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Phosphate-solubilizing microorganisms: a key regulator in the ecological effects of pesticides and soil phosphorus cycling

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Abstract
The widespread application of pesticides is critical for crop productivity, but their impacts on key soil functional microorganisms are often underestimated. This review elucidates how pesticides interfere with soil phosphorus cycling by altering phosphate-solubilizing microorganisms (PSMs), which are essential drivers of phosphorus bioavailability. It summarizes pesticide effects on soil microbial communities and the ecological environment, reviews PSM classification, phosphorus-solubilization mechanisms and functional roles in agricultural ecosystems, and analyzes pesticide-PSM interactions focusing on inhibition and microbial adaptive responses. For the first time, micro-scale interactions are explicitly linked to macro-scale soil phosphorus cycling. Evidence shows pesticide-PSM interactions significantly affect soil phosphorus fertility by altering phosphorus transformation efficiency and availability. This review provides new insights into mechanisms of pesticide-disturbed soil nutrient cycling and a scientific basis for green agricultural technologies to reduce pesticide and fertilizer inputs, supporting environmentally sustainable intensive agricultural systems.

Keywords – Ecological risk assessment, Pesticide, Phosphorus-solubilizing bacteria, PSMs, Sustainable agricultural development

Introduction
Global food security faces unprecedented challenges, making agricultural sustainability a paramount concern for humanity's future. The central challenge lies in meeting growing food demand within the constraints of finite arable land and resources under continuous population pressure (Abiria et al. 2023). Within this complex system, the widespread use of pesticides and the efficient nutrient uptake (especially phosphorus) by crops have a significant impact on sustainable agricultural development. While pesticides are indispensable for safeguarding global crop yields, their overuse incurs "hidden costs", such as environmental pollution, biodiversity loss, and threats to food safety (Pandiselvam et al. 2020, Bose et al. 2021, Hui et al. 2021). Conversely, nutrient supply is the lifeline of crop growth. Phosphorus, a non-renewable element, is the second most significant growth-limiting factor after nitrogen (Azziz et al. 2012, Kumar et al. 2018). Phosphorus directly regulates plant

development, and its deficiency leads to stunted growth and substantial yield loss (Rawat et al. 2021). A major bottleneck is that most soil phosphorus is locked in insoluble forms, unavailable to plants (Kruse et al. 2015). Applied phosphate fertilizers rapidly react with soil components, forming insoluble precipitates and drastically reducing their bioavailability (Zhu et al. 2018).

This background underscores the promise of phosphate-solubilizing microorganisms (PSMs). These microbes unlock insoluble soil phosphorus, converting it into forms accessible to plants (Abd-Alla 1994, Chen 2017, Yu et al. 2020). They enhance soil fertility, reduce fertilizer dependency, and improve crop resilience. The PSMs employ distinct biochemical pathways for organic phosphorus mineralization (e.g., via phosphatases) and inorganic phosphorus dissolution (e.g., via organic acids) (Patel et al. 2008, Sun et al. 2016, Bi et al. 2020, Yu et al. 2020). By activating fixed phosphorus, PSMs boost crop yields while mitigating environmental risks (Abd-Alla 1994, Chen 2017). Their ecological impact, however, may extend beyond phosphorus cycling, potentially influencing the availability of other nutrients and interacting with agrochemicals, complex interactions vital for sustainable soil management.

Indeed, the maintenance of soil health and fertility relies largely on the synergistic functions of beneficial soil microorganisms (Thepbandit & Athinuwat 2024, Qiu et al. 2025), among which PSMs are included. These microorganisms constitute the core linkage connecting soils, plants and even the effects of pesticides: they act as both responders to the environmental behavior of pesticides and drivers of soil nutrient cycling (Qiu et al. 2025). The soil microbiome, including PSMs, forms a critical nexus between soil, plants, and pesticides, acting as both a “responder” to chemical stressors and a “driver” of nutrient cycles. Pesticides inevitably disturb this intricate network (Ranjard & Richaume 2001), yet research has predominantly focused on broad community-level effects, often overlooking targeted impacts on key functional groups, such as PSMs. The interaction between pesticides as “environmental stressors” and PSMs as “functional executors” is pivotal: pesticides can inhibit microbial activity, while some microbes can degrade pesticides (Soil Microbiology Research Association, 1983). Understanding this interplay is crucial for assessing ecosystem health.

Current research on the intricate interactions between pesticides and PSMs remains fragmented and insufficient, lacking systematic synthesis. Therefore, an in-depth exploration of this interplay holds significant theoretical and practical value for comprehensively assessing the ecological risks of pesticides, guiding their rational application, and developing green agricultural technologies based on PSMs. Building on prior research, this paper will first systematically review known impacts of pesticides on soil microbial communities and their ecological environments, providing context for subsequent discussion. It will then elaborate on the classification of PSMs, their PSMs, and their roles in agricultural ecosystems. Finally, the focus will shift to a detailed examination of the interactions between pesticides and PSMs, covering the toxic effects of pesticides on these microbes, microbial degradation and transformation of pesticides, and the ultimate impact of such interactions on soil phosphorus cycling. By constructing a conceptual bridge linking pesticide impact and soil phosphorus fertility via PSMs, this work provides a novel perspective for reconciling plant protection with nutrient efficiency.

Focus on the Ecological Effects of Pesticides

The World Health Organization (WHO) defines pesticides as substances or mixtures containing any chemical or biological agent intended to repel, eliminate, or control any harmful organism or to regulate plant growth (Food and Agriculture Organization of the United Nations [FAO] & World Health Organization [WHO], 2025). Based on their targets, pesticides are primarily categorized into insecticides, fungicides, molluscicides, nematicides, herbicides, and plant growth regulators, among others (Tan 2016). Over the past five decades, the rise of intensive agriculture has driven a continuous increase in reliance on pesticides for pest and disease control (Belal et al. 2020). The global agricultural pesticide market was valued at $79.06 billion in 2024 and is projected to reach $ 83.80 billion between 2025 and 2033, with a compound annual growth rate of 6.0% during the forecast period (2025, https://www.globalgrowthinsights.com/zh/market-reports/pesticides-market-116195.). Pesticides have thus become a global necessity for enhancing crop yields and a cornerstone of modern agriculture (Savary et al. 2019, Walder et al. 2022, Guinet et al. 2023).

However, long-term use has revealed that most pests develop resistance to specific chemicals, leading to continuously escalating application rates (Bose et al. 2021). Furthermore, United Nations reports indicate that less than 1% of applied pesticides reach their intended targets; the remainder contaminates the environment through runoff or spray drift, forming residues (Pandiselvam et al. 2020, Hui et al. 2021). Approximately 64% of agricultural land worldwide is at risk of combined pollution from multiple pesticides. Among these, the types of contaminated farmland in China are more complex, with about 8.4% of cultivated land suffering from combined pollution by more than 20 pesticides (Tang et al. 2021). The mobility and persistence of pesticide residues in soil pose significant environmental and health risks. Highly mobile pesticides readily enter water bodies, inhibiting plankton growth and reproduction and disrupting aquatic ecosystems (Agarwal et al. 2015). Simultaneously, they enter the food chain via contaminated crops. In humans and livestock, pesticides may accumulate gradually through biomagnification, eventually reaching levels that cause poisoning. For instance, consumption of food containing organochlorine pesticides significantly increases the risk of breast cancer, uterine cancer, and endometrial disorders in women (Eldakroory et al. 2017). A study by Wendel et al. (2001) on individuals chronically exposed to dichlorodiphenyltrichloroethane (DDT) revealed varying degrees of neurological damage, suggesting that organochlorine pesticides may impair the immune system and cause carcinogenic, mutagenic, and teratogenic effects. Thus, chemical pesticides, initially developed to control pests, weeds, and mites, may, through misuse or uncontrolled application, inflict multifaceted harm on the human environment.

Moreover, as pesticide adsorption in soil increases and degradation decreases, their presence directly impairs soil ecosystem functions, affecting both abiotic and biological activities (Kafaei et al. 2020). In terms of abiotic processes, a healthy soil ecosystem is characterized by efficient nutrient cycling, energy flow, high biodiversity, and stability (Chen et al. 2024). It supports vital processes such as water supply and nutrient provision, forming the foundation for plant growth and food chain integrity. However, pesticide contamination and their degradation by-products can disrupt nutrient supply (Fiorenza et al. 2020), inhibit key enzyme activities (Sannino et al. 2001, De et al. 2019), and weaken soil respiration (Yan et al. 2009, Ma 2014), ultimately undermining agricultural sustainability. For example, organochlorine pesticides (e.g., DDT, heptachlor, and lindane) are chemically stable and readily alter soil pH, thereby affecting microbial communities including nitrogen-fixing bacteria, PSMs, and organic matter decomposers leading to a significant decline in soil fertility (Wendel et al. 2001, Fiorenza et al. 2020). Pesticide toxicity and bioavailability in soil are closely linked to soil physicochemical properties such as organic matter content, respiration, and enzyme activity. Hydrophobic interactions and the formation of dissolved-phase complexes with soluble organic matter can reduce pesticide bioavailability, as demonstrated for atrazine and paraquat (Kulovaara 1993, Devitt et al. 1998). Soil respiration and enzyme activity, key indicators of soil quality, are significantly influenced by pesticide type and concentration (Yan et al. 2009). Studies show that chlorimuron-ethyl suppresses soil respiration in a concentration-dependent manner (Ma 2014), whereas long-term exposure to low concentrations of organochlorine pesticides may not significantly alter respiration rates (Wang et al. 2011). Furthermore, herbicides like glyphosate and glufosinate exhibit divergent effects on urease activity, ranging from inhibition (De et al. 2019) to stimulation (Sannino et al. 2001) across different soil types. This indicates that the same herbicide may elicit contrasting enzymatic responses under varying pedological conditions—a finding corroborated by Jiang et al. (2014), who observed differential urease activity in two distinct soil types following glyphosate application. Similar complex responses may occur with other enzymes, such as sucrase and phosphatase.

Regarding biological activities, soil microorganisms represent the most dynamic component of the soil ecosystem (Zhang et al. 2023). As primary decomposers and drivers of material cycling, their community composition and activity are crucial for maintaining soil fertility. Pesticides, being biologically active and toxic, inevitably impact microbial communities when deposited in agricultural soils. In practice, 30%–50% of applied pesticides fail to reach their targets and instead accumulate on the soil surface (Vašíčková et al. 2019, Zhang et al. 2021b, Walder et al. 2022). Over 51% of EU agricultural topsoils contain residues of five or more pesticides (Silva et al. 2019), while more than 58% of managed grassland soils contain two or more pesticide residues (Hvězdová et al. 2018). Existing research has largely focused on the effects of individual pesticides or specific application rates on soil microbes. For instance, methoxyfenozide-M may induce fungicide resistance (Wang et al. 2008, Sim et al. 2022) and shift microbial community structure toward fungal dominance (Rashid et al. 2016, Sim et al. 2022). Gradual pesticide application reduces the relative abundance of dominant fungal taxa, increasing community evenness, whereas sudden application causes transient disruption without long-term proliferation of rare fungal variants (Riedo et al. 2025). Studies by Tan et al. (2016) demonstrated that pesticides like chlorothalonil, thiophanate-methyl, and carbendazim inhibit microbial growth, hydrogen ion and organic acid secretion, and phosphate-solubilization to varying degrees—effects that depend on both the microbial and pesticide species and exhibit concentration-dependent dose responses.

With the increasing use of pesticide mixtures, the combined effects of multiple residues have gained scholarly attention. For example, risk assessments by Deng et al. (2014) indicated that pesticides such as chlorpyrifos, acetamiprid, imidacloprid, azoxystrobin, and carbendazim pose significant short- or long-term ecological risks to soil biota. Accumulating evidence confirms that pesticide-induced environmental stress can alter intermicrobial competition (Johnsen et al. 2001, Walder et al. 2022), and reduce the complexity of microbial networks (Fournier et al. 2020, Zhang et al. 2021a, b). Under such stress, microbial community assembly tends to exhibit higher stochasticity. As a key exogenous input, pesticide residues ultimately exert a profound impact on soil microorganisms, the core biological components maintaining soil health and function (Köninger et al. 2026). Against this backdrop, in-depth investigation into how specific functional microbial groups respond to environmental pressures is particularly urgent. Among these, PSMs, a key group with dual roles in phosphorus activation and plant growth promotion (Abd-Alla 1994, Patel et al. 2008, Sui et al. 2016, Chen et al. 2017, Bi et al. 2020, Yu et al. 2020) offer an ideal research model for understanding microbial-driven soil fertility restoration and health maintenance. Their classification, solubilization mechanisms, and multifaceted roles in agricultural ecosystems provide a critical perspective for advancing sustainable soil management.

Phosphate-Solubilizing Microorganisms: Mechanisms, Efficacy, and Environmental Interactions

PSMs represent a functional group of microbes including bacteria, fungi, and actinomycetes that are capable of converting insoluble soil phosphorus into plant-available forms (Abd-Alla 1994, Yu et al. 2020). Research into PSMs dates to the early 20th century. In 1908, Sackett and his team isolated over 30 bacterial strains capable of dissolving insoluble phosphorus from phosphate rocks and bone meal, marking the inception of PSMs research (Sackett et al. 1908). Subsequently, in 1950, Menkina isolated *Bacillus megaterium*, which mineralizes organic phosphorus compounds such as nucleic acids and lecithin, and demonstrated its ability to significantly increase soil available phosphorus (Menkina 1950). In 1982, Craven & Hayasaka (1982) further revealed the correlation between rhizosphere phosphate-solubilizing bacteria and soil available phosphorus levels. In recent years, screening highly efficient PSMs from unique environments has become a research focus. For instance, Hamdali et al. (2008) isolated *Streptomyces griseus* M1323 from a Moroccan phosphate mine, which exhibited strong phosphate-dissolving capacity.

Corresponding research in China was initiated relatively later. In the 1950s, the Chinese Academy of Sciences isolated the first phosphate-solubilizing *Pseudomonadaceae* strain from northeastern black soil (Itano & Gan 1955). Subsequently, Yin (1988) systematically studied PSMs in dryland soils in China and found that their abundance and solubilizing capacity were significantly influenced by soil pH and phosphorus source type. Driven by the demands of agricultural production, researchers have conducted more systematic and in-depth investigations into PSMs. To date, diverse microbial resources with phosphate-solubilizing capabilities have been isolated and screened worldwide. For example, phosphate-solubilizing bacteria are the dominant group, accounting for approximately 1%–50% of all PSMs (Kalayu 2019). Common genera include *Acinetobacter*, *Bacillus*, *Burkholderia*, *Serratia*, *Providencia rettgeri* and *Pseudomonas*, as listed in Table 1. In contrast, phosphate-solubilizing fungi are fewer in variety and abundance, comprising only 0.1–0.5% (Kalayu 2019), and primarily include *Actinomycetes*, *Aspergillus niger*, *A. tubingensis*, *Talaromyces*, *Pantoea* species (e.g., *Pantoea agglomerans*), and some *Penicillium oxalicum* also possess phosphate-solubilizing capabilities. Although their proportion in natural soils is low, they hold considerable application potential in specific environments. Despite differences in taxonomy and ecological distribution, all these microorganisms have evolved the core ability to convert insoluble phosphorus into available forms, achieved through diverse solubilization mechanisms.

Regarding phosphorus solubilization mechanisms, the most extensively studied pathway to date is the organic acid solubilization pathway (Ma et al. 2025). PSMs metabolically secrete low-molecular-weight organic acids such as gluconic acid, 2-ketogluconic acid, oxalic acid, acetic acid, malic acid, and butyric acid (Abd-Alla

1994, Sui et al. 2016, Rawat et al. 2021). These acids release H^+ ions, lowering the ambient pH and converting fixed phosphorus (e.g., calcium phosphate, aluminum phosphate) into plant-available forms (Abd-Alla 1994). For example, Tan (2016) identified three oxalate-secreting strains-B1, A1, and F1-that degrade calcium phosphate (Table 1). Cunningham et al. (1992) also identified oxalic acid as the primary mechanism for dissolving calcium phosphate. Additionally, the carboxyl and hydroxyl groups of these acids can chelate metal cations (e.g., Ca^{2+}, Fe^{3+}, Al^{3+}), competitively displacing phosphate ions from adsorption sites and releasing them (Sun et al. 2016, Rawat et al. 2021). However, acidification is not the sole mechanism. In some cases, the ability to reduce pH does not correlate with the capacity to solubilize mineral phosphorus (Subbarao et al. 1982). Altomare et al. (1999) found that the plant-growth-promoting and biocontrol fungus T-22 could dissolve insoluble phosphates without producing organic acids, possibly due to the action of inorganic acids (e.g., hydrochloric, nitric, and sulfuric acids). Bacteria such as *Nitrosomonas* and *Thiobacillus* can also dissolve phosphate compounds by producing nitric or sulfuric acid (Azam et al. 1996), although hydrochloric acid solubilizes less phosphorus from hydroxyapatite than citric or oxalic acid at the same pH (Kim et al. 1997). Fan et al. (2002) demonstrated that *Penicillium* strain P8 employs at least two distinct solubilization mechanisms, confirming that organic acid production is not the only strategy. This physiological adaptability likely results from long-term environmental adaptation. Other mechanisms have also been identified. For instance, some microbes release H^+ via respiratory CO_2 conversion to carbonic acid or through NH_4^+ assimilation, thereby reducing the environmental pH and dissolving insoluble inorganic phosphorus (Pikovskaya et al. 1948, Tan 2016). These findings indicate that the process of converting insoluble phosphorus into available forms is complex and influenced by nutritional composition, physiological traits, and growth conditions, which together determine solubilizing efficacy.

The phosphate solubilization index (PSI) is commonly used to assess the solubilizing capacity of PSMs (Qin et al. 2009). Preliminary screening yields the PSI, while secondary screening measures the absolute amount of phosphorus solubilized. As summarized in Table 1, reported PSMs exhibit PSI values ranging from 1.03 to 4.60, with solubilization levels between 79.50 and 572.33 mg/L. For example, *Bacillus* strain Z1 showed the highest PSI of 4.60 but a solubilization amount of 510.21 mg/L, which was not the highest observed. In contrast, *Pseudomonas* strains isolated from the rhizosphere of sweet potato, corn, bean, and alfalfa achieved the highest solubilization amount of 572.33 mg/L with a PSI of only 1.10 (Chen et al. 2014). This indicates that a higher PSI does not necessarily correlate with greater solubilization performance. Moreover, functional stability under practical conditions affects efficacy. Some strains lose their solubilizing ability after repeated subculturing, suggesting that genetic stability and functional expression are influenced by cultivation conditions and physiological state (Lin et al. 2000, Tan 2016). For instance, Chen et al. (2014) isolated strain Y14 (*Pantoea* sp.) from reclaimed mining soil in Shanxi, whose liquid fermentation broth contained up to 663.67 mg/L of available phosphorus—significantly higher than the 71.92 mg/L reported by Lu et al. (2007) for bacteria B2. The discovery of multifunctional strains offers new resources for biofertilizer development. For example, *Bacillus velezensis* strains screened in studies by Sha et al. (2019) not only solubilize phosphorus but also exhibit disease resistance, growth promotion (Chen et al. 2021), disease suppression (Tan et al. 2021), and biocontrol activities (Xia et al. 2021), highlighting their broad agricultural application potential.

In summary, PSMs play a vital role in agricultural ecosystems due to their taxonomic diversity and efficient phosphorus solubilization mechanisms. However, under field conditions, these functional microbes do not exist in isolation. Their survival and activity are inevitably influenced by exogenous inputs, particularly pesticide residues, which are ubiquitous in modern agriculture. A critical scientific question thus arises: What complex interactions occur when pesticide residues encounter PSMs? Do pesticides inhibit or harm PSMs, or can PSMs tolerate or even degrade these pollutants? Ultimately, how do these interactions impact the efficiency of soil phosphorus cycling and agricultural sustainability? Clarifying the bidirectional relationship between pesticide residues and PSMs, encompassing pesticide toxicity, microbial degradation responses, and the subsequent effects on phosphorus cycling—is essential for the accurate assessment and effective utilization of these key functional microbes.

Pesticide-PSMs Interactions: Mechanisms and Agricultural Implications

Current research on microbial degradation of pesticides is extensive, and studies on PSMs have also largely focused on screening, growth-promotion mechanisms, and heavy-metal remediation. In contrast, research on the interactions between pesticides and PSMs under co-existence conditions remains limited, with few relevant reports domestically or internationally. Existing studies predominantly concentrate on the effects of fungicides and insecticides on a limited number of strains. In practice, residual pesticides in soil after application can significantly impact microorganisms, exhibiting a dual effect. On one hand, high concentrations of pesticides may cause microbial toxicity, inhibiting their growth and metabolic functions. On the other hand, some specialized degrading microorganisms can utilize pesticides as nutrient sources, decomposing and transforming them through metabolic activities (Soil Microbiology Research Association, 1983). The net impact of pesticides on soil microbes, particularly functional groups, is determined by the balance of these two effects.

The toxic impact of pesticides on soil microorganisms is a key ecological effect of their persistence in the environment. When exposed to excessively high pesticide concentrations, soil microbes often face risks including growth inhibition, metabolic disruption, and even cell death, thereby compromising their ecological functions (Thepbandit & Athinuwat 2024). As important functional microorganisms, PSMs in soil can substantially influence phosphorus availability (Yu et al. 2020, Pang et al. 2024). Multiple studies have shown that various common pesticides significantly inhibit the growth and phosphorus-solubilizing capacity of PSMs, typically in a concentration-dependent manner (Kumar et al. 2015, Tan 2016, Munira et al. 2019, Kaur et al. 2022). For example (Table 2), studies on the effects of fungicides like chlorothalonil, thiophanate-methyl, and carbendazim on PSMs such as *Pseudomonas* B1, *Streptomyces* A1, and *Talaromyces* F1 revealed that while *Pseudomonas* B1 exhibited strong tolerance to chlorothalonil and thiophanate-methyl with no significant growth inhibition, the growth of *Streptomyces* A1 and *Talaromyces* F1 was significantly suppressed with increasing pesticide concentration. More critically, all three fungicides markedly inhibited the strains' phosphate-solubilizing ability. Chlorothalonil inhibited phosphorus solubilization in A1 and F1 by 86.38% and 84.51%, respectively (Tan 2016) (Table 2). Further mechanistic studies suggested that chlorothalonil may bind to cysteine residues in glyceraldehyde-3-phosphate dehydrogenase, disrupting enzymatic activity, affecting cellular metabolism and organic acid secretion, and ultimately reducing phosphate-solubilizing capacity (Tan 2016).

Regarding insecticides, studies on chlorpyrifos and carbofuran's effects on PSMs such as *Arthrobacter oxydans* (PR1PSB2) and *Bacillus flexus* (PR2PSB1) showed that, while these strains retained some solubilizing ability in the presence of pesticides, their solubilization efficiency and plant growth-promoting effects decreased significantly with increasing concentration (Kaur et al. 2022). Similarly, pesticides like mancozeb, phorate, chlorantraniliprole, and endosulfan exhibited concentration-dependent inhibition of phosphate solubilization in *Burkholderia* species (Kumar et al. 2015). Kaur et al. (2022) observed a significant decline in PSM populations with increasing concentrations of chlorpyrifos and tetramethrin. Research by Sarnaik et al. (2006) in soybean rhizosphere soil further confirmed that pesticides such as phorate and chlorantraniliprole not only reduced the population of phosphate-solubilizing bacteria but also significantly impaired their solubilizing capacity, with effects more pronounced when coexisting with methyl bromide. However, some studies note that phosphate solubilization can still occur in certain environments (e.g., the wheat rhizosphere) despite the presence of pesticides (Munira et al. 2019), suggesting that microbial responses to pesticides are jointly regulated by species-specific traits, environmental conditions, and pesticide type. This may be partly due to "defense mechanisms" activated by PSMs under pesticide stress. For instance, bacteria may expel toxic substances via efflux pumps (Silver & Phung 1996), evolve metabolic pathways to decompose or enzymatically degrade pesticides (Herman et al. 2005), or modify cell surface receptors to block entry of harmful compounds or alter compound properties through mechanisms like methylation (Bentley & Chasteen 2002). These strategies collectively enhance PSM survival in pesticide-contaminated environments.

In soil environments, the interaction between pesticides and microbes is not solely one of toxicity or suppression. Some PSMs can degrade or even utilize pesticides as nutrient sources, thereby contributing to environmental remediation. Research on microbial degradation of pesticides dates to the 1940s, and as awareness of environmental protection has grown, studies in this field have become increasingly systematic (Huang et al. 2018). Microbial degradation involves various mechanisms, including oxidation, reduction, hydrolysis, dehydrogenation, dehalogenation, decarboxylation, rearrangement, conjugation, and isomerization, ultimately breaking down complex pesticide molecules into simple inorganic compounds (Hugo et al. 2014). Enzymes such as hydrolases, oxidoreductases, and transferases play key roles in this process (Fernández-López et al. 2017). Notably, some PSMs can utilize pesticide degradation products as carbon, nitrogen, phosphorus, or energy sources, enabling resource recycling (Gangola et al. 2022). For example, with the fungicide thiram, inoculation with *Acinetobacter calcoaceticus* reduced thiram residues by 69% in rhizosphere soil compared to uninoculated treatments (Jie et al. 2025), indicating strong degradation capability. *Pseudomonas otitidis* and *P. stutzeri* degraded 81% and 57% of thiram, respectively, within 4 days of inoculation, reaching 99% degradation after eight days, demonstrating high bioremediation potential (Chouhan et al. 2023). Regarding insecticides, *Bacillus cereus* and *Pseudomonas aeruginosa* effectively degraded malathion at pH<7, whereas *Raoultella ornithinolytica* showed lower efficiency, indicating strain-specific degradation capabilities (Chakma et al. 2019). *Arthrobacter oxydans* (PR_1PSB_2) and *Bacillus flexus* (PR_2PSB_1) exhibited high tolerance to chlorpyrifos and carbofuran (Kaur et al. 2022), tolerating 3 times and 2 times the recommended field doses, respectively, while maintaining phosphate-solubilizing function alongside pesticide degradation, highlighting their potential as bioremediation agents in pesticide-contaminated soil.

Table 1. Representative high-efficiency PSMs and their plant growth-promoting effects.

Type	Genus	Strain	Community distribution	Mechanism of action	PSI		References
					D/d	PSA mg/L	
Bacteria	*Bacillus*	L68	Soil	——	1.837	130.35	Tan (2016)
		J102	Corn rhizosphere soil	Description solely pertains to the secretion of organic acids	1.25	376.09	Li (2021)
		Z1	Wheat root zone soil	——	4.60	510.21	Zhang et al. (2020)
		Z2		——	3.80	567.30	Zhang et al. (2020)
		——	Commercialization	The anions of organic acids solubilize and release phosphorus by chelating metal cations, concurrently lowering the pH	2.17	355.53	Li et al. (2024a)
	Pseudomonas	HY-L5, HY-S7, HY-S25, HY-S36, HY-S37, HY-S44, HY-S58, HY-S70, HY-S78	Melon rhizosphere soil	Organic acids acidify the environment, inducing ion exchange in insoluble phosphates leading to phosphorus release	2.06–3.76	459.48, 283.26, 407.35, 443.67, 278.21, 281.91, 90.44, 276.61, 270.33	Li et al. (2024b)

	B1	Soil: vegetable fields, orchards, sloping farmland	They secrete organic acids, which lower the pH and chelate Ca^{2+}, thereby dissolving insoluble phosphorus	1.75	316.11	Tan (2016)
	H22			1.70	399.00	Chen et al. (2014)
	Y11	Soil: sweet potato, corn, alfalfa rhizosphere; fallow land	They produce and release organic acids, which function by lowering the pH and chelating metal cations	1.10	572.33	Chen et al. (2014)
	Y34			1.80	558.00	Chen et al. (2014)
	JD6			3.49	395.70	Li (2021)
	JD7	Corn rhizosphere soil	Description solely pertains to the secretion of organic acids	2.76	376.86	Li (2021)
Acinetobacter	B6			3.16	385.10	Li (2021)
Burkholderia	T4	Red soil-type paddy soil	They rely on the uptake of ammonium nitrogen to secrete H^{+} protons for phosphorus solubilization	——	334.20	Dai et al. (2011)
Serratia	AWH-NS6	Desert Saxual and spruce rhizosphere soil	They rely on the uptake of ammonium nitrogen to secrete H^{+} protons for phosphorus solubilization	1.17	480.07	Li (2023)
Providencia rettgeri	——	Commercialization	The secreted organic acids, whose anions dissolve phosphates by chelating metal ions, release phosphorus from tricalcium phosphate and reduce the pH	2.05	272.17	Li et al. (2024a)

Fungi	*Talaromyces*	F1	Vegetable fields, orchards, sloping farmland	It solely secretes oxalic acid. The phosphorus solubilization may stem from acid production via ammonium assimilation or carbonic acid from respiration	1.03	355.01	Tan. (2016)
	Penicillium oxalicum	P8	Poorly fertilized farmland or non-arable land	It secretes organic acids. It can utilize ammonium or nitrate nitrogen; the uptake of ammonium ions (NH_4^+) prompts H^+ proton secretion for phosphorus solubilization	1.26	——	Fan et al. (2002)
		Pn1		It secretes malic acid, acetic acid, citric acid, and succinic acid	1.07	——	Fan et al. (2002)
	——	A6		It primarily secretes acetic and propionic acids, but not malic acid	——	——	Fan et al. (2002)
	Aspergillus niger	——	*Caragana* rhizosphere soil	It releases small-molecular-weight organic acids to dissolve insoluble phosphates by altering pH	——	——	Zhang et al. (2011)
		P1-1	Soybean, lettuce, corn, and apple field soils	It secretes oxalic acid, gluconic acid, lactic acid, and glyceric acid. A negative correlation exists between the amount of dissolved phosphorus and the culture medium's pH	1.59	83.36	Yang et al. (2018)
	A.tubingensis	P2-2			1.76	79.50	Yang et al. (2018)
Actinomycetes	*Streptomyces*	A1	*Caragana* rhizosphere soil	It secretes oxalic acid, malic acid, formic acid, etc. These organic acids dissolve phosphorus by lowering pH and chelating Ca^{2+}	1.80	206.19	Tan (2016)
		PSPSA1	Peony rhizosphere soil	——	1.80	158.50	Xue et al. (2018)

	Micromonospora nigra	SY7	Corn rhizosphere soil	The pH of the fermentation broth correlates with the microbial phosphorus solubilization capacity	——	370.00+	Cong et al. (2021)
Pan-bacteria	*Pantoea*	Y14	Sweet potato, corn, alfalfa rhizosphere; fallow land	The released organic acids dissolve phosphorus by lowering pH and chelating metal ions such as Fe^{3+}, Al^{3+}, and Ca^{2+}	3.28	663.67	Chen et al. (2014)
	Pantoea agglomerans	CT-3	Root zone soil of crops in Inner Mongolia	It secretes oxalic acid, tartaric acid, pyruvic acid, and citric acid. The secretion of oxalic and lactic acids constitutes its primary phosphorus-solubilizing mechanism	2.53	452.29	Zhang et al. (2025)

Marks: PSI: Phosphorus solubilization index; D/d: the ratio of the diameter of the phosphate-solubilizing zone (D) to the diameter of the colony (d) on calcium phosphate medium; PSA: Phosphorus solubilization amount; ——: no information.

Table 2. Effects of pesticides on microbial interactions with soluble phosphorus in soil

Category	Pesticide	PSMs	Pesticide effects on PSMs		References
			Growth effects	Phosphorus-solubilization effects	
Fungicide	Chlorothalonil	*Pseudomonas* B1, *Streptomyces* A1, *Talaromyces* F1	No inhibition on B1. Increased concentration strongly inhibits A1 and F1	Minimal impact on the phosphorus solubilization of B1. The inhibition rates on the phosphorus solubilization of A1 and F1 are 86.38% and 84.51%, respectively	Tan (2016)
	Thiophanate-methy		No inhibition on B1. Increased concentration strongly inhibits A1 and F1	The inhibition rates on phosphorus solubilization for B1, A1, and F1 are 36.53%, 70.57%, and 76.93%, respectively	

	Carbendazim		B1 is inhibited at low concentration but not at high concentration. Increased concentration strongly inhibits A1 and F1.	The inhibition rates on phosphorus solubilization for B1, A1, and F1 are 40.78%, 86.38%, and 84.51%, respectively	
	Mancozeb	*Burkholderia* sp.	The toxicity level is low, but it still leads to a decrease in colony count	The toxicity is low. At the maximum dose, the extent of reduction in phosphorus solubilization follows: chlorpyrifos < mancozeb < endosulfan < phorate	Kumar et al. (2015)
Insecticide	Phorate, Chlorantraniliprole, Endosulfan	*Burkholderia* sp.	The toxicity level is low, but it still leads to a decrease in colony count	The amount of dissolved phosphorus decreases significantly with increasing concentration	Kumar et al. (2015)
	Carbofuran, Chlorpyrifos	*Arthrobacter oxydans*, *Bacillus flexus*	Growth is inhibited by concentration	The amount of dissolved phosphorus decreases significantly with increasing concentration	Kaur et al. (2022)
	Chlorpyrifos, Pyriproxyfen	*Pseudomonas putida*, *Pseudomonas* sp., *Pseudomonas fulva*	Growth is inhibited by concentration	Minimal impact on phosphorus solubilization	Munira et al. (2019)

Category	Pesticide	PSMs	Remediation effects of PSMs on pesticide contamination	
Fungicide	Thiram	*A.calcoaceticus*	Thiram residue in rhizosphere soil reduced by 69%	Jie et al. (2025)
		Pseudomonas otitidis	81% degradation within 4 days; 99% after 8 days	Chouhan et al. (2023)

		Pseudomonas stutzeri	57% degradation within 4 days; 99% after 8 days	
Insecticide	Malathion	*Bacillus cereus*	Optimal degradation occurs at pH < 7	Chakma et al. (2019)
		Pseudomonas aeruginosa	Optimal degradation occurs at pH < 7	
		Raoultella ornithinolytica	The degradation efficiency is low	
	Chlorpyrifos	*Arthrobacter oxydans, Bacillus flexus*	Both strains tolerate up to 7.5 µl mL^{-1} (3 times the recommended dose)	Kaur et al. (2022)
	Carbofuran		Both strains tolerate 0.75 g mL^{-1} (twice the suggested dose)	
Herbicide	MCPA	*Burkholderia* sp.	Significantly reduces toxicity in tomato plant roots	Zhang et al. (2021c)

Remark: PSMs: phosphate-solubilizing microorganisms.

For herbicides such as MCPA (4-chloro-2-methylphenoxyacetic acid), inoculation with *Burkholderia* (N3) significantly reduced toxicity in tomato roots (Zhang et al. 2021c), further confirming the potential of PSMs to mitigate pesticide phytotoxicity. Studies indicate that pesticide degradation depends not only on specific microbial metabolism but also on soil physicochemical properties (e.g., pH, organic matter content) (Yang & Ji 2015, Wang et al. 2022). For instance, beta-cypermethrin degrades rapidly in high-organic-matter soils due to enhanced microbial numbers and activity (Yang & Ji 2015). Wang et al. (2022) found that the degradation rate of benziothiazolinone was significantly higher in non-sterilized soil than in sterilized soil, with microbial remediation being the primary cause of rapid degradation, especially under anaerobic conditions. By systematically analyzing the complex interactions between pesticide application and PSM function, while pesticides suppress pests and diseases, they may also stress key functional soil microbes, PSMs, thereby weakening soil phosphorus vitality and creating a potential “nutrient bottleneck”. Concurrently, certain PSMs with pesticide-degrading capabilities can convert pesticide breakdown products into plant-available nutrients, thereby supplying essential elements (e.g., phosphorus and potassium) to plants (Abd-Alla 1994, Sharma & Shrivastav 2023). Based on these findings, some researchers have incorporated the impact on key soil functional microbes into pesticide management, promoting the establishment of more precise ecological risk assessment systems (Tan 2016, Chouhan et al. 2023, Jie et al. 2025). Furthermore, there are active efforts in agriculture to utilize or breed pesticide-tolerant PSM strains and develop integrated “pesticide-functional microbe” compatibility strategies (Kumar et al. 2015, Chakma et al. 2019, Kaur et al. 2022). This provides scientifically feasible solutions for building environmentally friendly, nutrient-efficient, and healthy farmland ecosystems from the ground up. However, such integrated studies remain relatively scarce. Current research still faces several areas requiring deeper exploration. Future studies should focus on: (1) elucidating the precise mechanisms of pesticide-PSMs interactions at the molecular level; (2) quantifying the practical impact of these interactions on crop phosphorus uptake and yield in complex field environments; and (3) screening and constructing efficient pesticide-tolerant PSM consortia based on interaction principles. In-depth exploration of these questions will ultimately lay a solid scientific foundation for reconciling the tension between agricultural chemical inputs and microbial ecological functions, achieving the dual goals of high productivity and environmental protection.

Conclusion

To address the conflict between pesticide, use and soil health in agricultural systems, this review systematically examines the complex interactions among pesticides, phosphate-solubilizing microorganisms (PSMs), and soil phosphorus cycling. We first summarize the broad-spectrum effects of pesticides on soil microecology, providing a macro-scale context for understanding their ecological impacts. We then describe the diversity of PSMs, their mechanisms of phosphorus solubilization, and their essential roles in agricultural ecosystems. The core focus of this review is the bidirectional interactions between pesticides and PSMs: under certain conditions, pesticides exert inhibitory or toxic effects on PSMs, whereas microbial communities may adapt to pesticide exposure through degradation and resistance mechanisms. These dynamic interactions ultimately regulate soil phosphorus availability and plant phosphorus nutrition. By shifting pesticide ecological risk assessment from the community level to the functional microbial level, this review offers new perspectives on the environmental consequences of pesticide application. Furthermore, it provides a theoretical foundation for reconciling crop protection with soil fertility enhancement. The development of green agronomic strategies based on PSM-mediated processes to reduce pesticide and fertilizer inputs has important implications for advancing sustainable agricultural systems.

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Data Availability

The data used to support the findings of this study are included within the article and support material.

Declaration of competing interest

The authors declare no conflicts of interest.

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