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Review article

Unlocking the interaction of organophosphorus pesticide residues with ecosystem: Toxicity and bioremediation

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A R T I C L E I N F O

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A B S T R A C T

Organophosphorus adulteration in the environment creates terrestrial and aquatic pollution. It causes acute and subacute toxicity in plants, humans, insects, and animals. Due to the excessive use of organophosphorus pesticides, there is a need to develop environmentally friendly, economical, and bio-based strategies. The microbiomes, that exist in the soil, can reduce the devastating effects of organophosphates. The use of cell-free enzymes and yeast is also an advanced method for the degradation of organophosphates. Plant-friendly bacterial strains, that exist in the soil, can help to degrade these contaminants by oxidation-reduction reactions, enzymatic breakdown, and adsorption. The bacterial strains mostly from the genus *Bacillus*, *Pseudomonas*, *Acinetobacter*, *Agrobacterium*, and *Rhizobium* have the ability to hydrolyze the bonds of organophosphate compounds like profenofos, quinalphos, malathion, methyl-parathion, and chlorpyrifos. The native bacterial strains also promote the growth abilities of plants and help in detoxification of organophosphate residues. This bioremediation technique is easy to use, relatively cost-effective, very efficient, and ensures the safety of the environment. This review covers the literature gap by describing the major effects of organophosphates on the ecosystem and their bioremediation by using native bacterial strains.

1. Introduction

Pesticides are used as insecticides, herbicides, fungicides, and in various other forms, to be implied for the cultivation of crops. In current agricultural practices, pesticides have become important features for efficient pest control and improved production of crops assisted by increased growth of global production (Gulnaz et al., 2023).

The improper use of pesticides results in environmental pollution and disturbs the biotic and abiotic components of the ecosystems (Ajiboye et al., 2022). Water and soil contamination also coincides with the loss of soil flora or fauna (Govarthanan et al., 2020). The excessive use of pesticides not only deteriorates the quality of soil but also reaches the groundwater and the aquatic ecosystem, so it is concluded that the effects of the pesticide are frequently uncertain thus the decontamination of the areas polluted by the pesticide is a very intricate process (Yao et al., 2023).

The most extensively and worldwide used group of pesticides is organophosphates (OP) including profenofos, quinalphos, malathion, methyl-parathion, and chlorpyrifos. Pesticides account for 45 % of the global market. (Fig. 1). Organophosphates are the esters of phosphoric acids contqining aliphatic, phenyl derivatives as an element of their complex chemical structures (Mali et al., 2023). The remediation of pesticides depends upon the pH, application rate, temperature, and moisture. The environmental conditions like low temperature, less ultraviolet light, excessive soil organic matter, and low pH cause the chemical to become constant and persistent (Bose et al., 2021; Shahid

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and Khan, 2022). Some plants absorb the organophosphate pesticides and have the potential to transport it from roots to leaves. Organophosphates are mostly stored in aerial parts of plants like leaves and stems (Olisah et al., 2021).

The incineration and chemical breakdown methods have been widely used to degrade the organophosphate compounds, but they are not environment friendly, so microbial remediation has gained more importance as the microorganisms are abundant in nature and possess a tremendous ability to eliminate harmful chemicals. Bioremediation, using microorganisms and their enzymes to break toxic substances into simpler nontoxic substances, makes the environments free of pollutants (Varghese et al., 2022). It is the most effective method to eradicate the pollutants as the microbes can do catalytic reactions. They degrade the pesticides by various metabolic processes (Dash et al., 2022).

Bioremediation is an innovative mechanism that has the ability to eradicate pesticide contaminants. The activity of bioremediation typically occurs in the soil where the pesticides are degraded by bacteria, fungi, and other microorganisms. All these microorganisms use pesticides as a source of carbon and energy and transform them into environment-friendly substances (Bokade et al., 2023; Jia et al., 2023).

2. Effects of organophosphorus pesticides on

2.1. Plants

Organophosphorus pesticides can cause adverse effects on plant growth and development by affecting the process of photosynthesis which is important for the production of food. It affects the synthesis of amino acids and fatty acids, causes oxidative stress in the cells, and degrades chlorophyll content (Sidhu et al., 2019). Organophosphorus pesticides can affect plants by reducing the carbon exchange and net stomatal conductance. They decrease the limit to absorb the CO_2 capacity of assimilation (Ding et al., 2011; Zobiole et al., 2011). They augment the production of ROS that harms the plant cell's survival and growth (Fig. 2) (Gomes et al., 2014). The continuous and excessive use of organophosphorus pesticides decreases cell elongation and growth which are important for plant growth and development (Mishra and Sabat, 2015). The growth and development of plant growth-promoting bacteria (PGPR) get affected when different pesticides or chemicals are used on the leaves or weeds of crops that can directly seep into the soil. Consequently, microbial communities can deteriorate (Kumar et al., 2019).

2.2. Humans

Human exposure to organophosphorus pesticides can cause neurodevelopmental disorders especially children are affected due to the organophosphate pesticides, which can cause serious nervous disorders and their ability to communicate (Sapbamrer and Hongsibsong, 2019).

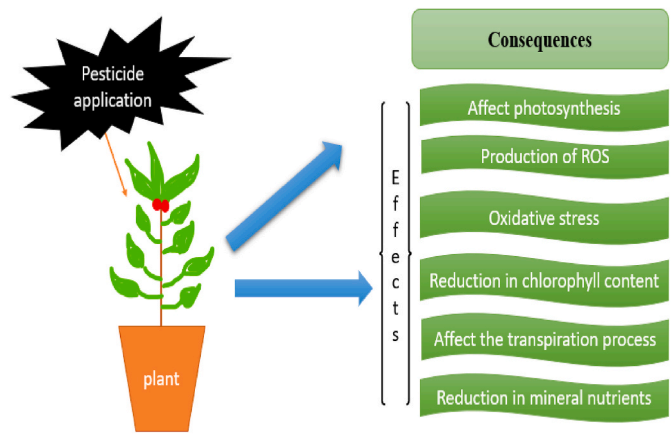

Fig. 2. Effects of organophosphorus pesticide on plants.

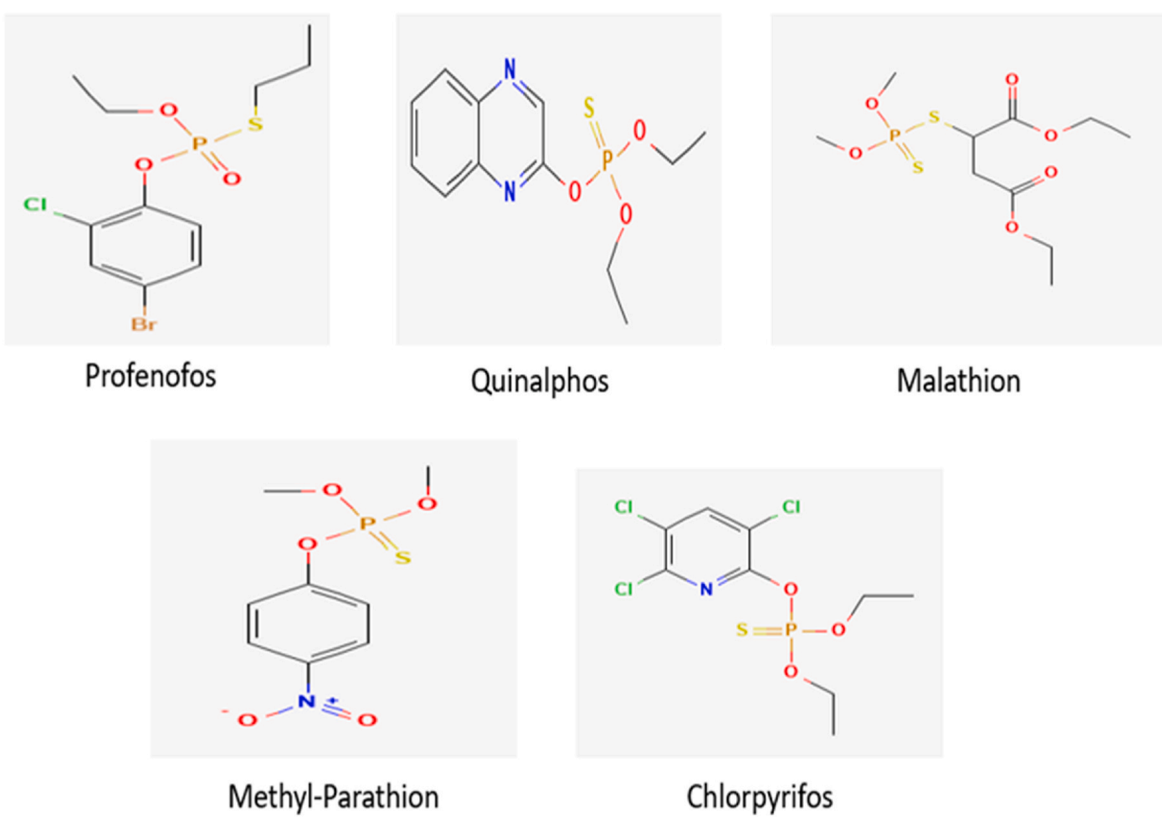

Fig. 1. Molecular structure of some organophosphorus compounds.

The harmful effect of organophosphate pesticides on the human central nervous system appears because of the blockage of an important enzyme called acetylcholine (Slotkin et al., 2019). The enzyme acetylcholinesterase acts as a neurotransmitter in nerve endings and regulation depends upon the amount of acetylcholine (Akter et al., 2020; Paul et al., 2018). Organophosphate pesticides block the action of the acetylcholinesterase enzyme by inhibiting acetylcholine that cause accumulation of ACh at the synaptic cleft which results in over-stimulation of muscarinic ACh and nicotinic receptors and impeded neurotransmission. The symptoms of poisoning include sweating, agitation, hypersalivation and muscle weakness (Ohbe et al., 2018).

Organophosphate pesticides are hazardous to human health, symptoms include muscle cramps, seizures, nausea, dizziness, headache, coma, and excessive concentrations can cause even death (Fig. 3) (Sulaiman et al., 2019). To overcome these adverse effects, it is important to use accurate amounts of organophosphate pesticides. The use of controlled amounts of pesticides can ensure the safety of lives (Ghorbani et al., 2021).

2.3. Terrestrial and aquatic life

The non-target plants and animal species can be affected by the uncontrolled use of organophosphorus pesticides which are investigated in different aquatic and terrestrial ecosystems (Blann et al., 2009). The adverse effects of the malathion in freshwater flagellate *Euglena gracilis* were investigated. It showed the toxic effects on the movement, population density, shape of the cell, photosynthesis ability, and light-harvesting pigments. The two other aquatic organisms, Decapod shrimp (*Caridina nilotica*) and Calanoid copepod (*Phyllodiaptomus annae*) were analyzed for toxicity of glyphosate (Deepananda et al., 2011). The higher concentration of pesticides can lead to reduced swimming ability, inhibit growth, and slow down the metamorphosis in larvae of toads (*Duttaphrynus melanostictu*) (Wijesinghe et al., 2011). A notable reduction in protein concentrations was recorded in different parts like the liver, plasma, kidneys, muscles, and gills. (Soyingbe et al., 2012).

The aquatic system contaminated with chlorpyrifos impart hazardous effects on the organisms. Under chlorpyrifos usage, a noticeable rate of mortality of frogs was observed which resulted in a decline in the population of amphibians (Srivastav et al., 2017). It has been studied that adverse effects of malathion in Nile tilapias (*Oreochromis niloticus*) cause significant changes in the gills, liver, kidney, and brain. Some of the abnormalities in gills are observed like lamellar fusion, hyperplasia, and epithelial lifting. The functioning of the liver was also disrupted in aquatic animals (Subburaj et al., 2018). Reduction in the number of sperm cells, nutritive cells, and interstitial cells was also examined by the use of malathion. (Sinha et al., 2018).

3. Bioremediation through plant growth-promoting rhizobacteria

There are different methods of bioremediation for the degradation of pesticide residues, while the use of plant growth-promoting rhizobacteria has been considered one of the most efficient, cost-effective, and eco-friendly methods. Native microbial communities have the ability to remove toxic contaminants naturally from the environment. They decontaminate the organophosphate residues, convert the toxins to harmless substances, and make them safer for the environment. However, the method of natural attenuation is sometimes hindered due to the inadequacy of microbial communities and their lack of access to polluted areas (Armenova et al., 2023; de Lipthay et al., 2003).

Microorganisms play a role in the degradation of pesticides that can be classified into two different categories. The category of microorganisms that directly participate in the pesticide's structure primarily involves pesticide degradation through enzymatic reactions. This category is often referred to as pesticide microbial degradation. The other category involves microorganisms that indirectly affect pesticides by modifying the chemical and physical environment through their microbial activity (Ye et al., 2018).

Some of the bacterial species degrade the pollutants present in the pesticides. They break the bonds and convert toxic forms of pesticide residues into non-toxic forms. The use of *Micrococcus* sp., *Xanthomonas* sp., *Klebsiella* sp., *Sphingomonas*, *Bacillus* sp., *Stenotrophomonas*, *Pseudomonas* sp., *Bacillus* sp., and *Brevundimonas* sp. decreases the content of pesticides residues in the soils (Bhende et al., 2022).

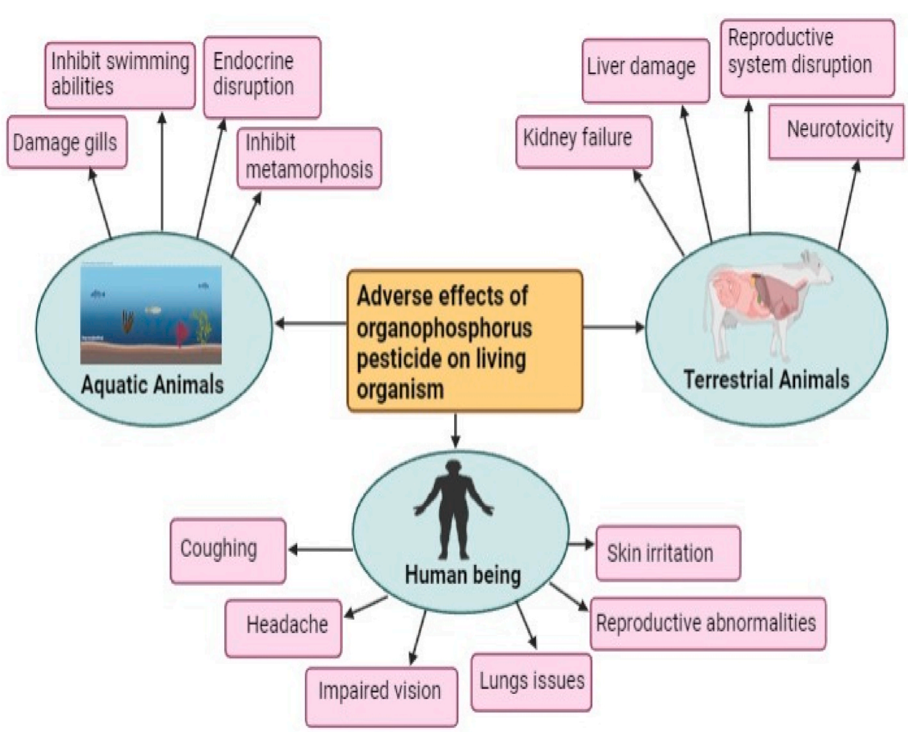

Fig. 3. Effects of organophosphates on humans, terrestrial and aquatic life.

The decomposition mechanism of the synthetic substances is oxidation, photolysis, and hydrolysis, with bacteria playing a vital role in conjunction with chemical and physical processes (Romano et al., 2015). Microbial remediation refers to the natural transformation of toxic chemical substances into harmless products. The process of pesticide conversion is only determined by microbial enzymes (Bhatt et al., 2021; Zhang et al., 2021). Microorganisms generate various kinds of esterase which mitigate the toxicity of ester-possessing pesticides. The esterase enzyme is involved in the hydrolyses of ester bonds of pesticides into acid and alcohol. They contain serine residues and by nucleophilic attack on the substrate, they catalyze the degradation of pesticides. The hydrolysis of ester bonds also increases the water solubility of pesticides stored in fatty tissues (Bhatt et al., 2020; Chen and Zhan, 2019).

Bioremediation of toxic contaminants is more effective by the utilization of enzymes in comparison to other chemical methodologies, and these enzymes are synthesized by potentially degrading microorganisms. The extracellular and intracellular enzymes are engaged in catabolic reactions throughout the process of biodegradation. Moreover, they exhibit wide-ranging substrate specificity, featuring adaptable active sites and robust affinities for diverse substrates. Consequently, the mineralization of organophosphorus is achieved through the hydrolysis of phosphoester (Bhatt et al., 2021) (Fig. 4). Organophosphate hydrolase, phosphotriesterases, and methyl parathion hydrolase are the main detoxifying enzymes for organophosphates The main decontaminating enzymes are the phosphotriesterases, methyl parathion hydrolase, and organophosphate hydrolase (Kumar et al., 2018).

3.1. Organophosphorus pesticide degradation

Different strains of plant growth-promoting rhizobacteria are tolerant/resistant to organophosphorus residues and they degrade them to less toxic compounds (Table 1). The inoculation of these strains causes a reduction in the level and toxicity of pesticides (Table 2) (Asim et al., 2021). The details are as below.

3.1.1. Profenofos

A promising method like bacterial degradation can be used to clean up the Profenofos residues where the microbes can be applied to eliminate the pollutants from the environment. This technique is environmentally friendly, productive, inexpensive, and adaptable. The profenofos-degrading bacteria that were isolated from the soil include *Bacillus subtilis, Pseudomonas putida DB17, Pseudomonas plecoglossicida PF1, Staphylococcus aureus, Pseudomonas aeruginosa* strains. These bacterial strains have the ability to remove the Profenofos in a typical laboratory atmosphere at normal pH levels, at room temperature, and under aerobic conditions. These bacteria could be helpful for the removal of contaminants from the soil and surface water (Subsanguan et al., 2020).

Some of the bacterial stains have the potential to degrade the Profenofos pesticides like *Pseudomonas plecoglossicida, Pseudomonas aeruginosa, Burkholderia gladioli, Bacillus subtilis,* and *Pseudomonas putida* (Dash and Osborne, 2020). There are reports for *Burkholderia gladiol* which clearly state that the esterase gene can be important for the breakdown of the ester bond found in organophosphorus pesticides and helps to eliminate Profenofos from the environment (Malghani et al., 2009).

The usage of bacteria is a good technique to eradicate pollutants from the environment and these bacteria can be managed under different environmental conditions (Akhtar et al., 2021). One of the genera of bacteria *Acinetobacter* has been used for the degradation of pesticides. Studies have shown that the genus *Acinetobacter* has potential and is efficacious for the removal of pesticides. Hence, an effective bacterial strain *Acinetobacter* sp.33F was used for the degradation of profenofos (Kumar et al., 2021). Studies have also shown that a bacterial strain psychrotolerant *Rahnella* sp. isolated from the western Himalayas has the potential of Profenofos degradation as well as abatement of pollution (Verma et al., 2021).

3.1.2. Quinalphos

The study of quinalphos biodegradation has revealed that the various bacteria belonging to the genera *Ochrobactrum*, *Pseudomonas*, and *Bacillus* are involved in the breakdown of quinalphos pesticide (Talwar and Ninnekar, 2015). Various bacterial species found in different samples have the degradation ability of quinalphos that are *Pseudomonas* spp., *Serratia* sp. *Pseudomonas aeruginosa* Q10, *Bacillus*, *Ochrobactrum* sp., and

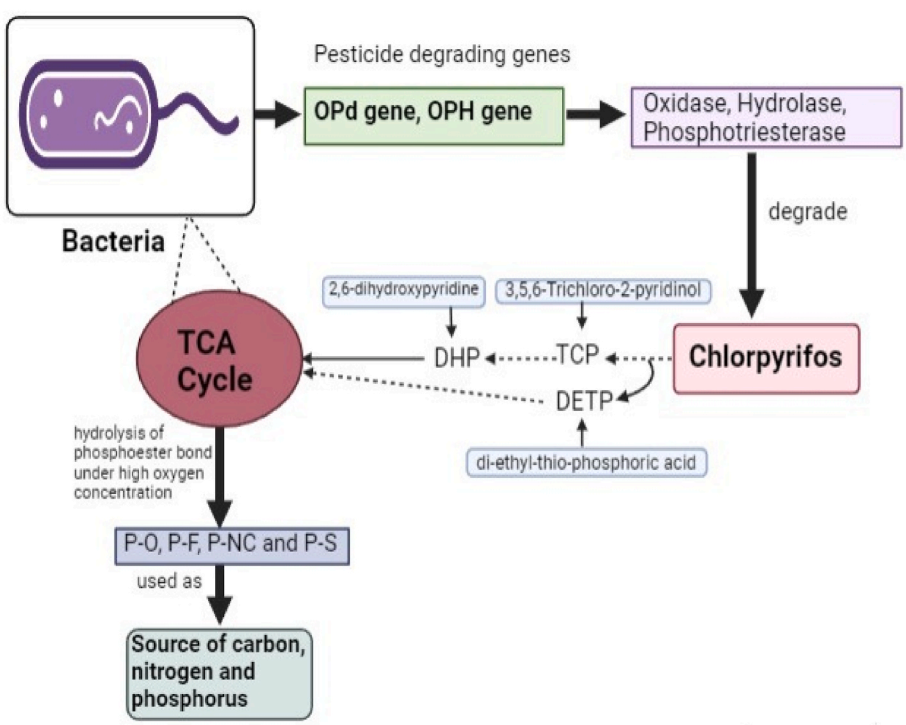

Fig. 4. Degradation of organophosphate by plant growth promoting rhizobacteria.

Table 1
Microbial degradation of Organophosphate residues.

Microorganism	Organophosphate compounds	Functions	Reference
Bacillus cereus, Enterobacter cloacae K7, Chryseobacterium sp. Y16C, *Ochrobactrum haematophilum* P6BS-III and *Rhizobium* sp. P44RR-XXIV	Glyphosate	Responsible for catabolism of organophosphorus pesticides and use it as phosphorus sole	Zhang et al. (2022)
Xanthomonas campestris pv. Translucens	Dimethoate	Dimethoate used as source of carbon for growth	Derbalah et al. (2021)
Xanthomonas, Pseudomonas, Rhizobium, Bacillus, Cyanobacterium	Chlorpyrifos	Reduce and deleterious effects of organophosphate pesticide residues and promote plant growth	Yadav et al. (2020)
Stenotrophomonas, Serratia, Burkholderia, Rhodanobacter, Ralstonia	Diazinon	Degrade the residual level and aid in the growth of the plant and use as a carbon sole	Nasrollahi et al. (2020)
Pseudomonas aeruginosa (KIBGE-AB9)	Malathion	Decontaminate the environment and abundantly use it as source of carbon	Khan et al. (2023)
Burkholderia cenocepacia CEIB S5-2	Parathion and Methyl-Parathion	Generates the biodegradation and transcriptional changes	Ortiz-Hernandez et al. (2021)
Lysinibacillus fusiformis ADI-01, Pseudomonas pseudoalcaligenes ADI-03, Pseudomonas pseudoalcaligenes ADI-06, Bacillus cereus ADI-10, Vibrio metschinkouii, Serratia ficaria, Serratia spp., and *Yersinia enterocolitica*	Profenofos	Follow the biodegradation mechanism and utilize the residues of the pesticide as a carbon source in the soil	Putra et al. (2021)
Roseomonas sp. Strain, *Proteus vulgaris*, Vibrio sp., Serratia sp., Acinetobacter sp., *Nocardia mediterranei* and Halomonas spp.	Dichlorvos	Bioremediate the dichlorvos contaminated soil and also protect the plant from harmful Insects	Aribodor et al. (2021)
Pseudomonas aeruginosa PM36 and *Bacillus* sp. PM37	Profenofos and Chlorpyrifos	Enhance the growth and development of plant and soil fertility	Paker et al. (2023)
Klebsiella sp. HSTU-F2D4R	Diazinon	Molecular docking and bioremediation potential	Haque et al. (2023)
Priestia megaterium NRRU-BW3, Bacillus siamensis NRRU-BW9, and *Bacillus amyloliquefaciens NRRU-TV11*	Chlorpyrifos	Production of IAA and EPS and degradation of the chlorpyrifos and enhance the growth of plant	Saengsanga and Phakratok (2023)
Bacillus altitudinis	Profenofos	Degrade the profenofos and use it as carbon source and energy	Mahajan et al. (2023)
Serratia liquefaciens	Chlorpyrifos	Cleaning up the chlorpyrifos contaminated soil	Bibi et al. (2023)
Lactobacillus plantarum, Lactobacillus rhamnosus, and *Bacillus shackletonii*	Glyphosate, chlorpyrifos, cypermethrin	Elimination of harmful effects of these pesticides and make it environment friendly	Malla et al. (2023)
Burkholderia sp. A11	Acephate	Detoxify the hazardous effects of insecticide and make degradation of acephate in soil efficient	Wu et al. (2023)
Cupriavidus nantongensis X1^{T}	Profenofos Chlorpyrifos Methyl parathion Parathion Triazophos Phoxim Fenitrothion Isocarbophos	Bioremediate the effects of pesticides and have genes which eradicate the aromatic pollutants	Zhang et al. (2023)
Acinetobacter, Bacillus, Proteus, Pseudomonas, Staphylococcus and *Streptomyces*	Chlorpyrifos	Restoring the soil fertility and better production of crop	Pailan (2023)
Acromobacter marplatensis and *Pseudomonas azotoformans*	Chlorpyrifos	Residual degradation and residue-free production of crop	Ahmed & Bora. (2023)
Enterobacter aerogenes CP2 and *Streptococcus pyogenes CP11*	Chlorpyrifos	Potential to use the organophosphate pesticide as a source of carbon and energy	Lourthuraj et al. (2022)
Bacillus sp. FYM31	Malathion	Used as source of carbon	Madbolly et al. (2022)
Pseudomonas esterophilus and *Rhodococcus ruber*	Parathion, methyl parathion, malathion, chlorpyrifos, diazinon, dimethoate, paraoxon, demeton-S- methyl	Toxic substrate degraded	Efremenko et al. (2022)
Pantoea, Acinetobacter, Kosakonia, Morganella, and *Enterobacter*	Chlorpyrifos and diazinon	Used as carbon sole and enhance the plant growth	Das et al. (2022)

Bacillus thuringiensis (Kumar et al., 2022).

Bacillus Fcl1 is resistant against quinalphos as well as has plant growth-promoting characteristics. It has been used to secure livestock and crops from diseases and it belongs to organophosphorus pesticides. It also shows the biological detoxification of quinalphos pesticide. Various genera of bacteria like *Flavobacterium*, *Xanthobacter*, *Pseudomonas*, and *Bacillus* and also shown the effectiveness of microbial communities for the management of pesticide residues (Juby et al., 2021).

The isolation of microorganisms from natural resources like soil and water is very efficient in degrading the quinalphos. The bacteria *Ochrobactrum* sp. strain HZM have been isolated from pesticide-contaminated soil and can degrade pesticide. This bacterium has deteriorated the quinalphos by hydrolysis. The strains of *Bacillus thuringiensis* have the potential to degrade the quinalphos and also optimize its degradation (Gangireddygari et al., 2020).

3.1.3. Malathion

Using microbial bioremediation for malathion pesticide is one the encouraging methods that is a cost-effective, productive, efficient, and positive approach that helps in the degradation of the toxic chemical into less harmful substances as compared to other methods. A bacterium known as *Bacillus* sp. AGM5 was isolated from the agricultural field

Table 2
Reduction in the level of pesticides by using beneficial microbes.

Species	Source	Pesticides	Rate of reduction	References
Bacillus cereus NRC1-PP, *Pseudomonas alcaligenes* NRC2-Gly, *Pseudomonas stutzeri* NRC3-8 PS, *Bacillus licheniformis* NRC4-1BL	Water canal	Glyphosate	28.96 % reduction in glyphosate content in 10 days	Abosereh et al. (2022)
and Immobilized *Bacillus* H27 strain	Pesticide-polluted agriculture soil	Chlorpyrifos	97.4 % removal in chlorpyrifos content in 7 h	Liu et al. (2023)
Acinetobacter. baumannii and *Acidothiobacillus. ferroxidans*	Industrial effluents and contaminated soil	malathion	53 % and 54 % reduction in malathion content in 10 days	Asim et al. (2021)
Pseudomonas fluorescens, Rhizobium leguminosarum, and *Bacillus megaterium*	Microbiology lab	Chlorpyrifos	58.90 %, 56.72 %, and 50.69 % reduction in chlorpyrifos after 14 days	Shoman et al. (2022)
Bacillus cereus AKAD 3–1	Soyabean rhizosphere	Chlorpyrifos, glyphosate	94.52 % and 83.58 % removal in chlorpyrifos and glyphosate content within 5 days	Malla et al. (2023)
Serratia and *Enterobacter cloacae*	Pesticide contaminated soil	Diazinon	98.25 % and 88.05 % reduction in diazinon content in 10 days	Mansouri et al. (2023)
Pseudomonas kilonensis MB490	Agriculture field	Dimethoate	81.5 % decrease within 9 days	Yasmin et al. (2022)
Lactiplantibacillus. plantarum 20,261	Purchased from China center of industrial culture collection	Dimethoate, trichlorfon, chlorpyrifos and parathion methyl	60.82 %, 33.04 %, 37.76 % and 49.50 % removal of dimethoate, trichlorfon, chlorpyrifos, and parathion methyl content in 16 h	Yuan et al. (2021)
Sphingomonas sp.	Pesticide contaminated soil	Chlorpyrifos	75.4 % reduction in chlorpyrifos after 21 days	Santillan et al. (2020)

which was the pesticide-contaminated field for the degradation of malathion pesticide. The bacterium was grown in the presence of various malathion concentrations under specific conditions and found efficient for the degradation of malathion (Dar and Kaushik, 2022).

Microorganisms have the ability to degrade environmental contaminants. The malathion-degrading bacteria include *Pseudomonas aureofaciens, Lysinibacillus, Pseudomonas putida, Micrococcuslylae, Acetobacter liquefaciens, Bacillus cereus, Brevibacillus,* and *Acinetobacter baumannii* they have potential to remediate the pesticide contaminated areas (Ma et al., 2022). The bacterium *Escherichia coli* IES -02 contains carboxylesterase enzymes for the deterioration of malathion pesticide residues (Sirajuddin et al., 2020). The bacterium *Ochrobactrum pituitosum* is also effective for biodegradation (Verma et al., 2021).

3.1.4. Chlorpyrifos

Different species of bacteria have been tested for chlorpyrifos degradation. It was observed that *Bacillus* sp., *Pseudomonas* sp., and two *Agrobacterium* sp., four *Pseudomonas* sp. were fastest at chlorpyrifos breaking followed by *Bacillus* sp., and *Agrobacterium* sp. The bacteria *Pseudomonas aeruginosa*, IRLM.1 were detected to degrade chlorpyrifos by using it as an energy source, phosphorus, and carbon sole and the enzymes which degrade the chlorpyrifos are cytoplasmic in nature (Elzakey et al., 2023; Dar et al., 2019).

The bacterium *Pseudomonas nitroreducens* AR-3 isolated from farmland is chlorpyrifos degrading and can remediate up to 97 % of chlorpyrifos. Another bacterium called *Stenotrophomonas* sp. *YC-1* could completely detoxify the toxic effects of chlorpyrifos. Moreover*, Rhizobium* sp. 4H1-M1, *Xanthomonas* sp. 4R3-M1 and *Pseudomonas* sp. 4H1-M3 has a phenomenal ability to degrade chlorpyrifos up to 100 % to carbon and water (Huang et al., 2021).

3.1.5. Methyl-parathion

There are many reports that microorganisms can break down the methyl-parathion through the process of hydrolysis (Fernandez-Lopez et al., 2017). *Sphingobium fuliginis* has the efficiency to degrade the methyl-parathion. The detoxification of an organophosphorus pesticides-polluted environment is carried out by *Azohydromonas australica* and this step has gained importance for biological degradation (Zhao et al., 2021). Several other studies have also shown the detoxification of methyl-parathion by bacterial species like *Pseudomonas* sp., *Alcaligenes* sp., and *Bacillus* sp. (Geed et al., 2019).

4. Bioremediation through biological catalysts

The use of enzymes for direct detoxification of organophosphates in the environment is one of the advanced methods. Researchers use recombinant cell-free synthetic biology to decontaminate the toxins. They are fast in action, non-flammable, environment-friendly non-corrosive, and easy to use. The enzyme-like Diisopropylfluorophosphatase (DFPase) obtained from Squid breaks the organophosphate bond i.e. diisopropylfluorophosphate. The calcium-dependent enzymes like paraoxonase synthesized in the human liver hydrolyze aryl esters and organophosphate. Phosphotriesterase is a zinc-dependent enzyme that can hydrolyze parathione while organophosphate hydrolyze was obtained from *Agrobacterium* can hydrolyze a wide range of organophosphates. The application of these enzymes in the environment produced results and efforts should be made for the identification, improved synthesis, and application of enzymes to recover the natural environment (Thakur et al., 2019).

5. Bioremediation through yeast

Yeast can hydrolyze the poorly hydrolyzed class of organophosphates like malathion and demeton-S. the breakage of the P–S bond by bacteria is 1000-fold slower as compared to the hydrolysis of the P–O bond. Organophosphates may enter the yeast cells by passive diffusion which is further linked with the size, structure, and charge of the particles. Recombinant yeast cells having S308L-OPH break the P–S bond in organophosphates and detoxify them (Makkar et al., 2013).

6. Conclusion

The review highlighted the issues of organophosphorus pesticide which has been used to control the pest attack but at the same time, its excessive application damages the growth and development of the flora and fauna. It implies havoc effects on plants, animals, aquatic life, and on the environment. The use of plant growth-promoting bacteria is a productive method to overcome the toxicity of organophosphorus pesticides. Plant growth-promoting bacteria have the potential to detoxify these contaminants. Different forms of organophosphates are degraded by bacterial strains and it's a better technique than physical and chemical methods. Indigenous bacterial strains like *Bacillus*, *Pseudomonas*, *Xanthobacterium,* and *Flavobacterium* can degrade dominants pesticides like chlorpyrifos, profenofos, quinalphos, and malathion. The pesticide-degrading enzymes can remediate the organophosphorus pesticide residues by utilizing various mechanisms like hydrolysis, and enzymatic mineralization. They perform oxidation-reduction reactions and also use organophosphate residues as a source of energy. Yeast, having active genes for organophosphate bond hydrolysis, is also an eco-friendly technique for bioremediation that impedes the process of detoxification of organophosphates. This technique is effective and makes the environment safe.

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Sadaf Tanveer: Writing – original draft. **Noshin Ilyas:** Conceptualization. **Nosheen Akhtar:** Data curation, Writing – review & editing. **Nazish Akhtar:** Investigation. **Nageen Bostan:** Data curation. **Zuhair Hasnain:** Methodology. **Abdullah Niaz:** Resources. **Gokhan Zengin:** Software. **Abdul Gafur:** Visualization. **Betty Natalie Fitriatin:** Writing – review & editing.

Declaration of competing interest

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Data availability

Data will be made available on request.

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