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MICROCOSMS AS AN IMPLEMENT FOR ASSESSING ECOLOGICAL PROCESSES IN AQUATIC AND TERRESTRIAL ENVIRONMENTS. REVIEW

Currently, microcosms are used for research and assessment of environmental impacts on the environmental components. Microcosms are useful instruments in ecological studies, toxicology, and ecotoxicology. Microcosms allow the experimental study of ecosystems in a controlled medium. This review article is focused on the experiences of the use of aquatic and terrestrial microcosms in practice. The knowledge gained from studies of aquatic microcosms has applications in the removal of microplastics, pesticides, antibiotics, and their residues, heavy metals (Hg, Cd, Zn, etc.), the modification of the features of acid mine drainage, and the wastewater treatment. Terrestrial microcosms are suitable for the adaptation of the microbial community to pollution and acidification. The studies have identified potential microorganisms for remediation of the polluted environments and examined the effects of factors such as light, temperature, and redox conditions on the removal and transformation of the pollutants in soil. The effects of biofilm bacteria on bioremediation of pesticides and polycyclic aromatic hydrocarbons were also examined. These studies provide valuable insights into the relationships among organisms, processes, and the environment, and can contribute to a better understanding of environmental risks and bioremediation opportunities in different ecosystems.

1. INTRODUCTION

Anthropogenic activity is currently causing serious global environmental problems. Chemicals in consumer products have various negative effects in the environment. In many cases, they have carcinogenic and endocrine effects, acting as poisons on the organism of individuals, and causing its damage [1]. These toxicants can deposit in the body and cause problems [2]. The substances can not only endanger the health of individuals but also damage the soil, drinking water sources, fauna, and flora. A significant

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group of toxicants are emergent pollutants. These are mainly pharmaceuticals (medicines, but also drugs and other products used in medicine and the pharmaceutical industry), nanomaterials, microplastics (polymers with various additives that are formed from the breakdown of larger plastic objects or microplastic products such as cosmetics, etc.), chemicals in food (used in the production and preservation of food, additives for shelf-life extension, coloring agents, flavorings), chemicals in agriculture [3].

It is important to monitor and study their impact on the environment and human health so that measures can be taken to regulate them and minimize the negative impact. Various studies have been carried out worldwide to ensure sustainability and a healthy environment for future generations. However, the problem of pollution, especially in the aquatic and terrestrial environment, is growing. Monitoring methods are still not well studied and harmonized, detection limits are limited and there is a lack of information on the fate of these substances in the environment [4], [5]. Reliable scientific studies on the evidence of the existence of these environmental problems and their risk effects on the environment are important.

One of the detection possibilities is the use of microcosms as experimental systems that simulate specific ecosystems. Microcosms allow the study of the behavior of toxicants and their impact on the structure and function of ecosystems, as well as environmental restoration processes. They are extremely valuable instruments in ecotoxicology, enabling ecological risk assessment and contributing to environmental protection [6]. Microcosms are simplified models of ecosystems that have a wide range of applications. They allow experimental investigation of the evolution and ecological processes on short-time scales. Experiments with them are carried out in laboratories or can be applied directly in nature. In the past, they have contributed to important ecological concepts. They are used for general ecological studies and to test the effects of substances or organisms that would not be safe to test in the natural environment. Their application requires careful planning of resources, space and time scales, replication, and similarity to natural ecosystems. Experiments are well complemented with mathematical models and field studies. Although the results are not always directly transferable to the real world, they provide useful insights for understanding ecosystems and biodiversity [7], [8]. Research in natural microcosms can lead to new insights into ecological processes and provide a useful basis for a wider view of ecosystem functioning. Using microcosms is also possible to demonstrate evolution in practice [7]. They represent a useful intermediate step between single-species toxicological tests and field studies. Their main characteristic is the introduction of multiple species into the same test system, usually from different taxonomic groups. Microcosms can also have different designs and levels of complexity. They are used not only to test toxicity to soil organisms, but also to assess chemical fate, ecological interactions, and other processes in other components of the environment [8], [9].

Microcosms are most often divided according to the medium in which they are realized. Aquatic microcosms are characteristic of standing waters up to 1 m^3 and flowing waters up to 1 m. It is possible to observe a benthic environment, a pond, a river, or a wastewater treatment microcosm. The aquatic environment is characterized by microorganisms (bacteria, yeasts, protozoa, fungi, and algae) which are involved in the degradation of almost all contaminants present in the waters [10]. Terrestrial microcosms are focused on the root system, soil core, etc. [11]. Studies applied in complex systems that include water, sediment, and plant and invertebrate communities are referred to as multispecies. They are used to assess the wider ecological impacts of chemicals [11]. According to the use of specific organisms, these are natural and artificial microcosms. Natural microcosms – microorganisms and model organisms that exist in nature and are used in various scientific disciplines. Artificial microcosms – organisms or model systems that have been genetically modified or created under laboratory conditions for scientific research or engineering. Natural microcosms are characterized as small biotopes that have significant advantages for ecological research. Their limited size allows for efficient replication of experiments and robust statistical analysis that ensures the removal of covariate effects [12]. For studies applied in natural microcosms, it is important to consider certain limitations and perceive their strong sides [13]. For ecotoxicity assessment, methods have been developed in complex, multi-stage configurations to simulate natural conditions and serve as models to assess ecological relationships between organisms. In these systems, both direct and indirect effects can be monitored [11]. Artificial (laboratory) microcosms are created in a controlled environment to study different aspects of microorganisms and their interactions. Laboratory microcosms are the basis for scientific experiments that simulate real environmental conditions or the response of organisms to changes in their environment. The creation of artificial microcosms involves the setting up of a controlled environment with given parameters such as temperature, humidity, pH, the presence of nutrients, and other factors that affect the microorganisms. The creation and study of artificial microcosms are dynamic and constantly evolving [11].

The article is an overview of the studies carried out in aquatic and terrestrial microcosms and their need for implementation in different conditions. Presented studies provide an overview of the impact of different chemicals on populations and communities under simulated natural conditions.

2. USE OF AQUATIC MICROCOSMS IN PRACTICE

The created wetland microcosm with the plants *Spathiphyllum wallisii* and *Zantedeschia aethiopica*, a substrate made of plastic waste, is effective in removing contaminants from the aquatic environment. The substrate had a positive effect on the removal of contaminants and the proper development of plants, which represents an innovation in the use of this material. The use of another substrate, red volcanic gravel, is beneficial in the removal of nitrates, phosphates, biochemical oxygen demand, and fecal coliform bacteria [14]. Another study [15] investigated the effect of three species of terrestrial plants and their role in the removal of pollutants from wastewater in constructed wetlands. Two types of substrates were used: plastic and mineral. Both substrates were effective in removing pollutants such as nitrates, phosphates, and fecal coliform bacteria. Systems with vegetation achieved significantly higher efficiency than systems without vegetation. However, the use of polyethylene terephthalate as a substrate did not adversely affect plant growth. A study performed by Crisafi et al. [16] compares biostimulation and bioaugmentation using a scrubbing agent to clean up an oil spill in the Gulf of Taranto, Italy. Biostimulation with inorganic nutrients enabled the biodegradation of 73±2.4% of hydrocarbons. Bioaugmentation with a selected hydrocarboclastic consortium consisting of *Alcanivorax borkumensis*, *Alcanivorax diesel olei*, *Marinobacter hydrocarbonoclasticus*, *Cycloclasticus* sp. 78-ME and *Thalassolituus oleivorans* degraded 79±3.2%, while addition of nutrients and detergent enabled degradation of 69±2.6%. The microbial community in the microcosm was seriously affected by the addition of the detergent and the product was able to inhibit the growth of most of the strains forming the selected consortium at the tested concentration [16]. Cheng et al. [17] investigated the effects of fourteen plastic particles and six fibrous materials on the growth of organisms used in microcosm experiments. Higher concentrations and smaller sizes of plastic particles caused lower growth rates of *Chlorella* spp. Fibrous plastic particles inhibited the growth of *Chlorella* spp. compared to fragmented plastic particles. All types of plastics inhibited the growth of *Euglena*, while aerobic bacteria *Bacillus* subtilis were inhibited by plastics more than facultative anaerobic bacteria and yeasts. The presence of micro plastics negatively affected the growth and reproduction of *Daphnia magna*. Plastics selectively affect the growth of different species in the same environment and may have the potential to alter species composition in natural ecosystems [17]. The influence of microplastics on a simplified aquatic ecosystem of mosses and caddisflies was investigated for 60 days in a study described by Grgić et al. [18]. Moss acts as an absorber of microplastics in the freshwater environment, brooks served as a way of transferring microplastics into aquatic food webs. The study highlights the adverse effects of microplastics on these aquatic species and highlights the role of aquatic organisms in the redistribution of microplastics between aquatic and terrestrial environments. Zhu et al. [19] investigated the influence of floating microplastics on sediment microbial ecosystems. Floating microplastics affect the diversity and composition of the sediment microbial community. Some bacteria responsible for organic matter decomposition, nitrification and denitrification decreased significantly in response to floating microplastics, which may have affected the carbon and nitrogen cycles in the sediment. Floating microplastics reduced the complexity of microorganism networks and increased negative correlations [19, 20]. The influence of microplastics on microbial communities in intertidal (tidal) sediment was investigated in a study presented by Fang et al. [20]. The experiment ran for 30 days and involved the use of different types of microplastics, including biodegradable and conventional plastics at different concentrations. Microplastics at low concentrations rapidly affected the composition of the microbial community. Changes were influenced by factors such as the content of organic carbon and nitrite nitrogen in the sediment and urease activity. Changes in the microbial community mainly affected the microorganisms *Alphaproteobacteria* and *Nitrososphaeria* [20]. The toxicity and fate of polystyrene nanoparticles with the addition of palladium was monitored in a freshwater environment on two primary producers: the cyanobacteria *Anabaena* sp. and the green alga *Chlamydomonas reinhardtii* and one primary consumer crustacean *Daphnia magna*. Polystyrene with the addition of palladium causes overproduction of reactive oxygen species, membrane damage, and metabolic changes in cyanobacteria and green algae. Toxicity to *Daphnia magna* is concentration dependent [21].

The study [22] investigated the effect of a pesticide (2-13-C,15-N-glyphosate) using plant filters (*Phalaris arundinacea*). In the microcosms, a high amount of glyphosate was removed, and its decomposition was greater compared to the standard method. The test results helped to better understand the fate of pesticides in the filters and thereby contribute to the development of more effective strategies for pesticide removal in the future [22]. The study [23] investigated the use of natural agro-industrial materials as suspended fillers in floating wetlands to enhance nutrient removal. Incorporating fillers into wetlands improved the removal of total nitrogen by 20–57% and total phosphorus by 23–63%. The fillers also increased macrophyte growth and biomass production, increasing nutrient stores. The use of a mixture of fillers in wetlands promoted biofilm formation and enriched microbial communities involved in nitrogen removal processes [23]. The fate of the chiral fungicide Mandipropamid (MDP) in aquatic ecosystems at the enantiomeric level is dealt with in a study by Zhang et al. [24]. The fungicide is gradually decomposed and adsorbed in microcosms in water and in sediment, while enantioselective differences were not observed. R-MDP was preferentially degraded in the water of Lake and Yangtze River (ingested to form microcosms), while S-MDP was preferentially degraded in Yangtze River and Yellow River sediments (added to microcosms). Degradation products have been identified and some of them have been found to pose a potential threat to aquatic ecosystems [24]. Nitrate pollution is a common problem in aquatic environments. In a study given by Li et al. [25] the relationships between denitrification and dissimilatory reduction of nitrate to ammonia under iron(II) supply were investigated. Microcosms with sediments from freshwater lakes were used in the experiment and the rate of nitrate reduction was monitored. The presence of iron stimulated both processes. Metagenomic analysis showed enrichment of iron(II)-dependent nitrate reducers and Beta-*proteobacteria* [25].

The study [26] focused on antimony (Sb) in irrigated rice fields, its release, and volatilization during common agricultural practices. Flooding of the soil causes a temporary release of Sb into the pore environment while reducing the sulfate content. Soil fertilization affected the concentration of Sb in the aqueous pore environment, and increased the evaporation of Sb. Effective removal of mercury (Hg) from contaminated water/wastewater is of great importance due to its extremely high toxicity. Chang et al. [27] used granular biochar and gravel (control) in intermittently aerated constructed wetland microcosms to remove Hg for 100 days. Biochar wetlands had significantly better Hg removal than gravel systems. Plants (*Lythrum salicaria*) absorbed more than ten times more Hg in biochar than in gravel systems, with roots acting as the main sink. Biochar showed higher removal levels of COD, N, and P. Hg import only slightly affected the removal of these pollutants. Fill material has a more important role in shaping wetland microbial communities than Hg. The proportion of some dominant genera (*Arenimonas*, *Lysobacter*, *Micropruina*, and *Hydrogenophaga*) increased in the presence of Hg, indicating their tolerance to Hg toxicity and potential roles in Hg detoxification in wetlands [27]. The study [28] investigated the potential risks associated with the use of wastewater containing Hg, Cd, Se, and As in microalgae aquaculture. The aim was to evaluate the distribution of these elements between the biomass, the medium, and the gas phase, but also to quantify the leakage. *Arthrospira maxima* and *Chlamydomonas reinhardtii* were cultured in a medium contaminated with specific concentrations of these contaminants. Most contaminants accumulate in the medium and microalgae biomass. In the case of mercury, 48±2% was associated with *Arthrospira maxima* and 55±8% with *Chlamydomonas reinhardtii*. The presence of the element's arsenic, selenium and cadmium increases the association of mercury with *Chlamydomonas reinhardtii* to 85±11%. Small and variable volatilization of mercury was observed in all microalgae cultures [28].

A study performed by Wang et al. [29] was devoted to a multi-stage wetland microcosm, which was used to clean acid mine drainage (AMD) and municipal wastewater. The study lasted 270 days. The microcosm effectively raised the pH of the wastewater and removed dissolved metals and pollutants, including sulfates and organics. The addition of the fermentation broth promoted the activity of microorganisms, while the metal-rich sludge allowed for the recovery of these metals, thus minimizing their presence. The results showed the potential of this system as an environmentally friendly technology for cleaning AMD and promoting a sustainable solution to the environmental problems associated with AMD [29]. The study [30] investigated the effects of external organic substrates and small-molecule organic acid for the treatment of acid mine drainage (AMD). The results showed that organic wastes such as sugar pomace, compost, shrimp, and crab shells, together with organic propionic acid, contribute to the removal of harmful substances and the creation of a favorable environment for the growth of microorganisms [30].

The study [31] used microcosms to investigate the stability of enteric viruses in the aquatic environment. The study used sediments and water from a lagoon, into which adenovirus (AdV-GFP) and mouse norovirus were subsequently introduced. Viruses exposed to natural sunlight lost their infectivity faster than in dark conditions. A negative correlation was found between temperature and infectivity of viruses in water and sediment samples [31]. In studies by Elmahdy et al. [32] the influence of non-antibiotic antimicrobial substances on the expression of antibiotic resistance genes and virulence factors in aquatic ecosystems was investigated. Microcosms in a freshwater environment were used in the study. Silver nanoparticles (AgNPs) inhibit the expression of antibiotics and virulence factors. They reduce the number of pathogenic microorganisms that express these genes. On the contrary, azoxystrobin increases their expression, but at the same time reduces the number of pathogens that show resistance. Non-antibiotic antimicrobial agents have different effects on the manifestation of antibiotic resistance and pose different ecological risks [32]. The study [33] investigated the expression profiles of antibiotic resistance genes and virulence factors under the influence of ciprofloxacin, glyphosate, and sertraline hydrochloride. Ciprofloxacin led to increased expression of resistance, especially multidrug resistance genes. Environmental xenobiotics, including test compounds, can disrupt microbial ecology, promote resistance, and pose a risk to human health [33]. The study [34] investigated the spread of antibiotic-resistant bacteria through wastewater and their persistence and proliferation in receiving aquatic ecosystems. Microcosm experiments with enriched untreated river water or treated wastewater showed a significant increase in antibiotic-resistant bacteria compared to microcosms containing only river water [34]. The study [35] investigated the effect of wastewater irrigation on bacterial communities and antibiotic resistance in soil and vegetables. Metagenomic techniques were used to analyze bacterial diversity and detect antibiotic resistance genes. The results showed a shift in the bacterial community profile with a decrease in the *Proteobacteria phylum* and an increase in the *Firmicutes phylum* after wastewater irrigation. Using shotgun metagenomics, diverse resistant antibiotics were detected in wastewater, while only blaTEM (beta-lactamase) and aadA (aminoglycoside) genes were found in soil and blaTEM on vegetable surfaces. The presence of blaTEM in all samples indicated the potential spread and persistence of this resistance gene. Antibiotic resistance monitoring in agrosystems is of fundamental importance for informing sustainable wastewater use policies in water-scarce countries [35]. The study [36] investigated the toxic effects of the antidepressant paroxetine on meiobenthic nematodes. Three types of microcosms made of polyvinyl chloride tubes, each containing two sediment compartments (upper and lower), were used in a laboratory experiment for 15 days. The experimental setup was focused on the migration behavior of the organisms that were exposed to paroxetine (in the concentration range of 0.4 and 40 $\mu g/dm^3$). Multivariate analyses revealed significant taxonomic differences between contaminated and uncontaminated compartments [36]. The impact of biofilm in the water supply for the needs of drug degradation (morphine, fentanyl, cocaine, and amphetamine) was investigated by Pagsuyoin et al. [37], for 48 hours. In parallel, microcosm tests were carried out with wastewater with and without suspended biofilm. The results indicated that amphetamine was the most stable in all microcosms, with the maximum removal after 48 hours being only 34%. The study reports on the impact of biofilm in the water supply for the degradation of fentanyl.

The study [38] investigated the effects of porous media and plants that will be used to remove substances in vertical wetlands built by subsurface flow. Twelve microcosms contained porous river rock and twelve contained tepezil as the porous medium. Typha spp, *Zantedeschia aethiopica*, and *Alpinia purpurata* were planted in each porous medium. Both porous media were effective in pollutant removal. Phosphates were reduced by more than 40%, BOD by 80% and nitrates by 40%. The authors propose the use of these plants for wastewater treatment. This study also recommends the use of these porous media materials in the design of new wetlands [38]. The effect of wastewater from the textile industry on adult *Danio rerio* fish was studied by Wang et al. [39]. The potential impact on the environment and the health of organisms was investigated. Fish were exposed to real water from wastewater treatment plants from textile plants in aquatic microcosms for six months. The results showed a significant deterioration in the growth of adult *Danio rerio* fish, which was manifested by inhibition of growth, deterioration of the fitness coefficient, and a significant increase in mortality. At the same time, there were significant changes in the intestines of fish after chronic exposure to wastewater. An increased occurrence of some occasional pathogens such as *Flavobacterium*, *Aeromonas*, and *Escherichia* has been reported, which may represent a potential health risk factor. Conversely, some species of bacteria such as *Cetobacterium*, *Bacteroides*, and *Planctomyces* increased after exposure [39]. A study presented by Marín-Muñiz et al. [40] focused on the removal of pollutants from wastewater by tropical plants (195 days). Monocultures of the hybrid *Canna*, *Alpinia purpurata*, and *Hedychium coronarium* and polycultures of the same plants, whose substrate was porous river rock, were planted in the wetlands. The best results in the research were achieved by the Canna hybrid, which had the highest length and volume of roots, the highest height, and number of flowers. Ammonia nitrogen removal was significantly higher in microcosms with *C. hybrid* monocultures than in *A. purpurata* monocultures, but not significantly different from *H. coronarium* monocultures. Conversely, the removal efficiency of this ion was significantly higher in the polyculture than the *A. purpurata* and *H. coronarium* cocultures but not significantly different from the C. hybrid monoculture.

3. USE OF TERRESTRIAL MICROCOSMS IN PRACTICE

Yu et al. [41] investigated the adaptation of the microbial community to long-term hexabromocyclododecane (HBCDs) pollution and acidification in the soil. Microorganisms, specifically eukaryotes and fungi, have shown a significant ability to adapt to these adverse conditions. The eukaryotic taxa *Eufallia* and *Syncystis* and the fungal taxa *Wickerhamomyces* occurred only after 20 months of pollution. In addition, the eukaryotic taxa *Caloneis* and *Nitzschia* and the fungal taxon *Talaromyces* were dominant in most microbial communities. The study provides new insights into how microorganisms respond to long-term HBCDs pollution and acidification through different mechanisms and adaptation strategies [41]. Yu et. al. [42] investigated microbial community restoration in microcosms with contaminated mangrove sediments. Contamination with hexabromocyclododecane (HBCD) caused the transformation of HBCD to lower brominated products and acidification of the environment. As a result, there was a decrease in the abundance of microorganisms and viruses in contaminated sediments. Also, selected groups of microorganisms, such as *Zetaproteobacteria*, *Deinococcus-Thermus*, *Spirochaetes*, and *Bacteroidetes*, reacted positively to the presence of HBCDs, and changes in the microbial community were dependent on the type of sediment [42]. A study [43] focused on the decomposition of commercially available biodegradable plastic (BDP) in different soils and its effect on microbial communities. After 360 days, there was a weight loss of BDP in the range of 42.0–48.0%. Decomposition took place in two phases, while the first phase (day 0 – 30) was characterized by significant weight loss and the formation of specific bacterial communities on the surface of the plastic. In the second phase (day 30 – 360), the decomposition of the remaining BDP components took place at a slower rate and microbial communities gradually recovered. BDP decomposition was influenced by the resistance of individual components and changes in soil microbial communities during the decomposition process [43]. The decomposition of diesel fuel in soil using artificial microcosms over 180 days was investigated by Fernández et al. [44]. Microcosms were formed by soil columns, on which various plants were planted, earthworms were added, and the local microflora was created. The course and interactions affected by diesel fuel decomposition were investigated. The system of microcosms made it possible to study the effectiveness of remediation under real conditions and to monitor the effect of diesel substances on organisms and their possible excretion into the soil. Plants were not effective in remediation even though they stimulated microbial biomass. On the contrary, earthworms had a positive effect on diesel decomposition. Some plant species were more resistant to soil contaminated with petroleum hydrocarbons. The release of hydrocarbons – petroleum substances into the soil was negligible and did not depend on the combination of organisms in the microcosms [44]. The study [45] characterized bacteria isolated from an oil well and their potential for hydrocarbon degradation in contaminated soil. They analyzed the properties of the bacteria, including surfactant production, emulsification ability, and biofilm formation. *Pseudomonas bacteria* showed different abilities to produce surfactants and emulsify hydrocarbons, and integration of selected strains into microbial consortia led to more efficient degradation of contaminated soil.

Burrows et al. [46] tested integrated soil microcosms as model terrestrial ecosystems to assess pesticide effects on a range of representative soil organisms and ecosystem processes. The interaction between organisms and processes that can affect the overall environmental impact and fate of the pesticide was monitored. Microcosms with carbendazim and copper provide reproducible results on pesticide effects [46]. Soil microbial biodiversity supports crop productivity and agroecosystem functioning in experimental microcosms [47]. The study examined the impact of soil biodiversity loss on multiple ecosystem functions, including plant production and geochemical cycles. Experimental simplification of the soil microbial community in microcosms demonstrated that a decline in soil biodiversity led to a reduction in ecosystem multifunctionality, including lower plant productivity and soil nutrient retention capacity. On the contrary, the application of mineral fertilizers had only a small effect on multifunctionality [47]. A study given by D'Aquino et al. [48] is focused on growing basil plants using microcosms that simulate real growing conditions. They compared two lighting modes: white and blue, and red in terms of their impact on plant growth, biomass yield, photosynthesis efficiency, intake of nutrients and secondary metabolites. Both lighting modes support intensive plant growth and biomass yield. The blue-red light mode promotes taller plants, earlier flowering, and higher yields. Nutrient concentrations differed between the two regimes, indicating that yield and nutrient content were not directly related. Photosynthetic efficiency was similar in both regimes [48]. Gorodylova et al. [49] assessed the effectiveness of a bio augmentation approach using biofilms on zeolites as inoculants in microcosm experiments. A microbial consortium capable of degrading MCPA herbicide was grown as a biofilm on natural and iron-modified zeolite grains. They applied these biocomposites to soil and sand microcosms with the addition of MCPA herbicide. The selected biocomposites showed a similar ability to biodegrade MCPA, achieving up to 80% MCPA degradability in 2 days in soil and 5 days in sand. They found that zeolite-supported biofilms can be effective inoculants for pesticide biodegradation in polluted agricultural areas [49]. Gautam et al. [50] investigated the degradation of imidacloprid using the bacterium *Sphingobacterium* sp. in the soil microcosm. *Sphingobacterium* sp. can degrade imidacloprid with an efficiency of approximately 79% using enzymes that are encoded in its genome. Enzymes can catalyze the oxidative degradation of imidacloprid and subsequent decarboxylation of intermediates [50]. Egene et al. [51] investigated greenhouse gas emissions from soil enriched with 18 different bio-based fertilizers and mineral fertilizers. Fertilizers may have lower nitrogen oxide N_2O emissions compared to mineral fertilizers. The dominant process for N_2O production was nitrification. The application of some fertilizers caused increased CO_2 emissions, while the solid fraction of fertilizers showed slow mineralization patterns. Fertilization did not affect CH_4 emissions. Fertilizers from anaerobic decomposition have a lower ecological impact than untreated digestate [51]. Zhang et al. [52] investigated the effect of microbial activity, light, and redox conditions on the removal and transformation of nine cyanotoxins in controlled soil microcosms for 28 days. Cyanotoxins were eliminated in soil microcosms through biological reactions in both aerobic and anaerobic soils, with anaerobic conditions accelerating the biological removal of some cyanotoxins. Some cyanotoxins were also degraded by photolytic degradation, but not all.

Some cyanotoxins remained in the soil in an extractable form even after exposure to light, redox conditions, and low microbial activity [52].

The study [53] conducted an “open microcosm” experiment by creating connected sedimentary compartments with different qualities. The migratory behavior of nematodes exposed to pyrene for 30 days was tested. The nematofauna was collected with the sediment from a reference site in the Bizerte Lagoon. After a one-week acclimatization period, the settled sediments were covered with azoic sediments with a pyrene concentration of 150 μg/kg. Pyrene concentration from the sediments was measured weekly. A steady state of nematode assemblages was achieved between the upper and lower compartments in each microcosm. During the first two weeks, an upward exploratory phase was observed, probably induced by the repellent chemodetection of pyrene. This observation was confirmed by the toxicokinetic properties and molecular interactions of pyrene with the germline developmental protein and the sex-determining protein of *Caenorhabditis elegans* as a model nematode. The study [54] used a bacterial biofilm consortium for the bioremediation of polycyclic aromatic hydrocarbons in soil. Some bacteria in the consortium showed a chemotactic movement towards hydrocarbons and increased their solubility in extracellular polymeric substances. The result was a significant improvement in the degradation of phenanthrene and pyrene in the soil microcosm. The enzymatic activity of catechol 2,3-dioxygenase indicated that carbohydrate metabolism was occurring via the catechol pathway. The study points to the potential of biofilm bacteria in removing the hydrocarbons in question from the soil.

Mieczan et al. [55] investigated the effect of simulated climate warming on the microbiome of pastures of the *Utricularia vulgaris*. An increase in temperature caused an increase in some microorganisms and a decrease in others, as well as a change in the size structure of microbes. Temperature, organic matter, and biogenic compounds are important factors influencing the microbial community.

A study given by Yang et al. [56] deals with soil fauna, specifically isopods (*Porcellionidae* and *Armadillidiidae*), during the decomposition of waste and its influence on soil nutrients. Experiments in field microcosms lasted three months. The presence of isopods significantly accelerated the decomposition of waste and increased the content of organic carbon, nitrogen, and potassium in the soil. Soil fauna can improve surface soil quality by promoting litter decomposition [56].

4. CONCLUSION

Pollutants from anthropogenic activity pose threats to water and soil ecosystems. Their harmful effects are not sufficiently studied. Microcosms are simplified models of ecosystems in a controlled environment that allow experimental investigation of evolutionary and ecological processes. They enable ecological risk assessment and contribute to environmental protection. Their use has a wide range, from ecological studies to testing the toxicity of substances that bring valuable knowledge about the functioning of ecosystems and their reactions to various factors using diverse test organisms, from microorganisms to entire populations.

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