Pesticide–Microbe Interaction: Investigating the Response of Pseudomonas Spp. To Pesticide Exposure

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Abstract
The use of pesticides has significantly increased agricultural productivity but at the cost of causing significant environmental and ecological issues because of their persistence and toxicity. Investigation of microbial responses, particularly those of Pseudomonas spp., is important as these bacteria are extremely resistant and metabolically very active. Studies indicate that pesticides modify microbial diversity, enzyme activity, and soil health. Pseudomonas spp. exhibit good biodegradation potential, activating antioxidant systems and supporting detoxification of the soil. However, there are gaps in species-specific responses and long-term effects. These results identify the possible application of Pseudomonas spp. in sustainable agriculture, restoration of soil ecology, and bioremediation measures. This review focuses on the response of Pseudomonas spp. to pesticide exposure, their biodegradation mechanisms, resilience strategies, and potential applications in soil health restoration and bioremediation.

Keywords: Pesticides, Pseudomonas spp., Biodegradation, Microbe–pesticide interaction.

1. INTRODUCTION

Pesticides are toxic chemicals sprayed to kill insects or to control weeds (Ngegba et al., 2022). According to the Food and Agriculture Organization (FAO), a pesticide is any product or combination of products used to prevent, eliminate, or repel pests, including disease carriers affecting humans and animals, unwanted plant or animal species, or to protect the production, processing, transport, storage, or marketing of food, horticultural produce, wood, animal feed, and related materials.

Pesticides cover a broad category of chemical substances, including herbicides, insecticides, fungicides, rodenticides, molluscicides, nematicides, and plant growth regulators. The introduction of synthetic insecticides—like organophosphates (OPs), carbamates, pyrethroids, and contemporary herbicides and fungicides—has made major strides in pest control and increased agricultural production (Khan et al., 2023). The main goals of the use of pesticides are to boost crop yields, promote soil efficiency, improve product quality, reduce crop loss, and regulate insect vectors that transmit diseases to humans and animals (Tudi et al., 2021). Moreover, pesticide and herbicide use has become more widespread in agriculture for food product preservation and storage.

A Pesticide ought to be harmful to the pests that targets and should be harmless to non-target organisms (Stanley et al., 2016). But pesticide consumption by target pests accounts for a tiny portion of the total amount administered (Elhamalawy et al., 2024). Organochlorine (OC) pesticides, which effectively controlled diseases like malaria and typhus, were prohibited or restricted in many developed countries after 1960's (Indu et al., 2022). According to Pimentel, 99.7% of pesticides used did not reach the target pest and instead ended up in the environment. This resulted in ongoing debate about the proper application and abuse of pesticides (Aung, 2023).

1.1 Pesticides in Modern Agriculture

Pesticides are categorized into carbamates, organochlorines, organophosphates, and pyrethroids according to their chemical structure. The World Health Organization (WHO) has divided them into four classes based on their toxicity – Class Ia , Class Ib, Class II, Class III. Moreover, pesticides are grouped into five categories based on their mode of action. In addition, according to the target organism, pesticides can be categorized into different specific groups. The table 1 and 2 outlines the classification and types of pesticides.

Table 1. Pesticide classification based on mode of action, and its efficacy (Yadav and Devi, 2017).

S No.	Pesticides	Description	Example
1	Physical poison	These pesticide classes kill a single insect by causing a physical reaction.	Activated clay
2	Protoplasmic poison	These chemicals are the cause of protein precipitation.	Arsenicals
3	Respiratory poison	Respiratory poisons are substances that inhibit respiratory enzymes.	Hydrogen cyanide
4	Nerve poison	Chemicals prevent impulse conduction.	Malathion
5	Chitin inhibition	These compounds prevent pests from producing chitin.	Diflubenzuron

Table 2. Types of pesticides, its target organisms and examples (Yadav and Devi, 2017; Baweja et al., 2020; khan et al., 2023; Ahmad et al., 2024).

S No.	Types	Target Organisms	Examples
1	Acaricides	Ticks and Mites	Carbamates, Bifenazate, Dicofol, Dienochlor
2	Algaecides	Algae	Dichlone, Copper sulfate, Endothal, Fentin, Diuron
3	Avicides	Birds	Avitrol, CPTH, Strychnine, Chloralose
4	Bactericides	Bacteria	Vancomycin, Potassium persulfate, Daptomycin, Hypochlorites
5	Desiccants	Unwanted plants	Boric acid
6	Fungicides	Blights, mildews, molds	Nimbin, Acibenzolar, Benomyl, Famoxadone Monocerine

7	Herbicides	Weeds	Dicamba, Fluoroxypyr, Metolachlor, Picloram
8	Insecticides	Insects, Arthropods	Allethrin, Lindane, Malathion, Profenofos, Chlorpyrifos, Aldicarb
9	Larvicides	Larvae	Methoprene, Temephos
10	Lampricides	Lamprey's larvae	Trifluromethyl nitrophenol
11	Molluscicides	Molluscs (slugs, snails)	Allicin, Ferric Sodium EDTA, Metaldehyde, Methiocarb
12	Moth balls	Moth larvae, molds	Dichlorobenzene
13	Nematicides	Nematodes	Aldicarb, Abamectin, Carvacrol, Diamidafos, Imicyafos
14	Ovicides	Insect or mite's egg	Benzoxazin
15	Piscicides	Fish	Rotenone, Fintrol, Niclosamide Rotenone, TFM
16	Rodenticides	Rodents	Bromethalin. Difethialone, Flupropadine, Norbormide, Pindone, Pyrinuron
17	Repellents	Pests	Methiocarb
18	Silvicides	Woody vegetation	Tebuthiuron
19	Termicides	Termites	Fipronil
20	Virucides	Viruses	Scytovirin, Cyanovirin – N, Urumin

India currently has 293 officially listed pesticides, of which 104 continue to be manufactured or marketed in the country despite being prohibited in several other countries across the globe (Pandey, 2023). Significantly, up to 50% of the entire insecticide consumption in the country is used by cotton production, indicating a significant dependence on chemical pest control in this crop (Voora et al., 2020). The extensive and unregulated application of insecticides has given rise to various adverse effects, including chemical contamination of food crops, pest resistance, secondary pests, pollution of natural ecosystems, and harmful effects on the health of humans and wildlife. These problems highlight the necessity for adopting environmentally sustainable pest control practices. Figure 1 outlines different types of pesticides used to control various insect pest infestation.

Fig 1. Different types of pesticides used to control various insect pest infestation

In comparison with global pesticide use, India's consumption is relatively low. In 2017, the country used approximately 0.31 kilograms of pesticides per hectare—significantly lower than the usage in countries like Saint Lucia, Hong Kong, Ecuador, Taiwan, and China (Piploda et al., 2022). Some nations, like the United States, have even recorded a decline in pesticide use per hectare in recent years. The trend of pesticide consumption in India also varies from that in the world. In India, insecticides are the most widely used category, followed by herbicides, then fungicides and bactericides, and lastly other pesticides (Reddy et al., 2024). Globally, however, herbicides lead in usage, followed by fungicides, bactericides, insecticides, and others. India has become the fourth largest pesticide-producing nation in the world. In 2019, India's pesticide market was valued at ₹214 billion and was projected to reach ₹316 billion by the year 2024, with a compound annual growth rate of approximately 8.1% (Shukla et al., 2021).

Chlorpyrifos is currently the most commonly applied insecticide, with an increment in use remarkably from 2014 to 2020. Sulphur is the most commonly used fungicide, while the most commonly applied herbicides include 2,4-D amine salts. Zinc phosphide continues to be the favoured rodenticide. In terms of chemical classes, organophosphates are the most widely used insecticides, followed by neonicotinoids and pyrethroids. Amongst crops, cotton leads in pesticide use, followed by vegetables, wheat, millets, and mustard, reflecting heavy dependence on chemical pest control in major agricultural crops (Nayak and Solanki, 2021).

Pesticide usage patterns among tomato farmers were extensively studied in research conducted in Anantapur district, Andhra Pradesh. The researchers found that pesticide type, frequency of application, seasonal use, dosage, and sources of information all significantly influenced their practices. Interestingly, pesticide application was higher during summer, with only half of the farmers following the acceptable dosage guidelines. Nearly 28% farmers applied pesticides above recommended levels, thus increasing the risk of toxic residues in produce. The majority of farmers, according to the survey, consulted pesticide traders instead of agricultural experts. These findings highlight the importance of regulatory measures and educational efforts to promote safer pesticide use (Ribka et al., 2020).

1.2 Pesticides: Mode of action and Environmental Fate

1.2.1 Herbicides

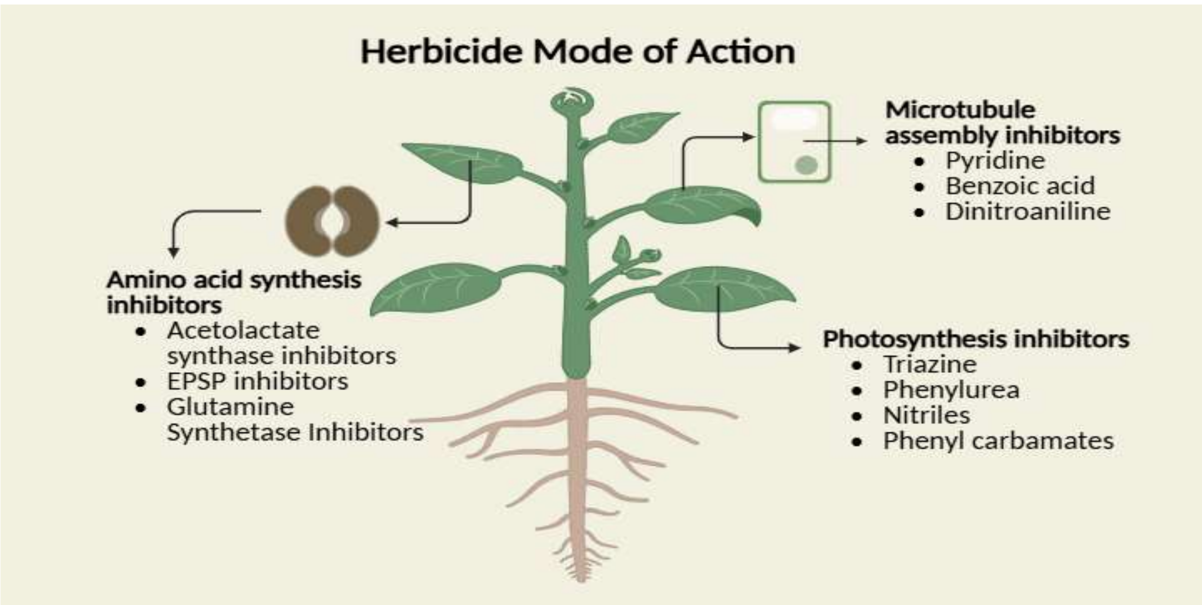

Fig 2. Mode of action of Herbicide

Herbicides work by inhibiting certain physiological or biochemical processes vital to plant growth and development (Cobb, 2022). One of the primary modes of action is the inhibition of amino acid synthesis, where herbicides block enzymes that are involved in the production of essential amino acids. For instance, Acetolactate synthase (ALS) inhibitors, such as sulfonylureas, prevent the synthesis of branched-chain amino acids. Similarly, glyphosate acts on the enzyme 5-enolpyruvoyl-shikimate-3-phosphate synthase to prevent the production of aromatic amino acids like phenylalanine, tyrosine, and tryptophan, which ultimately halts plant growth. Glutamine synthetase, an enzyme that catalyzes the conversion of ammonia and glutamate into glutamine, is another important target enzyme whose inhibition distrupts nitrogen metabolism in plants (Hall et al., 2020). Figure 2 outlines the mode of action of herbicide.

Certain herbicides disrupt microtubule formation by interacting with tubulin and thus inhibit cell division (Hess, 2020). These occur in chemical classes like pyridines, benzoic acids, and dinitroanilines. Photosynthesis inhibitors are equally important; chemicals like triazines, phenylureas, nitriles, and phenyl carbamates interfere with photosynthetic processes and electron transport systems, destroy protective pigments, and result in the production of toxic free radicals. Chemical structural diversity and site specificity enable herbicides to be categorized according to target sites (Sousa et al., 2020).

1.2.2 Insecticides

Insecticides act by disrupting the insect nervous system. Major classes such as pyrethroids and organochlorines inhibit neural signal transmission. Organochlorines such as lindane and endosulfan inhibit GABA (gamma-aminobutyric acid)-gated chloride channels, reducing neuronal inhibition, causing overstimulation, and ultimately causing insect death (Baratzhanova et al., 2024). Another common mechanism is cholinesterase inhibition. Organophosphates and carbamates both inhibit acetylcholinesterase (AChE), the enzyme that degrades acetylcholine. This leads to accumulation of acetylcholine in nerve synapses, leading to repetitive nerve stimulation, paralysis, and death. Some insecticides, including benzoylureas, also disrupt chitin production in the insect exoskeleton by interfering with the formation of N-acetylglucosamine chains, inhibiting molting and growth (Mdeni et al.,2022).

1.2.3 Fungicides

Fungicides have a wide range of action mechanisms. One such common mechanism is the inhibition of cell division where drugs like benzimidazoles (e.g., carbendazim, benomyl) bind with tubulin, inhibiting the production of microtubules and, consequently, mitosis (Gupta, 2022). Another action involves the targeting of sulfhydryl (-SH) groups in fungal enzymes. Fungicides like captan and folpet bind with SH-containing enzymes, causing cellular disruption and integrity loss in the membranes. Certain fungicides interfere with ergosterol biosynthesis, which is an essential for maintaining fungal cell membrane structure and function. This group consist of demethylase inhibitors such as pyridines, morpholines, and piperazines, which inhibit sterol biosynthesis and disrupt membrane function. Additionally, certain fungicides affect multiple biochemical targets, including antioxidant enzymes, disrupting cellular redox balance and interfering with crucial signaling pathways such as NF-κB (nuclear factor kappa B), ultimately hindering fungal development and survival (Shi et al., 2020).

1.2.4 Persistence of Pesticides in the Environment

Although the majority of organochlorine (OC) pesticides have been banned, their residual presence in soil, sediments, and the biosphere continues to be an important environmental problem (Olisah et al., 2020). Chemicals such as toxaphene, DDT, and lindane, were routinely used in agriculture and continue to pollute ecosystems long after use has ceased (Banik, 2021). These pesticides remain in agricultural soils and are able to leach through surface runoff and erosion, poisoning neighbouring water bodies. In Nicaragua, for

instance, pesticide residues from previous uses in agriculture have been seen to leach into aquatic system and threaten aquatic life, especially shrimp aquaculture in coastal lagoons (Betts et al., 2020). Such contaminants are threats to aquatic ecosystems, especially coral reefs, where herbicides kill symbiotic algae on which coral relies.
According to European and American research, Pesticide residues remain in coastal sediments and marine fauna decades since their ban (Ali et al., 2021). The residues of chemicals remain in the Mediterranean Sea, the North Sea, and the Baltic Sea, and they exhibit low degradation rates (Jalkanen et al., 2024). Legacy pesticides have already been discovered in contaminating coastal ecosystems and riverine systems of Brazil, Mexico, Vietnam, and the Philippines. Figure 3 outlines the accumulation and bioleaching of pesticides in the environment.

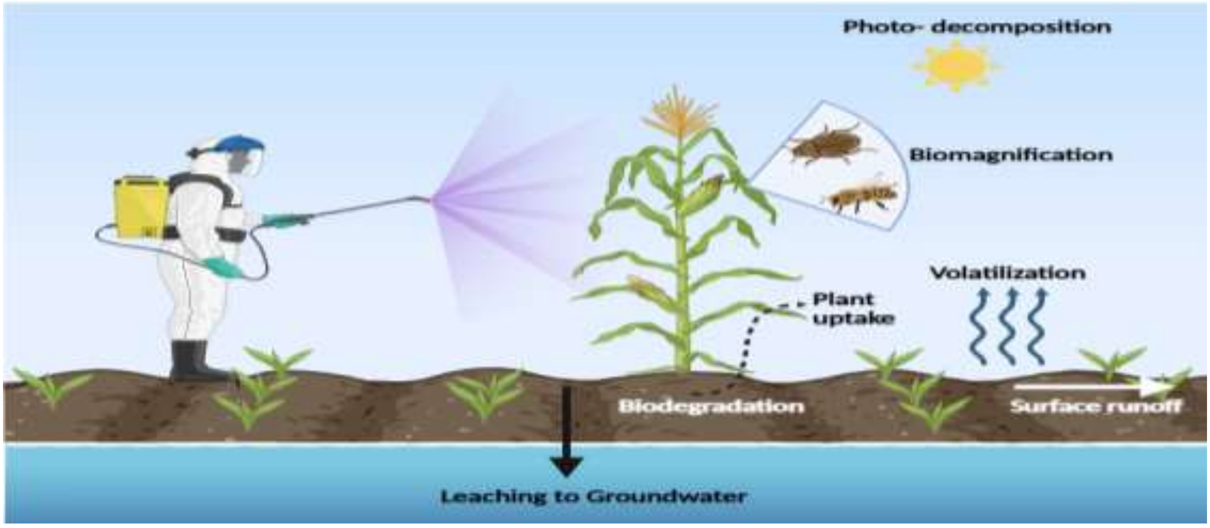

Fig 3. Accumulation and bioleaching of pesticides in the environment

1.3 Microbial Communities in Ecosystem

Soil microorganisms are essential in sustaining soil health by promoting nutrient cycling processes, detoxifying toxic substances, and facilitating plant growth and productivity (Patle et al., 2023). These microorganisms, such as bacteria, fungi, archaea, and protozoa, constitute a dynamic and highly diverse community of the soil ecosystem. Their operation is mainly localized in the topsoil, where they degrade organic residues, control the availability of key nutrients, and make a general contribution to the rhizosphere's overall functioning—the vital zone of interaction between roots and soil (Asghar et al., 2024).
Microorganisms play a key role in nutrient cycling by converting complex organic materials into simpler, plant-accessible forms. Bacteria break down organic residues and mineralize nutrients like nitrogen, phosphorus, and sulfur. Nitrogen-fixing bacteria such as Rhizobium fix atmospheric nitrogen into ammonium, making it available to plants. Nitrosomonas and Nitrobacter bacteria perform nitrification, reducing ammonium to nitrate, which is easily taken up by plant roots. Archaea also play an important role in nitrogen cycling by oxidizing ammonia. Fungi, particularly mycorrhizal fungi, increase phosphorus absorption by establishing symbiotic relationships with plant roots and decomposing recalcitrant plant residues such as lignin, further enriching the soil with nutrients (Hu and Yin, 2024).
Microorganisms are also responsible for detoxifying processes in the soil. By breaking down organic waste and contaminants, they transform toxic substances into less harmful forms, thereby maintaining a balanced

and healthy soil environment. Soil organic matter (SOM) is pivotal in this endeavor, serving both as a detoxifier and as a buffer. Microbial function facilitates the decomposition of pesticides, heavy metals, and synthetic organics, keeping them out of the environment and protecting crop integrity and ecosystem integrity (Jayaram et al., 2022).

From a plant health perspective, soil microbes serve as indispensable allies. They suppress soil-borne pathogens through competitive exclusion, production of antimicrobial compounds, and activation of plant systemic resistance. By increasing nutrient availability and producing growth-promoting substance, these microbes increase plant immunity and resistance. Protozoa, for instance, prey on bacteria and promote maintenance of microbial homeostasis and indirectly regulates nutrient cycling and availability. In addition, soil enzymes like phosphatase, urease, and dehydrogenase produced by microbes play key roles in the catalysis of nutrient transformation processes in the soil (Patle et al., 2023).

1.4 Why Pseudomonas?

Among various microbial candidates, Pseudomonas species are most well known for their extensive metabolic diversity and variety of enzymatic pathways, thereby being the most promising candidates for the degradation of pesticides (khoshru et al., 2025). Pseudomonas spp. is a highly heterogeneous group of bacteria that occurs in all habitats such as soil, water, plants, and animals (Urgancı et al., 2022). Pseudomonas spp. is a member of the Proteobacteria phylum of the Bacteria domain. It is a member of the Pseudomonadaceae family, Pseudomonadales order, and Gammaproteobacteria class. These microbes can degrade a wide range of organic compounds, including pesticides, as a source of carbon and nitrogen, thereby being extremely useful applications in the field of bioremediation. For example, Pseudomonas aeruginosa PAO1 has shown tremendous potential in the degradation of beta-cypermethrin and its toxic metabolite, 3-phenoxybenzaldehyde, in aquatic and soil environments, with 91.4% degradation within 120 hours of observation (Chen et al., 2023).

In addition, some Pseudomonas species, like Pseudomonas sp. strain ADP, are made up of specialized enzymes, like atrazine chlorohydrolase (AtzA), that help degrade hard pesticide molecules into less toxic entities. Their genetic adaptability, normally facilitated by plasmid-mediated horizontal gene transfer, enhances their ability to adapt and biodegrade diverse pesticides (John and Jisha, 2022). Besides, their viability under varied environmental conditions such as high pH, high temperature, and toxic pollutants makes them suitable in polluted environments. Biofilm formation potential and starvation-resistant conditions of the Pseudomonas species make them more suitable for bioremediation processes (Sarwan, 2022). These features all in all make Pseudomonas a suitable organism for pesticide biodegradation, providing a green process of elimination of pesticide pollution. This review seeks to provide knowledge on Pseudomonas responses to pesticides.

2. Pesticides and their effects on Environment and Human health

Pesticide residues not only persist in the environment but also modify ecosystems. Pesticides that penetrate aquatic ecosystems profoundly impact aquatic food webs through bioaccumulation and biomagnification (Ray and Shaju, 2023). The chemicals themselves at first might be present at very low concentrations in water bodies, but they are consumed by primary producers such as algae. Zooplanktons, small aquatic animals, consume the infested algae and accumulate chemicals in their bodies. When the large fish consume these small animals, the concentration of pesticides rises with each trophic level. This is due to biomagnification, a process that results in the top predators such as giant fish, sea mammals, and birds having the largest concentration of harmful chemicals. Due to this, the predators will most likely experience reproductive issues, developmental defects, and elevated mortality (Tongo et al., 2020).

These chemicals affect aquatic species and other target species by absorption through the skin, respiration, and ingestion of polluted water. These pesticides enhance environmental stressors such as algal blooms and decrease biodiversity by disrupting ecological balance. (Zahoor and Mushtaq, 2023). In addition to earlier pesticides, newer chemicals such as chlorpyrifos, glyphosate, and parathion are increasingly found in water bodies, some of which exhibit increasing quantities over time (Syafrudin et al., 2021). Bioaccumulation of pesticides in food webs is toxic to predators and reduces avian, amphibian, and animal populations. Pesticides like carbaryl and glyphosate are the causes of excessive amphibian mortality, while malathion affects plankton and periphyton ecological processes which affects tadpole development. Furthermore, organophosphates like chlorpyrifos and endosulfan are extremely hazardous to amphibians (Brice and Kenko, 2022). Birds are especially sensitive because pesticides persist in their tissues, causing population losses, as seen by bald eagles who are exposed to DDT.

Pesticides have an equivalent impact on terrestrial ecosystems. The overutilization of inorganic fertilizers and pesticides profoundly affects the number and variety of beneficial microorganisms in the soil. These pesticides and fertilizers alter the functional diversity of microbial communities in agricultural ecosystems by directly affecting their abundance and activity. Inorganic fertilizers, for example, have been reported to greatly decrease beneficial microbial populations like those of Pseudomonas spp. (Reid et al., 2021). This decrease in microbial biomass also coincides with a decrease in the activity of important soil enzymes such as dehydrogenase, catalase, invertase, urease, casein protease, and arylsulphatase, which play an essential role in soil biochemical processes (Baweja et al., 2020).

Long-term exposure of pesticides to the soil results in toxic effects and brings about considerable changes in microbial populations. As inorganic content of the soil increases, microbial numbers go down, mainly due to acidification of the soil by chemical residues. The resulting low pH condition depletes sensitive and beneficial microorganisms responsible for maintaining soil structure, mineralization of organic matter, and degradation of pollutants. Legume crops, for instance, depend on soil bacteria to fix nitrogen, whereas mycorrhizal fungi aid in nutrient acquisition. Nonetheless, certain pesticides like oryzalin, trifluralin, and triclopyr have been reported to be toxic to these fungi and their spores (Aktar et al., 2009). Some pesticides, such as carbofuran (insecticide), iprodione (fungicide), and simazine (herbicide), on the other hand, are reported to have less impact on soil microflora (Prashar and Shah, 2016).

Pesticide application can also cause the suppression of some microbial communities and enhance the growth of others by destroying competition. Such a disturbance upsets critical biochemical processes in the soil such as nitrogen fixation, nitrification, and ammonification, mainly through disrupting microbial function and enzymatic activity (Yadav et al., 2017). Besides influencing microbial life, herbicides and pesticides adversely affect earthworms that are crucial for soil health. Chemicals like glyphosate and chlorpyrifos injure earthworm DNA, while neonicotinoids are lingering in the ground and play their role in population loss (Baweja et al., 2020; Tang et al., 2021). These disturbances in combination decrease fertility in soil as well as farming productivity.

Human health risks

Pesticides' endurance in the environment eventually exposes humans to tainted water, food, and air. Several pesticides have been linked to severe human health hazards. Topsin-M has been associated to liver and endocrine consequences (Moo-Muñoz et al., 2021), while bifenthrin can cause stomach ache and sore throat (Park et al., 2021). Trifluralin has been connected to throat irritation and cancer (Rani et al., 2021), whereas atrazine has been linked to tumors, breast and uterine cancer, and lymphoma (Rohr, 2021). Nausea, sweating, and headaches have been linked to fipronil (Song et al.,2021), while central nervous depression and aspiration pneumonia have been linked to emamectin benzoate (Niu et al., 2020). Pretilachlor has induced cell necrosis and gill cohesion (Shilpakar et al., 2020), while metribuzin has been linked to liver failure and organ dysfunction (Samir et al., 2020). Nausea and respiratory failure are induced by acetamiprid (Ma et al., 2019), while epigastric pain and vomiting have been induced by fenoxaprop-p-ethyl (Tandon, 2019).

Pendimethalin has been associated with headache and nausea (Ansari et al., 2018), whereas exposure to imidacloprid has been associated with vomiting, nausea, and tachycardia (Mahajan et al., 2018). S-metolachlor has been associated with diarrhea and anemia, whereas paraquat causes kidney failure and coma (Quintaneiro et al., 2018). Sulfosulfuron exposure has been associated with scarring of the lungs and tachycardia, whereas ethoxysulfuron has been associated with headache and nausea (Sharma and Singhvi, 2017). These observations point to potential health effects of pesticide exposure towards demanding stronger controls and alternatives**.** Pesticides induced health hazards include various types of cancer such as renal cell cancer and lymphocytic leukemia, as well as neurodegenerative diseases like Parkinson’s disease and Alzheimer’s disease. Pesticide exposure is also linked to cardiovascular conditions, including artery disease, and metabolic disorders like type 2 diabetes. Additionally, it can lead to reproductive disorders, birth defects, and hormonal imbalances, which may manifest as infertility or breast pain. Respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD) have also been connected to pesticide exposure (Yadav et al., 2017).

3. Pseudomonas spp. in Agroecosytems

Pseudomonas spp. are major bacterial residents of agroecosystems, performing critical roles in soil fertility and plant productivity. Their metabolic diversity, competence for the rhizosphere, and production of secondary metabolites position them as top candidates for promoting plant growth promotion, facilitating bioremediation, and disease control (Saranraj et al., 2022; Singh et al., 2022; Khoshru et al., 2025). The genus is highly adaptable to various soil types and climates and tends to make up 1–34% of the overall bacterial community in soils, particularly in areas with high resource availability and simple carbon sources (Agaras et al., 2017). The abundance and functionality of Pseudomonas communities are influenced by agricultural practices like tillage management, crop rotation, and agrochemical application (Agaras et al., 2014).

Ecologically, Pseudomonas spp. are involved in nutrient cycling processes such as nitrogen fixation, phosphate solubilization, and organic matter mineralization. In addition, they release a range of enzymes and secondary metabolites that promote plant growth and inhibit phytopathogens (Khalil et al., 2022). Their physiological and genetic flexibility facilitates their survival in diverse soil environments, including marginal or degraded soils. No-tillage and high organic matter levels are likely to enhance Pseudomonas density, particularly in the 5–10 cm soil horizon, to ensure improved soil health and sustainability (Agaras et al., 2014).

They are relatively tolerant to environmental stresses because of their metabolic adaptability. They can survive drought, nutritional stress, and chemical stress. Moreover, excessive application of herbicides and pesticides, particularly glyphosate and glufosinate, can lower their populations or alter community composition in a negative way (Zobiole et al., 2011). Interestingly, repeated exposure to certain herbicides can make Pseudomonas populations capable of degrading these compounds, like P. oryzihabitans and P.

putida (Gimsing et al., 2004; Travaglia et al., 2015). This ambivalence makes Pseudomonas an important asset in phytoremediation strategies for polluted soils.

Rhizosphere interactions between Pseudomonas spp. and plants are both specific and functionally significant. The bacteria form symbiotic interactions with crops such as soybean, maize, and wheat and enable nutrient acquisition and enhance stress tolerance (Rajkumar et al., 2017). Plant species, cultivar, and root exudate composition regulate their colonization—a process referred to as the "rhizosphere effect" (Mendes et al., 2014). Fluorescent pseudomonads are generally enriched in maize rhizospheres because of their beneficial exudate composition, and systemic signaling which can even activate beneficial Pseudomonas populations throughout root systems during pathogen attack (Dudenhöffer et al., 2016).

They are also strong biocontrol agents through the production of antibiotics (e.g., DAPG, phenazines, pyrrolnitrin), siderophores, and hydrogen cyanide, which inhibit a wide range of soil-borne diseases (Höfte, 2021). They are usually associated with suppressive soils, including those that resist take-all disease in wheat or Fusarium wilt in other crops (Kyselková and Moënne-Loccoz, 2012; Ullah et al., 2020). Also, their plant growth-promoting characteristics—phosphate solubilization and hormone production—make them effective as biofertilizers, enhancing nutrient efficiency and minimizing chemical input requirements (Ghadamgahi et al., 2022). Additionally, its ability to produce antimicrobial chemicals and biosurfactants increases its environmental tolerance and biocontrol activity (Singh and Walker, 2006; Silby et al., 2011; Zamioudis et al., 2013).

The table 3 provides a list of significant species of the genus Pseudomonas along with their significant ecological and functional characteristics.

Table 3: Ecological and Functional characteristics of Pseudomonas spp

Species Name	Description	Reference
Pseudomonas aeruginosa	Bioremediation, Antibiotic resistance	Singh et al., 2006; Silby et al., 2011; Zamioudis et al., 2013
Pseudomonas diminuta	Organophosphate degradation	Singh et al., 2006
Pseudomonas entomophila	Biocontrol agent	Silby et al., 2011
Pseudomonas fluorescens	PGPR, Biocontrol agent	Silby et al., 2011; Zamioudis et al., 2013
Pseudomonas putida	Hydrocarbon degradation	Silby et al., 2011; Zamioudis et al., 2013
Pseudomonas mendocina	Biodegradation, Bioremediation	Silby et al., 2011; Zamioudis et al., 2013
Pseudomonas pseudomallei	Biodegradation	Singh et al.,2006
Pseudomonas monteilii	Biodegradation	Singh et al.,2006

4. Response of Pseudomonas spp. to pesticide exposure

Pesticide pollution in farm soils causes immense stress to non-target microbial populations, resulting in oxidative stress, diminished diversity, and compromised ecological function (Zhou et al., 2024). Moreover, Pseudomonas spp. have shown impressive resilience and adaptive mechanisms under these conditions, and they are of great value for soil health maintenance and bioremediation processes (Song et al., 2025). One of the key reactions of Pseudomonas spp. to herbicide treatment is the induction of strong antioxidative defense mechanisms. For example, Pseudomonas sp. CMA-7.3, derived from pesticide-polluted environments, showed high tolerance to the herbicide 2,4-D by the concerted action of antioxidative enzymes like superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), and guaiacol peroxidase (GPX). This strain was able to maintain hydrogen peroxide production even under treatment with 25 times the agricultural dose of 2,4-D, displaying an effective oxidative stress response potentially controlled by quorum sensing molecules (de Oliveira et al., 2021).

In addition, research has shown that Pseudomonas spp. exhibit metabolic plasticity, allowing them to adjust various antioxidative systems according to the type of herbicide stress. Pseudomonas sp. CMA 6.9 exhibited tolerance to two herbicides, Boral® and Heat®, through different antioxidative mechanisms: glutathione-S-transferase (GST) played a pivotal role under Boral® stress, whereas catalase, APX, and GPX played a vital role under Heat® stress. This capacity to change antioxidative strategies without initial herbicide selection indicates that Pseudomonas spp. possesses generalized metabolic mechanisms for surviving chemical stress (Rovida et al., 2021).

Apart from enzymatic defense, some strains of Pseudomonas actively induce plant resistance to pesticide stress. For instance, Pseudomonas protegens DA1.2 not only enhanced the plant growth of wheat exposed to drought and herbicide stress but also regulated the inner phytohormone balance of the plant, which involved the enhancement of the indole-3-acetic acid (IAA)/ Abscisic acid (ABA) ratio and suppression of markers of oxidative stress such as malondialdehyde (Bakaeva et al., 2022). This shows that Pseudomonas can detoxify toxic substances and also induce plant systemic tolerance mechanisms. In addition, Pseudomonas sp. PGR-11 showed excellent tolerance to several fungicides (metalaxyl, carbendazim, and tebuconazole) and even under pesticide stress still continued to produce plant growth-promoting compounds like indole-3-acetic acid (IAA), siderophores, and ACC deaminase. Inoculation with this bacterium improved the growth, photosynthetic parameters, and physiological well-being of Vigna radiata plants cultivated in pesticide-polluted soils, indicating its capability for pesticide bioremediation and sustainable agriculture (Al-Enazi et al., 2022).

5. Biodegradation potential of Pseudomonas spp.

Pseudomonas spp. show high biodegradation capacity due to their metabolic plasticity and ability to withstand stress. For example, it was shown that Pseudomonas aeruginosa PAO1 effectively broke down pyrethroid insecticides like etofenprox, D-cyphenothrin, and allethrin, with as much as 94.27% of etofenprox degraded within 36 hours. The esterase enzyme that is coded by the estA gene was pivotal in this degrading process, and its deletion dramatically decreased degradation efficiency (Liu et al., 2025).

Likewise, a study found that Pseudomonas sp. WL DumpQ10, isolated from rhizosphere, efficiently biodegraded the organophosphorus insecticide Quinolphos efficiently. The research identified that 90.4% degradation was achieved in a glucose-supplemented medium, and efficiency of degradation reduced to 38.2% in the absence of glucose, highlighting the significance of co-metabolism. Maximum biodegradation was observed between 30–35°C and 6.0–8.0 pH (Pawar and Mali, 2014). Another research demonstrated that Pseudomonas aeruginosa PF1 showed strong chlorpyrifos degradation ability in rice soils, achieving up to 94% degradation through enzymatic processes involving hydrolysis and oxidation. Similarly, strains like Pseudomonas putida MAS-1 and P. aeruginosa demonstrated effective chlorpyrifos degradation and complete mineralization into nontoxic end-products such as carbon dioxide and water within 20–30 days (Gilani et al., 2016: Lakshmipathy et al., 2018).

Pseudomonas spp. obtained from contaminated environments have been found to break down and catabolize a broad array of pesticide molecules. For instance, Pseudomonas sp. strain ADP was said to degrade the s-triazine herbicides (atrazine, ametryn, and melamine) effectively using catabolic processes, exemplifying their possibility for herbicide detoxification of agricultural soils (Esquirol et al., 2020). Likewise, Pseudomonas putida KT2440 has been found to degrade several pesticides such as carbofuran, carbaryl, chlorpyrifos, cypermethrin, fenpropathrin, and methyl parathion with 100% degradation under laboratory conditions (Gong et al., 2018).

Additionally, Pseudomonas spp. can act alone or in microbial consortia to biodegrade combinations of pesticides more efficiently. A Pseudomonas spp. consortium was reported to biodegrade neonicotinoid pesticides imidacloprid and thiamethoxam with degradation efficiencies of about 70% under optimal conditions within 14 days (Bhattacherjee et al., 2020). In addition, extending beyond pesticide degradation, new evidence showed that Pseudomonas aeruginosa DSM 50071 was capable of oxidatively degrading polystyrene (PS), and the process involves the action of serine hydrolase enzymes. This discovery makes Pseudomonas spp. not only important agents in pesticide bioremediation but also potential agents for the degradation of synthetic polymers in polluted environments (Kim et al., 2020).

Research has shown that these bacteria, as they are rich in the production of extracellular enzymes such as lipases, are very important in the degradation of petroleum hydrocarbons and polycyclic aromatic hydrocarbons (PAHs), degrading them into non-toxic end products such as carbon dioxide, water, and simpler compounds (Medić and Karadžić, 2022; Alaidaroos, 2023). Experiments conducted by Shivendra Sharma et al. proved that Pseudomonas spp. from petroleum-contaminated soils were able to degrade petroleum oil, dodecane, and octadecane quite efficiently with generation times of 20, 22, and 25 hours, respectively.

Immobilization of the bacteria on supports such as perlite was seen to improve their stability and degradation efficiency. In addition, Pseudomonas sp. strain DQ8 has been proved to degrade diesel, crude oil, n-alkanes, and PAHs through terminal oxidation pathways. The potential for degradation of Pseudomonas is not limited to oil contaminants alone. Pseudomonas are also known to degrade aromatic hydrocarbons like naphthalene and pyrene. Through HPLC analysis, it was shown that Pseudomonas sp. was able to degrade naphthalene by as much as 80% in a period of one week (Sharma and Pathak, 2014). In another work, oil-contaminated soil isolates displayed effective pyrene degradation and utilized the ortho-cleavage pathway through catechol 1,2-dioxygenase activity, validating their excellent prospect for bioremediation of PAH-contaminated environments (Obayori et al., 2008).

6. Application of Pseudomonas-Mediated Biodegradation

Global food and energy demand is rapidly increasing, and leading to greater agricultural production. Agrochemicals and synthetic plant growth regulators are used in the pursuit of more production, but their environmental impacts are a concern (Warra and Prasad, 2020). In this regard, Pseudomonas spp. can be considered as an ideal eco-friendly alternative with their diverse beneficial traits. Pseudomonas spp. producing ACC deaminase can alleviate the plant stress by lowering the ethylene concentration, and can also be used as biological substitute for synthetic inhibitors (Singh et al., 2022). Pseudomonas spp. that solubilizes phosphate can reduce the use of chemical fertilizers and reduce costs of production and environmental burden (Rawat et al., 2021).

With increasing environmental pollution from industrial and municipal wastes that are rich in toxic heavy metals and petroleum hydrocarbons, Pseudomonas spp. has been proposed as potential candidates for remediation (Feruke et al.,2023). These bacteria are ubiquitous in the rhizosphere and by increasing plant stress tolerance indirectly assist in phytoremediation through degradation or transformation of contaminants (Saeed et al., 2021). The strains of Pseudomonas tested have also shown differential tolerance to metals and can degrade organic pollutants such as anthracene, naphthalene and phenanthrene (Benedek et al., 2020; Medic et al., 2022). Their success in phytoremediation is attributed to their strong root colonization ability and interaction with plants and pollutants.

Another characteristic of Pseudomonas spp. in pollutant degradation is they are biosurfactant producers. Biosurfactant is an amphiphilic compound that increases the solubility and bioavailability of hydrophobic pollutants such as hydrocarbons and pesticides, so it facilitates the degradation by microbes (Gayathiri et al., 2022). Biosurfactant possesses benefits over chemical surfactant like biodegradable, non-toxic and efficient at extreme conditions. Rhamnolipids and other biosurfactants are produced by Pseudomonas aeruginosa that enhance biodegradation of crude oil and confer resistance in plants against pathogens like damping-off in chili and tomato (Ghadamgahi et al., 2022; Mehmood et al., 2023).

Besides rhamnolipids, Pseudomonas spp. also produces lipopeptides and exopolysaccharides with a wide range of environmental applications. For instance, P. stutzeri has demonstrated potential for adsorption of heavy metals like lead, cobalt, and copper from contaminated water. Ag-nanoparticles immobilized with Pseudomonas strains have shown enhanced bioremediation of heavy metals like Pb, Cd, and Ni from municipal wastewater (Coelho et al., 2020; Palanivel et al., 2020). Pseudomonas spp. can also be a biological alternative to chemical herbicides. Excessive herbicide application poses risk to the environment and the threat of weed resistance. Certain Pseudomonas strains can reduce weeds by producing phytotoxins like IAA (Poprzen et al., 2023). The advantage of these strains is that they exhibit specificity toward weeds such as great brome without affecting the crop (e.g., durum wheat) (Dar et al., 2022). This specificity makes Pseudomonas a promising component of integrated weed management.

Furthermore, some genes from the Pseudomonas strains, such as ACC-deaminase and citrate synthase, have been introduced into tomato and tobacco to decrease stress-induced ethylene and increase aluminium tolerance, respectively (Fuente et al., 1997; Pandey and Gupta, 2020; Chauhan et al., 2021). Using the Pseudomonas stutzeri-derived nitrous oxide reductase expressed in plants, nitrous oxide, a major greenhouse gas, could be converted to inert nitrogen, thus contributing to climate change mitigation (Wan et al., 2012; Kumari et al., 2015). Generally, Pseudomonas spp. has numerous applications in environmental biotechnology, including direct biodegradation, augmented phytoremediation, biosurfactant production, and genetic engineering approaches.

Conclusion

Pseudomonas spp. are key agents in alleviating pesticide stress in agricultural ecosystems due to their excellent biodegradation ability and resistance mechanisms. They help detoxify pesticide-contaminated soils, restore microbial community diversity, and promote plant growth under pesticide stress. However, the excessive use of pesticides may affect soil microbial community, leading to reduced soil fertility and ecological imbalance. Therefore, it is important to know the interactions among pesticides and microbial populations, particularly Pseudomonas, in order to create sustainable bioremediation processes. Such understanding is very critical in fostering environmental sustainability, sustaining soil fertility, and conserving microbial ecology and provides great avenues for the prevention of chemical pollution and facilitates ecological agriculture.

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