combined sewer overflows (CSO) (Durand et al., 2020). Wastewater treatment plants (WWTPs) also have a downside, producing sludge that is challenging to utilize and expensive to incinerate and dispose of (Schuijt et al., 2021). This sludge contains hazardous pollutants and phytotoxic metabolites that pose risks to living creatures, especially humans (Ahadi et al., 2020). Additionally, industrial activities located far from residential areas, such as petroleum exploitation, pose significant global environmental problems (Zhou et al., 2022).

Pollution from landfills in cities, agricultural land, and industrial areas leads to a decline in the quality of soil and water consumed by humans (Yeheyo et al., 2024). Pollutants can be categorized into organic, inorganic, and biological types. Remediation is a key strategy to mitigate the dangers posed by pollution. While physical and chemical remediation methods are pretty effective, bio-ecological remediation offers effective results without the risk of secondary pollution (Zhou et al., 2024)

Remediation requires careful cost management, technological complexity, and accurate efficiency calculations. Bio-ecological remediation, also known as bioremediation, strikes a balance between efficiency and cost. Implementing bioremediation often does not require specialized engineering skills (Novakovskiy et al., 2021).

Bioremediation often utilizes microorganisms, which can be applied both in situ and ex situ, with the help of bacteria or fungi. Microremediation using bacteria can save time; however, various reports indicate a significant drawback: bacteria often struggle to adapt and can trigger the growth of harmful organisms and interactions (Gifford et al., 2007; Zhou et al., 2022).

The use of fungi as microremediation agents has proven effective in dealing with heavy metals, such as *Trichoderma harzianum*, and hydrocarbons, such as *Phanerochaete chrysosporium* (Delsarte et al., 2021; Jakovljević & Vrvić, 2018). Fungal microremediation yields different results compared to bacterial methods. Fungi possess unique biological and ecological characteristics that enable them to effectively treat a variety of contaminants under diverse environmental conditions. However, the hydrophobic nature of fungal cell membranes can inhibit the effectiveness of microremediation (Treifeldt et al., 2020).

Bioremediation, aided by plants, serves as an effective alternative to using microorganisms. Watercress (*Pistia stratiotes*) is commonly used as a phytoremediation agent for treating residential wastewater pollutants (Dadebo et al., 2024). Dry powder from the rhizomes and leaves of *Vossia cuspidata* is effective against methylene blue dye (Awad et al., 2023). Additionally, Pennisetum purpureum can improve soil contaminated with pollutants (Rahman et al., 2024). However, these methods require a considerable amount of time to be effective, and the contaminants do not entirely disappear from the area. Moreover, this can lead to bioaccumulation of pollutants in the food chain, potentially harming higher organisms (Liang et al., 2024; Zhang et al., 2024).

Animal-assisted bioremediation has been employed for a considerable period. The application of zooremediation is not widely known and remains underdeveloped due to ethical concerns. However, animals possess the ability to tolerate toxicity. Freshwater aquaculture production incorporating zooremediation with aquatic animals began during the global aquaculture boom in the 1990s (Gifford et al., 2007). Soil invertebrates also demonstrate the capability to manage leachate (Junior et al., 2021). Numerous scientific reports have documented favorable results from zooremediation. A comprehensive review of these reports will assess the positive and negative impacts of zooremediation, providing a foundation for further research and broader application.

The objective of this study is to conduct a comprehensive evaluation of the role of animals in environmental remediation by critically examining the advantages and limitations associated with zooremediation strategies. Although existing literature increasingly highlights the potential of zooremediation, current research remains fragmented, lacks standardized methodological frameworks, and provides insufficient consideration of ecological risks and ethical dimensions. These deficiencies represent significant knowledge gaps that this review aims to address systematically.

Methods

Literature Search Strategy

A comprehensive literature search was conducted across several academic databases, specifically MDPI, PubMed, Scopus, and Google Scholar. The primary keywords utilized for this search included "Zooremediation, bioremediation, and animal pollution control." To ensure a complete historical overview of the developments in the field of zooremediation, no date restrictions were applied during the search process.

Inclusion and Exclusion Criteria

To guarantee the relevance and quality of the selected literature, stringent inclusion and exclusion criteria were applied. Inclusion criteria encompassed studies published in peer-reviewed journals; articles specifically addressing the direct application of animals (both vertebrates and invertebrates) for environmental remediation of various pollutants (e.g., heavy metals, organic compounds, and pathogenic microorganisms); and research articles, review articles, and conference papers directly discussing zooremediation mechanisms, applications, or efficacy. Conversely, exclusion criteria included studies not directly related to environmental remediation by animals, articles primarily focusing on phytoremediation, mycoremediation, or microbial bioremediation without significant animal involvement, grey literature, and duplicate publications.

Data Extraction and Synthesis

From each article that met the selection criteria, relevant information was systematically extracted and categorized. The collected data included: the type of pollutants addressed (e.g., heavy metals, pathogenic bacteria, organic compounds), the animal species utilized (such as Anadara granosa, Hymeniacidon perlevis, Geukensia demissa, Anodonta californiensis), the environmental matrix of the study (e.g., freshwater, seawater, or terrestrial environments), the remediation mechanisms involved (e.g., zooextraction, biofiltration, neutralization, or bacterial introduction), as well as observed efficacy and key findings, including quantitative data like removal rates or concentration reductions where available. Information regarding the geographical location of the study was also recorded if relevant. All extracted data were then thematically synthesized to identify overarching trends, significant applications, and key findings, which subsequently formed the basis for the "Results and Discussion" section. This approach facilitated a structured overview of the current state of zooremediation research, highlighting both established capabilities and emerging areas of application.

Result

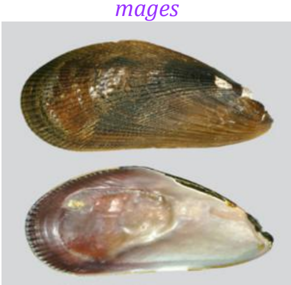
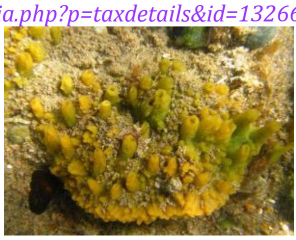
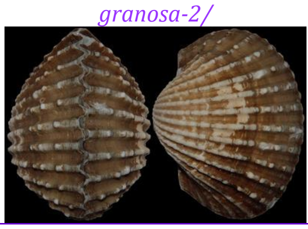
Zooremediation

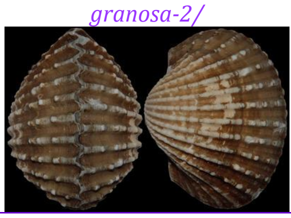
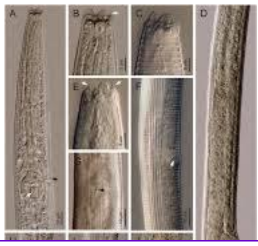
Zooremediation is a form of bioremediation that utilizes animals to address environmental pollution. Although not widely known, animals used in zooremediation can withstand toxicity and offer economic benefits. The use of aquatic animals in freshwater aquaculture production for zooremediation began during the global aquaculture boom in the 1990s (Gifford et al., 2007). Additionally, soil invertebrates have demonstrated the ability to manage leachate effectively (Junior et al., 2021).

Animals employed in water and land remediation processes exhibit various capabilities, such as neutralizing metals (Gravina et al., 2022; Jóźwiak et al., 2019; Serra et al., 2019), assisting in bacterial remediation (Ismail et al., 2015; Longo et al., 2016; Longo et al., 2022), or introducing bacteria into the remediation process (Shaikhulova et al., 2021).

Zooremediation can be implemented using individual animals or groups of animals (Longo et al., 2016). The field of zooremediation is continually evolving, as demonstrated by the scientific reports summarized in Table 1.

Table 1. Review of Current Research on Zooremediation Applications

Species		Location and time of research	Research results	Reference
Geukensia demissa	*https://www.marinespecies.org/aphia.php?p=taxdetails&id=156859#images* 	Location: Queens, New York City, USA. Time: fall and summer seasons, 2012.	*Geukensia demissa* effectively reduces pathogenic bacterial contamination, thereby enhancing the quality of the urban water environment.	(Durand et al., 2020) (WORMS, 1817)
Hymeniacidon perlevis dan *Mytilus galloprovincialis*	*Hymeniacidon perlevis* *https://www.marinespecies.org/aphia.php?p=taxdetails&id=132663*  *Mytilus galloprovincialis* *https://www.marinespecies.org/aphia.php?p=taxdetails&id=140481* 	Location: Apulian coast, Northern Ionian Sea. Time: -.	*Hymeniacidon perlevis* and *Mytilus galloprovincialis* can reduce bacterial levels in aquaculture environments, thereby enhancing water quality.	(Longo et al., 2016) (WORMS, 1817) (WORMS, 1819)
Hymeniacidon perlevis	*Hymeniacidon perlevis* *https://www.marinespecies.org/aphia.php?p=taxdetails&id=132663* 	Location: Torre a Mare, southern Italy. Time: 2022.	*Hymeniacidon perlevis* has proven successful in reducing concentrations of pathogenic bacteria and enhancing water quality in land-based experimental fish farms.	(Longo et al., 2022) (WORMS, 1814)
Anodonta californiensis	*https://www.inaturalist.org/taxa/738202-Anodonta-californiensis* 	Location: South Fork Eel River near Branscombe, CA. Time: 2013.	*Anodonta californiensis* can act as an effective bioremediation agent in reducing *Escherichia coli* contamination in urban freshwater environments.	(Ismail et al., 2015) (iNaturalist, n.d.-a)
Anadara granosa	*https://pacificraya.wordpress.com/2012/12/28/kerang-darah-anadara-granosa/anadara-granosa-2/* 	Location: West Java, Indonesia. Time: 2020.	*Anadara granosa* cleans polluted environments by accumulating and degrading organic pollutants.	(Sari et al., 2022) (Pacific Raya, n.d.)

Anadara granosa	*https://pacificraya.wordpress.com/2012/12/28/kerang-darah-anadara-granosa/anadara-granosa-2/* 	Location: Indonesia. Time: -.	*Anadara granosa* functions as a biofilter to reduce nitrogen (N) and phosphorus (P) waste in vaname shrimp ponds.	(Renitasari et al., 2023) (Pacific Raya, n.d.)
Daphnia magna	*https://freshwaterbiodiversity.org.bd/species/daphnia-magna/* 	Location: Spain. Time: -.	*Daphnia magna* effectively filters small particles and organic contaminants (ammonium, nitrite, nitrate, and phosphate) through filtration and absorption processes.	(Serra et al., 2019) (FBIS, n.d.)
Axinella damicornis	*https://www.marinespecies.org/aphia.php?p=taxdetails&id=132472* 	Location: Tyrrhenian Sea and Latium coast, Italy. Time: 2019.	*Axinella damicornis* can accumulate heavy metals in its tissues, thereby helping to reduce heavy metal concentrations in the environment and potentially clean contaminated seawater.	(Gravina et al., 2022) (WORMS, 1974)
Tubificidae	*https://www.gbif.org/species/6962* 	Location: Aquadip B.V., The Netherlands. Time: -.	*Tubificidae* efektif dalam mengurangi lumpur, memulihkan fosfor, dan meningkatkan produktivitas tanaman air *Azolla filiculoides* dalam pengolahan air limbah.	(Schuijt et al., 2021) (GBIF, n.d.)
Acrobeloides maximus	*https://www.sciencedirect.com/science/article/pii/S0044523124000561* 	Location: India. Time -.	*Acrobeloides maximus* is capable of degrading chlorpyrifos (CPF) with an efficiency exceeding 99%. It can address environmental pollution caused by complex organic compounds, such as organophosphate pesticides.	(Thakar et al., 2024)
Eisenia fetida	*https://www.inaturalist.org/taxa/127409-Eisenia-fetida* 	Location: Poland. Time: -.	*Eisenia fetida* effectively accumulates environmental toxins. These earthworms collect and process toxins in their tissues, improve organic substrates, maintain longevity and fertility, and have a strong reproductive capability.	(Jóźwiak et al., 2019) (iNaturalist, n.d.-b)
Eisena fetida and *porcellio* sp.	*Eisena fetida* *https://www.inaturalist.org/taxa/127409-Eisenia-fetida* 	Location: Iran. Time: 2017.	The combination of interactions between these two macrofauna can increase the efficiency of the organic waste bioremediation process, reduce heavy metal contamination, and improve the quality of the contaminated environment.	(Ahadi et al., 2020) (iNaturalist, n.d.-b) (Weird Pets PH, n.d.)

	https://www.weirdpets.ph/products/porcellio-sp-sevilla 			
Folsomia candida	*https://www.naturespot.org/species/folsomia-candida* 	Species origin: Aarhus University in Denmark. Soil origin: Jiangxi, Zhejiang, Hunan, Guangdong, in China. Time: -.	*Folsomia candida* has the potential to remediate soil contaminated with heavy metals through its antioxidant enzyme activity.	(Dai et al., 2018) (Spot, 2017)
Caenorhabditis elegans	*https://www.socmucimm.org/resources/news-media/an-overview-of-the-model-organism-c-elegans/* 	Location: USA. Time: -.	*Caenorhabditis elegans* serves as a carrier for oil-degrading bacteria, such as *Alcanivorax borkumensis*, into oil-contaminated environments. Its exceptional survival capability in areas exposed to crude oil positions it as a promising candidate for oil spill remediation.	(Shaikhulova et al., 2021) (SOCMUCIMM, 2014)
Caenorhabditis elegans, Cephalobus persegnis, and *Rhabditis marina*	*Caenorhabditis elegans* *https://www.socmucimm.org/resources/news-media/an-overview-of-the-model-organism-c-elegans/*  *Cephalobus persegnis,* https://images.wur.nl/digital/collection/nematode_pict/id/846/  *Rhabditis marina* *http://taxondiversity.fieldofscience.com/2015/01/rhabditoidea.html* 	Oil origin: Jiangsu, China. Soil origin: Anhui, China. Species origin: Genetics Centre, USA.	Three nematode species contribute to oil degradation by influencing the activity of soil microorganisms and enzymes, thereby aiding in the removal of oil pollutants from the soil.	(Zhou et al., 2022) (SOCMUCIMM, 2014) (WUR Library, n.d.) (Taylor & Ramos, 2015)

Zooremediation has shown beneficial results in addressing pollution. It has been tested in various countries and with several species. Factors such as location and time significantly influence the effectiveness of different species in remediation. For example, *Anadara granosa* demonstrates the ability to remediate several heavy metals through a zooextraction process (Sari et al., 2022). Additionally, other studies have shown that A. granosa also exhibits biofilter properties in its remediation efforts (Renitasari et al., 2023).

Applications of Zooremediation in Aquatic Environments

Zooremediation for Controlling Pathogenic Bacteria

Hymeniacidon perlevis, a member of the Porifera group, demonstrates significant individual remediation capabilities, effectively reducing the concentrations of pathogenic bacteria such as *Vibrio* sp., fecal enterococci, total coliforms, and fecal coliforms (Longo et al., 2022). Similar studies have confirmed these findings, showing that *H. perlevis* offers superior remediation performance compared to *Mytilus galloprovincialis* from the bivalve group. However, combining *H. perlevis* with *M. galloprovincialis* in the same environment enhances the overall effectiveness of the remediation process (Longo et al., 2016).

Other bivalves, such as *Geukensia demissa*, are effective at filtering water from pathogenic bacteria, particularly *Enterococcus* sp. and *Escherichia coli*. Bivalve species of *G. demissa* assimilate these bacteria as a food source, thereby improving urban water quality. This capability has been scientifically tested in New York, specifically on water affected by combined sewer overflow (CSO) (Durand et al., 2020). Additionally, *Anodonta californiensis* can treat *E. coli* using the zooextraction method. *A. californiensis* effectively reduced *E. coli* levels from 10^9 CFU/100 mL to 10^5 CFU/100 mL within 22 hours, achieving a removal rate of 0.82 hours^{-1} per mussel (Ismail et al., 2015).

Zooremediation for Inorganic Materials

Heavy metals are among the most significant environmental pollutants (Yeheyo et al., 2024). The prevalence of heavy metals in the environment is steadily increasing. *Axinella damicornis*, a sponge from the Porifera group, is used in zooremediation to address heavy metal contamination in seawater, particularly lead and cadmium (Gravina et al., 2022). In addition, metals contaminating wastewater on land can be effectively managed by animals such as those from the Tubificidae family (Schuijt et al., 2021), *Daphnia magna* (Serra et al., 2019), and *Anadara granosa* (Renitasari et al., 2023).

Anadara granosa, also known as the tern clam, serves as an effective remediation agent in seawater. Scientific studies have reported that while lead (Pb) levels in seawater can be as low as 0.16 mg/L, *A. granosa* can accumulate lead concentrations of up to 1.07 mg/kg. Although virgin shellfish containing metal contaminants pose a risk as a food source for humans, the use of *A. granosa* is relatively inexpensive and yields water that is suitable for use (Sari et al., 2022). The low cost of *A. granosa* is a significant advantage in its application for water remediation.

Zooremediation for Inorganic Materials

Anadara granosa also plays a similar role in managing organic pollutants by accumulating nitrogen (N) and phosphorus (P) in vannamei shrimp (*Litopenaeus vannamei*) cultivation. This remediation method involves treating blood cockles with different size categories (3-7 cm and 8-12 cm) and densities (15 individuals and 30 individuals) as treatment factors. The results indicated that the interaction between cockle density and size significantly affected the reduction of N and P waste, particularly nitrate levels. Treatment with a density of 30 individuals and a size of 8-12 cm proved most effective in absorbing N and P, as well as in reducing ammonia (NH3) and organic matter in *L. vanamei* cultivation (Renitasari et al., 2023).

Daphnia magna can convert wastewater into water that meets quality standards, providing an alternative method to alleviate pressure on usable water resources. Research by Serra et al. (2019) observed the effectiveness of *D. magna* in altering concentrations of ammonium, nitrite, nitrate, and phosphate over 7 days. Using the zooextraction method, *D. magna* extracts contaminants through filtration and absorption. Following toxicity testing, the treated water met quality standards. The sludge produced from this wastewater processing can be further treated with Tubificidae water worms. Scientific studies have validated the effectiveness of the zooextraction method and biocascade system. Tubificidae contribute to remediation by reducing sludge by 45%, recovering phosphorus, and enhancing the growth of the aquatic plant *Azolla filiculoides*, which is effective in phytoremediation (Schuijt et al., 2021). When combined with Tubificidae, *A. filiculoides* can further stimulate phytoremediation activity.

Zooremediation Methods for Aquatic Systems

Zooremediation in water employs various methods, with the zooextraction method being predominant for organisms such as *Geukensia demissa, Tubificidae, Daphnia magna,* and *Axinella damicornis* (Durand et al., 2020; Gravina et al., 2022; Schuijt et al., 2021; Serra et al., 2019). The zooremediation method for Hymeniacidon perlevis has not been extensively detailed in previous studies (Longo et al., 2016, 2022). However, a recent scientific report from 2024 describes the use of the zootransformation method in *H. perlevis*. This method involves changing or eliminating contaminants in the aquatic environment through the sponge's internal biochemical processes (Amato et al., 2023).

The use of aquatic animals as remediation agents offers several advantages and disadvantages. One significant benefit of zooremediation compared to microremediation is its ability to remove contaminants efficiently while maintaining high survival rates and low costs (Renitasari et al., 2023; Schuijt et al., 2021; Serra et al., 2019). However, a key drawback is the potential for introducing invasive species. For example, *Geukensia demissa*, when introduced into new environments, can disrupt local ecosystems by competing with native species for resources and altering the structure of existing biological communities (Durand et al., 2020). Additionally, the risk of transferring heavy metals from *Anadara granosa* to other organisms in the food chain is a concern (Sari et al., 2022), and the process can be time-consuming depending on the pollutant levels (Penha-Lopes et al., 2009). Therefore, the application of zooremediation in aquatic environments requires careful supervision by experts to prevent ecological imbalances and potential harm to the water ecosystem.

Applications of Zooremediation in Terrestrial Environments

Zooremediation in Agricultural Environments

The growing human population drives increased food production, necessitating significant and effective contributions from the agricultural sector (Ditta & Arshad, 2016; Kaur et al., 2023). To address food production challenges, farmers often rely on fertilizers. However, commercial fertilizers are typically used in large quantities due to their low efficiency and high susceptibility to being washed away by water currents. This inefficiency contributes to a decline in soil and groundwater quality, leading to environmental pollution (Bhattacharyya et al., 2022; Dai et al., 2018; Shahane & Shivay, 2021). Remediation using earthworms has proven effective in reducing pollutants and enhancing soil fertility in agricultural settings.

Folsomia candida, a species from the Collembola group, has garnered scientific interest for its role as an indicator of soil quality (Zhou et al., 2023) and its effectiveness in cleaning soil from various pollutants (Dai et al., 2018). *F. candida* exhibits remarkable drought tolerance (Le et al., 2022), feeds on plant pathogenic fungi (Gruss et al., 2022), and is used as a test species in developing nanomaterial applications in agriculture (Mendes et al., 2015). Laboratory tests using the zooextraction method on contaminated soil and soil spiked with heavy metals have shown that *F. candida* can successfully remediate environments polluted with cadmium (Cd), copper (Cu), zinc (Zn), and lead (Pb). Its effectiveness as a zooremediation agent is attributed to the activity of its antioxidant enzymes. Importantly, *F. candida* is not considered an invasive species that disrupts ecosystems; instead, it generally functions as part of the soil food chain in various habitats and does not exhibit invasive tendencies. The utilization of *F. candida* for zooremediation is relatively low-cost, but its application requires careful supervision due to its complex interactions with environmental factors (Dai et al., 2018).

Nematodes play a significant role in agricultural soil management and are used to address various types of waste in both water and land, particularly within agricultural ecosystems (Filgueiras et al., 2023). *Chlorpyrifos* (CPF), a pesticide pollutant, is commonly found in food and poses health risks to humans (Li et al., 2015). *Acrobeloides maximus* is a nematode with exceptional efficiency in degrading CPF, achieving over 99% removal. Its ability to tackle environmental pollution from complex organic compounds, such as organophosphate pesticides, highlights its value in zooremediation. *A. maximus* can be utilized as a zooremediation agent through zooextraction, zootransformation, and zoostabilization methods. The risk of *A. maximus* becoming an invasive species is relatively low. However, it has limitations, including its capacity to degrade only specific types of pollutants and its requirement for suitable environmental conditions (Thakar et al., 2024).

Zooremediation in Urban and Residential Areas

Human settlements contribute to soil pollution, necessitating remediation efforts, particularly in urban areas with landfills. Rainwater can wash pollutants from these landfills, leading to the formation of leachate. The pollutants carried by leachate can cause diseases and disrupt soil ecosystems (Jóźwiak et al., 2019; Junior et al., 2021).

Leachate contains toxic compounds that pose a significant threat to microorganisms, making microbial remediation challenging (Slack et al., 2005). A practical alternative for addressing leachate and contaminated soil is the use of the red worm *Eisenia fetida*. This worm is capable of mitigating various environmental toxins (Suthar et al., 2008). The use of *E. fetida* is cost-effective and versatile in its application. However, it requires careful monitoring to prevent potential invasiveness (Ahadi et al., 2020; Jóźwiak et al., 2019).

Scientific reports from 2019 evaluated the performance of *Eisenia fetida* over a period from initial use to nine months. The findings demonstrated that *E. fetida* effectively accumulated environmental toxins, processing them within its tissues, thereby improving the soil substrate and maintaining both longevity and fertility. Additionally, these earthworms showed a significant increase in population, growing from 25 individuals at the start of the study to 298 individuals after six months (Jóźwiak et al., 2019). The use of *E. fetida* can be complemented by woodlice (*Porcellio sp.*). While *E. fetida* focuses on degrading organic matter and reducing heavy metal content in the soil, *Porcellio sp*. aids in the decomposition of organic materials and the removal of heavy metals from the environment (Ahadi et al., 2020).

Zooremediation in Oil Industry Areas

The petroleum mining industry is rapidly expanding, but excessive exploitation has disrupted the balance of ecosystems. Oil spills, which pollute the land, represent a significant global issue. Petroleum contamination can taint groundwater and pose serious health risks to humans (Helmy & Kardena, 2024). Native soil microorganisms are susceptible to pollutants (Xu et al., 2019). Soil nematodes play a crucial role in supporting oil-degrading microorganisms (Shaikhulova et al., 2021), and are instrumental in decomposing nutrients and organic matter in the soil (Zhou et al., 2022).

Caenorhabditis elegans, a nematode, is known for its rapid reproduction and short life cycle, making it an ideal biological model for zooremediation. Its quick reproductive system allows for faster pollutant cleanup compared to other species. The brief life cycle of *C. elegans* helps prevent it from becoming an invasive species (Zhang et al., 2024). *C. elegans* also exhibits high antioxidant potential and resilience to various oxidative stresses, enabling it to survive under diverse conditions (Yen et al., 2023). With increased application in zooremediation, *C. Elegans*—which contains a range of fatty acids and bioactive compounds (Yu et al., 2024)—could be utilized in research on anti-aging (Zhang et al., 2024), genetics and molecular biology (Yen et al., 2023), toxicity testing (Zhou et al., 2023), and pharmaceutical development (Goyache et al., 2024).

Caenohabditis elegans is capable of surviving various oil pollutants and feeding on oil, which aids in the oil degradation process (Shaikhulova et al., 2021; Zhou et al., 2022). *C. elegans* also supports the role of *Alcanivorax borkumensis* in the remediation process, both in zooremediation and microremediation, and has been extensively tested. The effectiveness of combining *C. elegans* with *A. borkumensis* was investigated using the research framework illustrated in Figure 1 (Shaikhulova et al., 2021).

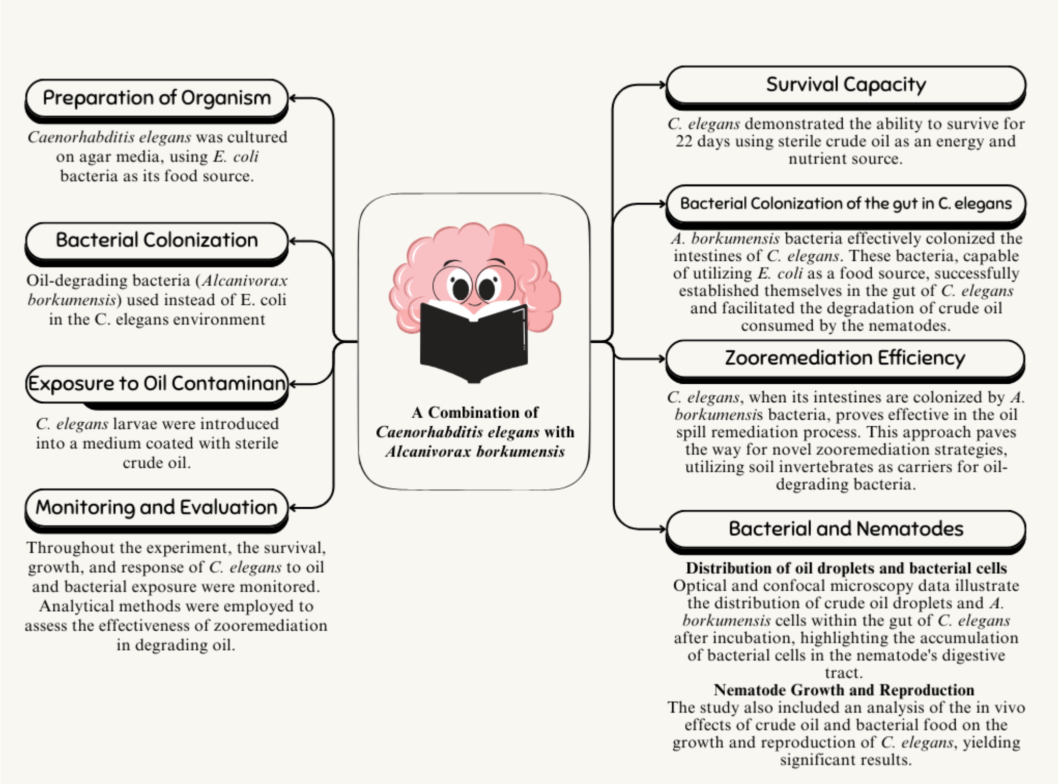


Figure 1. The combination of *C. elegans* and *A. borkumensis* for addressing oil spills and promoting a cleaner and healthier environment

Alcanivorax borkumensis is a marine hydrocarbonoclastic bacterium known for its effectiveness in degrading oil. Its ability to break down complex hydrocarbons makes it a valuable agent in bioremediation processes. When *A. borkumensis* colonizes the gut of *Caenorhabditis elegans*, it enhances the oil degradation process. In the context of zooremediation, the combination of *C. elegans* and *A. borkumensis* presents a promising approach for addressing oil spills and promoting a cleaner and healthier environment (Shaikhulova et al., 2021).

The nematode *Cephalobus persegnis* contributes to the bioremediation process by influencing soil microbial activity and altering the microbial community structure in oil-contaminated soils. Similarly, *Marina rhabditis* shows potential in enhancing oil degradation and the activity of soil microorganisms in polluted environments. The combination of *Cephalobus persegnis*, *Rhabditis marina*, *Caenorhabditis elegans*, and other organisms presents a promising new alternative for zooremediation (Zhou et al., 2022). While zooremediation offers a viable method for addressing soil pollution, its application as an alternative solution requires thorough investigation. Scientific research into the potential risks of invasive species remains crucial, and comprehensive studies are necessary to prevent possible future challenges.

Challenges in Applying Zooremediation

Zooremediation presents a promising and innovative approach to environmental pollution by utilizing animals as agents for remediation. Several studies have demonstrated the effectiveness of various animals in removing pollutants such as heavy metals, pathogenic bacteria, and other contaminants from the environment. Despite its potential, several challenges persist. There is a limited understanding of how remediation animals interact with their environments and the long-term impacts of their use, including the risk that these animals may become invasive species. Ensuring animal protection and welfare is crucial in the development and implementation of zooremediation to prevent adverse effects on animal populations. Addressing these challenges is essential for the broader adoption and success of zooremediation in the future.

Zooremediation is an emerging biotechnological strategy that utilizes animal species to remove or neutralize pollutants in contaminated environments, including soil, water, and sediment. Numerous studies have highlighted the ability of organisms, such as mollusks, fish, and annelids, to absorb heavy metals, pathogenic microbes, and organic pollutants, offering a potentially sustainable alternative to conventional remediation methods. This approach is particularly valued for its low energy requirements and minimal secondary pollution.

However, the implementation of zooremediation faces several significant challenges. Key limitations include insufficient understanding of the ecological interactions between remediation species and their environments, as well as the long-term impacts, such as the potential for these species to become invasive. Additionally, animal welfare considerations are frequently neglected, with remediation processes often exposing organisms to toxic conditions without ethical safeguards. The scalability of zooremediation remains limited, and its effectiveness is highly dependent on stable environmental parameters. Furthermore, the absence of standardized regulatory frameworks presents significant barriers to the safe and ethical deployment of these technologies. Addressing these challenges requires a multidisciplinary research agenda that incorporates ecological, moral, and regulatory perspectives to ensure the responsible advancement of zooremediation technologies.

Conclusions

In conclusion, zooremediation emerges as a compelling and innovative strategy for addressing environmental pollution by leveraging the natural abilities of animals to remediate contaminated environments. Studies have highlighted the effectiveness of various animal species, such as *Geukensia demissa*, *Daphnia magna*, *Anadara granosa*, and *Caenorhabditis elegans*, in managing pollutants, including heavy metals, pathogenic bacteria, and organic contaminants. The diverse methods employed in zooremediation — such as zooextraction, zootransformation, and zoostabilization — demonstrate its potential to offer cost-effective and efficient solutions to environmental challenges.

However, the practical application of zooremediation is not without its challenges. Key issues include the limited understanding of interactions between remediation animals and their environments, the potential for these species to become invasive, and the need for careful monitoring to ensure the welfare of these animals. Addressing these challenges is essential to enhance the feasibility and effectiveness of zooremediation. Future research must focus on understanding the long-term impacts, optimizing protocols, and safeguarding both ecological and animal health to realize the full potential of zooremediation in managing environmental pollution on a global scale.

Declaration statement

The authors report no potential conflict of interest.

References

Ahadi, N., Sharifi, Z., Hossaini, S. M. T., Rostami, A., & Renella, G. (2020). Remediation of Heavy Metals and Enhancement of Fertilizing Potential of a Sewage Sludge by the Synergistic Interaction of Woodlice and Earthworms. *Journal of Hazardous Materials*, *385*. https://doi.org/10.1016/j.jhazmat.2019.121573

Amato, A., Esposito, R., Federico, S., Pozzolini, M., Giovine, M., Bertolino, M., Guida, M., Manfra, L., Libralato, G., Zupo, V., & Costantini, M. (2023). Marine Sponges as Promising Candidates for Integrated Aquaculture Combining Biomass Increase and Bioremediation: an Updated Review. *Frontiers in Marine Science*, *10*, 1–16. https://doi.org/10.3389/fmars.2023.1234225

Awad, H. E. A., Mohammad, A. M., & Farahat, E. A. (2023). Potential Use of Dry Powder of *Vossia Cuspidata* (Roxb.) Griff. Rhizomes and Leaves in Methylene Blue Dye Remediation. *Scientific Reports*, *13*(1), 1–17. https://doi.org/10.1038/s41598-023-37987-0

Bhattacharyya, S. S., Leite, F. F. G. D., France, C. L., Adekoya, A. O., Ros, G. H., de Vries, W., Melchor-Martínez, E. M., Iqbal, H. M. N., & Parra-Saldívar, R. (2022). Soil Carbon Sequestration, Greenhouse Gas Emissions, and Water Pollution Under Different Tillage Practices. *Science of the Total Environment*, *826*. https://doi.org/10.1016/j.scitotenv.2022.154161

Dadebo, D., Obura, D., & Atukunda, A. (2024). Phytoremediation of Laundry Wastewater using Pistia Stratiotes and Recycling of Spent Plant Biomass for Sustainable Biomethane Production. *Bioresource Technology Reports*, *26*(December 2023), 101855. https://doi.org/10.1016/j.biteb.2024.101855

Dai, W., Ke, X., Li, Z., Gao, M., Wu, L., Chiristie, P., & Luo, Y. (2018). Antioxidant Enzyme Activities of *Folsomia candida* and Avoidance of Soil Metal Contamination. *Environmental Science and Pollution Research*, *25*(3). https://doi.org/10.1007/s11356-017-0489-x

Delsarte, I., Cohen, G. J. V., Momtbrun, M., Höhener, P., & Atteia, O. (2021). Soil Carbon Dioxide Fluxes to Atmosphere: The role of Rainfall to Control CO_2 Transport. *Applied Geochemistry*, *127*(November 2020). https://doi.org/10.1016/j.apgeochem.2020.104854

Ditta, A., & Arshad, M. (2016). Applications and Perspectives of Using Nanomaterials for Sustainable Plant Nutrition. *Nanotechnology Reviews*, *5*(2), 209–229. https://doi.org/10.1515/ntrev-2015-0060

Durand, S. E., Niespor, R., Ador, A., Govinda, N., Candia, M., & Torres, K. (2020). Ribbed Mussel in an Urban Waterway Filters Bacteria Introduced by Sewage. *Marine Pollution Bulletin*, *161*. https://doi.org/10.1016/j.marpolbul.2020.111629

Filgueiras, C. C., Kim, Y., Wickings, K. G., El Borai, F., Duncan, L. W., & Willett, D. S. (2023). The Smart Soil Organism Detector: An Instrument and Machine Learning Pipeline for Soil Species Identification. *Biosensors and Bioelectronics*, *221*. https://doi.org/10.1016/j.bios.2022.114417

FBIS. (n.d.). *Daphnia magna*. Freshwater Biodiversity Information System. https://freshwaterbiodiversity.org.bd/species/daphnia-magna/

GBIF. (2023). *Tubificidae*. Global Biodiversity Information Facility. Axinella damicornis

Gifford, S., Dunstan, R. H., O'Connor, W., Koller, C. E., & MacFarlane, G. R. (2007). Aquatic Zooremediation: Deploying Animals to Remediate Contaminated Aquatic Environments. *Trends in Biotechnology*, *25*(2), 60–65. https://doi.org/10.1016/j.tibtech.2006.12.002

Goyache, I., Yavorov-Dayliev, D., Milagro, F. I., & Aranaz, P. (2024). Caenorhabditis Elegans as a Screening Model for Probiotics with Properties Against Metabolic Syndrome. *International Journal of Molecular Sciences*, *25*(2). https://doi.org/10.3390/ijms25021321

Gravina, M. F., Longo, C., Puthod, P., Rosati, M., Colozza, N., & Scarselli, M. (2022). Heavy Metal Accumulation Capacity of *Axinella damicornis* (Esper, 1794) (Porifera, Demospongiae): A Tool for Bioremediation of Polluted Seawaters. *Mediterranean Marine Science*, *23*(1), 125–133. https://doi.org/10.12681/mms.27792

Gruss, I., Twardowski, J., Matkowski, K., & Jurga, M. (2022). Impact of Collembola on the Winter Wheat Growth in Soil Infected by Soil-Borne Pathogenic Fungi. *Agronomy*, *12*(7). https://doi.org/10.3390/agronomy12071599

Helmy, Q., & Kardena, E. (2024). Enhancing Field-Scale Bioremediation of Weathered Petroleum Oil-Contaminated Soil with Biocompost as a Bulking Agent. *Case Studies in Chemical and Environmental Engineering*, *9*(November 2023), 100735. https://doi.org/10.1016/j.cscee.2024.100735

iNaturalist. (n.d.-a). *Anodonta californiensis*. INaturalist. https://www.inaturalist.org/taxa/738202-Anodonta-californiensis

iNaturalist. (n.d.-b). *Eisenia fetida*. INaturalist. https://www.inaturalist.org/taxa/127409-Eisenia-fetida

Ismail, N. S., Dodd, H., Sassoubre, L. M., Horne, A. J., Boehm, A. B., & Luthy, R. G. (2015). Improvement of Urban Lake Water Quality by Removal of *Escherichia coli* Through the Action of the Bivalve Anodonta Californiensis. *Environmental Science and Technology*, *49*(3), 1664–1672. https://doi.org/10.1021/es5033212

Jakovljević, V. D., & Vrvić, M. M. (2018). Potential of Pure and Mixed Cultures of *Cladosporium cladosporioides* and *Geotrichum candidum* for Application in Bioremediation and Detergent Industry. *Saudi Journal of Biological Sciences*, *25*(3), 529–536. https://doi.org/10.1016/j.sjbs.2016.01.020

Jóźwiak, M. A., Jóźwiak, M., Kozłowski, R., & Żelezik, M. (2019). Zooremediation of Leachates From Municipal Waste using *Eisenia fetida* (SAV.). *Environmental Pollution*, *254*. https://doi.org/10.1016/j.envpol.2019.07.039

Junior, S. F. S., Mannarino, C. F., Bila, D. M., Taveira Parente, C. E., Correia, F. V., & Saggioro, E. M. (2021). Lethal and long-term effects of landfill leachate on Eisenia Andrei Earthworms: Behavior, Reproduction and Risk Assessment. *Journal of Environmental Management*, *285*.

Kaur, H., Hussain, S. J., Mir, R. A., Chandra Verma, V., Naik, B., Kumar, P., & Dubey, R. C. (2023). Nanofertilizers – Emerging Smart Fertilizers for Modern and Sustainable Agriculture. *Biocatalysis and Agricultural Biotechnology*, *54*. https://doi.org/10.1016/j.bcab.2023.102921

Le, N. G., van Ulsen, P., van Spanning, R., Brouwer, A., van Straalen, N. M., & Roelofs, D. (2022). A Functional Carbohydrate Degrading Enzyme Potentially Acquired by Horizontal Gene Transfer in the Genome of the Soil Invertebrate Folsomia candida. *Genes*, *13*(8). https://doi.org/10.3390/genes13081402

Li, R., He, L., Wei, W., Hao, L., Ji, X., Zhou, Y., & Wang, Q. (2015). Chlorpyrifos Residue Levels on Field Crops (Rice, Maize And Soybean) in China and Their Dietary Risks to Consumers. *Food Control*, *51*, 212–217. https://doi.org/10.1016/j.foodcont.2014.11.023

Liang, Z., Neményi, A., Kovács, G. P., & Gyuricza, C. (2024). Incorporating functional traits into Heavy Metals Phytoremediation: The Future of Field-Based Phytoremediation. *Ecological Indicators*, *166*(April). https://doi.org/10.1016/j.ecolind.2024.112262

Longo, C., Cardone, F., Corriero, G., Licciano, M., Pierri, C., & Stabili, L. (2016). The Co-Occurrence of the Demosponge Hymeniacidon Perlevis and the Edible Mussel Mytilus Galloprovincialis as a New Tool for Bacterial Load Mitigation in Aquaculture. *Environmental Science and Pollution Research*, *23*(4), 3736–3746. https://doi.org/10.1007/s11356-015-5587-z

Longo, C., Pierri, C., Mercurio, M., Trani, R., Cardone, F., Carbonara, P., Alfonso, S., & Stabili, L. (2022). Bioremediation Capabilities of *Hymeniacidon perlevis* (Porifera, Demospongiae) in a Land-Based Experimental Fish Farm. *Journal of Marine Science and Engineering*, *10*(7). https://doi.org/10.3390/jmse10070874

Martínez-burgos, W. J., Porto, L., Vandenberghe, D. S., Fátima, A., Mello, M. De, Carvalho, J. C. De, Valladares-diestra, K. K., Manzoki, C., Scapini, T., Pozzan, R., Liew, R. K., Soccol, T., & Soccol, C. R. (2024). Bioremediation Strategies Against Pesticides: An Overview of Current Knowledge and Innovations. *ECSN*, 142867. https://doi.org/10.1016/j.chemosphere.2024.142867

Mendes, L. A., Maria, V. L., Scott-Fordsmand, J. J., & Amorim, M. J. B. (2015). Ag Nanoparticles (Ag NM300K) in the Terrestrial Environment: Effects at Population And Cellular Level in *Folsomia Candida* (Collembola). *International Journal of Environmental Research and Public Health*, *12*(10), 12530–12542. https://doi.org/10.3390/ijerph121012530

Novakovskiy, A. B., Kanev, V. A., & Markarova, M. Y. (2021). Long-Term Dynamics of Plant Communities After Biological Remediation of Oil-Contaminated Soils in Far North. *Scientific Reports*, *11*(1), 1–12. https://doi.org/10.1038/s41598-021-84226-5

Pacific Raya. (2015). *Anadara granosa*. Pacific Raya-Science and Technology Reviews. https://pacificraya.wordpress.com/2012/12/28/kerang-darah-anadara-granosa/anadara-granosa-2/

Pahalvi, H. N., Rafiya, L., Rashid, S., Nisar, B., & Kamili, A. N. (2021). Microbial Degradation of Organic Constituents for Sustainable Development. In *Microbiota and Biofertilizers, 2: Ecofriendly Tools for Reclamation of Degraded Soil Environs*, 2. https://doi.org/10.1007/978-3-030-61010-4_5

Penha-Lopes, G., Torres, P., Narciso, L., Cannicci, S., & Paula, J. (2009). Comparison of Fecundity, Embryo Loss and Fatty Acid Composition of Mangrove Crab Species in Sewage Contaminated and Pristine Mangrove Habitats in Mozambique. *Journal of Experimental Marine Biology and Ecology*, *381*(1), 25–32. https://doi.org/10.1016/j.jembe.2009.08.009

Rahman, M. E., Uddin, M. K., Shamsuzzaman, S. M., Mahmud, K., Shukor, M. Y. A., Ghani, S. S. A., Nabayi, A., Sadeq, B. M., Chompa, S. S., Akter, A., & Halmi, M. I. E. Bin. (2024). Potential use of Pennisetum Purpureum for Phytoremediation of Arsenic in Treatment Sand: A Phytotoxicity Study. *Biocatalysis and Agricultural Biotechnology*, *60*(April), 103300. https://doi.org/10.1016/j.bcab.2024.103300

Renitasari, D. P., Ihwan, I., & Syahrir, M. (2023). Minimaliser limbah N dan P Tambak Udang Vaname dengan Memanfaatkan Biofilter Kerang Darah (*Anadara granosa*). *Sains Akuakultur Tropis: Indonesian Journal of Tropical Aquaculture*, *7*(1), 139–145. https://doi.org/10.14710/sat.v7i1.17237

Sari, M. P., Riyantini, I., & Ihsan, Y. N. (2022). Kontaminasi Logam Pb (Timbal) pada *Anadara granosa* di Pantai Utara Kabupaten Cirebon. *Buletin Oseanografi Marina*, *11*(3), 248–254. https://doi.org/10.14710/buloma.v11i3.38451

Sarwar, M., Patra, J. K., Ali, A., Maqbool, M., & Arshad, M. I. (2020). Effect of compost and NPK fertilizer on improving bio chemical and Antioxidant Properties of *Moringa oleifera*. *South African Journal of Botany*, *129*, 62–66. https://doi.org/10.1016/j.sajb.2019.01.009

Schuijt, L. M., van Bergen, T. J. H. M., Lamers, L. P. M., Smolders, A. J. P., & Verdonschot, P. F. M. (2021). Aquatic Worms (Tubificidae) Facilitate Productivity of Macrophyte Azolla Filiculoides in a Wastewater Biocascade System. *Science of the Total Environment*, *787*. https://doi.org/10.1016/j.scitotenv.2021.147538

Serra, T., Soler, M., Pous, N., & Colomer, J. (2019). Daphnia Magna Filtration, Swimming and Mortality Under Ammonium, Nitrite, Nitrate and Phosphate. *Science of the Total Environment*, *656*, 331–337. https://doi.org/10.1016/j.scitotenv.2018.11.382

Shahane, A. A., & Shivay, Y. S. (2021). Soil Health and Its Improvement Through Novel Agronomic and Innovative Approaches. *Frontiers in Agronomy*, *3*, 1–31. https://doi.org/10.3389/fagro.2021.680456

Shaikhulova, S., Fakhrullina, G., Nigamatzyanova, L., Akhatova, F., & Fakhrullin, R. (2021). Worms Eat Oil: Alcanivorax Borkumensis Hydrocarbonoclastic Bacteria Colonise *Caenorhabditis Elegans* Nematodes Intestines as a First Step Towards Oil Spills Zooremediation. *Science of the Total Environment*, *761*. https://doi.org/10.1016/j.scitotenv.2020.143209

Slack, R. J., Gronow, J. R., & Voulvoulis, N. (2005). Household Hazardous Waste in Municipal Landfills: Contaminants in Leachate. *Science of the Total Environment*, *337*(1–3), 119–137. https://doi.org/10.1016/j.scitotenv.2004.07.002

SOCMUCIMM. (2014). *Caenorhabditis elegans*. Society for Mucosal Immunology. https://www.socmucimm.org/resources/news-media/an-overview-of-the-model-organism-c-elegans/

Spot, N. (2017). *Folsomia candida*. Nature Spot-Wildlife and Wild Places of Leicestershire & Rutland. https://www.naturespot.org/species/folsomia-candida

Suthar, S., Singh, S., & Dhawan, S. (2008). Earthworms as Bioindicator of Metals (Zn, Fe, Mn, Cu, Pb and Cd) in Soils: Is Metal Bioaccumulation Affected by Their Ecological Category? *Ecological Engineering*, *32*(2), 99–107. https://doi.org/10.1016/j.ecoleng.2007.10.003

Taylor, C., & Ramos, K. (2015). *Female Rhabditis*. Variety of Life. http://taxondiversity.fieldofscience.com/2015/01/rhabditoidea.html

Thakar, S. P., Dabhi, R. C., Rathod, S. L., Patel, U. P., Rana, A., Shrivastav, P. S., George, L. B., & Highland, H. (2024). In Situ Chlorpyrifos (CPF) Degradation by Acrobeloides maximus: Insights from Chromatographic Analysis. *Journal of Chromatography A*, *1714*. https://doi.org/10.1016/j.chroma.2023.464555

Treifeldt, J. E. Von, Firestein, K. L., Joseph, F. S., Zhang, C., Siriwardena, D. P., Lewis, M., & Golberg, D. V. (2020). Fungal bioremediation: An Overview of the Mechanisms, Applications and Future Perspectives. *Materials & Design*, 109403. https://doi.org/10.1016/j.enceco.2024.07.002

Weird Pets PH. (n.d.). *Porcellio sp.* Weird Pets PH. https://www.weirdpets.ph/products/porcellio-sp-sevilla

Workineh, M. (2020). Impact of Application of Organic Fertilizer on Production of Some Cereal Crops: A Review. *Academic Research Journal of Agricultural Science and Research*, *8*(3), 214–226. https://doi.org/10.14662/ARJASR2020.145

WORMS. (1794). *Axinella damicornis*. World Register of Marine Species. https://www.marinespecies.org/aphia.php?p=taxdetails&id=132472

WORMS. (1817). *Geukensia demissa*. World Register of Marine Species. https://www.marinespecies.org/aphia.php?p=taxdetails&id=156859#images

WORMS. (1814). *Hymeniacidon perlevis*. World Register of Marine Species.

WORMS. (1819). *Mytilus galloprovincialis*. World Register of Marine Species.

WUR Library. (n.d.). *Cephalobus persegnis: female posterior body*. Wageningen University & Research. https://images.wur.nl/digital/collection/nematode_pict/id/846

Xu, J., Zhang, Q., Li, D., Du, J., Wang, C., & Qin, J. (2019). Rapid Degradation of Long-Chain Crude Oil in Soil by Indigenous Bacteria using Fermented Food Waste Supernatant. *Waste Management*, *85*, 361–373. https://doi.org/10.1016/j.wasman.2018.12.041

Yeheyo, H. A., Ealias, A. M., George, G., & Jagannathan, U. (2024). Bioremediation Potential of Microalgae for Sustainable Soil Treatment in India: A Comprehensive Review on Heavy Metal and Pesticide Contaminant Removal. *Journal of Environmental Management*, *363*(April), 121409. https://doi.org/10.1016/j.jenvman.2024.121409

Yen, P., Lin, T., Chuah, W. L., Chang, C., Tseng, Y., Huang, C., Yang, J., Hsu, F., & Liao, V. H. (2023). Methanol Extracts from *Cirsium japonicum* DC. var. australe Kitam. and Their Active Components Reduce Intracellular Oxidative Stress in Caenorhabditis elegans. *Molecules*, *28*(19). https://www.mdpi.com/1420-3049/28/19/6923

Yu, D., Guo, M., Tan, M., & Su, W. (2024). Lipid-Lowering and Antioxidant Effects of Self-Assembled Astaxanthin–Anthocyanin Nanoparticles on High-Fat Caenorhabditis elegans. *Foods*, *13*(4). https://doi.org/10.3390/foods13040514

Zhang, L., Zhu, Y., Gu, H., Lam, S. S., Chen, X., Sonne, C., & Peng, W. (2024). A Review of Phytoremediation of Environmental Lead (pb) Contamination. *Chemosphere*, *362*(December 2023), 142691. https://doi.org/10.1016/j.chemosphere.2024.142691

Zhang, X., Chen, Q., Chen, L., Chen, X., & Ma, Z. (2024). Anti-Aging in Caenorhabditis Elegans of Polysaccharides from Polygonatum cyrtonema Hua. *Molecules*, *29*(6), 1276. https://doi.org/10.3390/molecules29061276

Zhou, J., Xu, X., Huang, G., Li, W., Wei, Q., Zheng, J., & Han, F. (2022). Oil Degradation and Variation of Microbial Communities in Contaminated Soils Induced by Different Bacterivorous Nematodes Species. *Ecotoxicology and Environmental Safety*, *229*. https://doi.org/10.1016/j.ecoenv.2021.113079

Zhou, Q., Han, L., Li, Y., Li, J., & Yang, X. (2023). Neutral Dietary Effects of Two MicroRNAs, Csu-Novel-260 and Csu-Mir-14, on the Non-Target Arthropod Folsomia candida. *Plants*, *12*(9). https://doi.org/10.3390/plants12091885

Zhou, Q., Wu, K., Yao, L., Chen, R., Liu, S., Xing, H., Nie, L., & Wu, Z. (2024). Bio-ecological Remediation of Freshwater Aquaculture Environments: A Systematic Review and Bibliometric Analysis. *Water Biology and Security*, *3*(1). https://doi.org/10.1016/j.watbs.2023.100229

Zhou, T., Wu, J., Liu, Y., & Xu, A. (2023). Seawater Accelerated the Aging of Polystyrene and Enhanced Its Toxic Effects on Caenorhabditis elegans. *International Journal of Molecular Sciences*, *24*(24). https://doi.org/10.3390/ijms242417219