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Utilization of *Pseudomonas fluorescens* Bacteria in Weed Control and Phosphate Supply in Oil Palm (*Elais Guineensis Jacq.*) Plantations

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ABSTRACT

With growing environmental concerns, sustainable management practices in oil palm plantations are becoming increasingly essential. This review examines the potential of Pseudomonas fluorescens as a biological agent for both weed control and phosphate solubilization in oil palm (*Elaeis guineensis*) cultivation. A systematic literature search was conducted across Google Scholar, Scopus, and ScienceDirect databases, focusing on studies published between 2007 and 2023. Studies that investigated the role of *P. fluorescens* in enhancing plant growth through weed suppression or improving phosphate uptake were selected. The findings reveal that *P. fluorescens* can significantly benefit plant health by minimizing weed competition and enhancing the availability of phosphorus in the soil. However, challenges such as the variability in environmental conditions, strain specificity, and scalability of application persist. The review highlights the importance of further field trials and experimental research to refine the practical use of *P. fluorescens* in achieving more sustainable oil palm production.

Keywords: Palm oil, *Pseudomonas fluorescens*, sustainable agriculture, weed control

INTRODUCTION

On facing agricultural demands that keep on increasing, palm oil plantations remain the most crucial in terms of Indonesia's horticulture and state revenue. With the increasing pressure to take into serious matters of environmental concerns, the integration of biological solutions like *Pseudomonas fluorescens* could be the next frontier in oil palm cultivation. In the matter of palm oil as horticulture commodity, Indonesia hold its status as the largest manufacturer of palm oil, with 1.7 billion liters (bL) of biodiesel exported (with records that crude palm oil (CPO) as the main feedstock for biodiesel production in Indonesia) (Khatiwada *et al.* 2018). Aside from its usage on biodiesel main ingre-dients, CPO are also widely used for food and other industrial non-food uses. Palm oil has its own advantages as vegetable oil that

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make it superior when compared with other edible oils. To benchmark with other important horticultural commodities in Indonesia, such as rubber, oil palm cultivation offers higher returns with respect to both land use and labor demands (Krishna *et al.* 2017). Soaps, detergents, and grease are a few examples of non-food industrial uses of palm oil, which make it inseparable from our daily lives. As a result, there is a strong tendency for the palm oil industry to have a stronghold contributing to the Indonesian economy, not only on the scale of country income but also on enhancing household welfare and improving local infrastructure (Euler *et al.* 2016).

According to Anjani *et al.* (2022), Indonesia is the world's largest producer and exporter of palm oil with production greater than 18 million tons per year. The palm oil industry contributes significantly to the national economy by generating a state revenue of up to IDR 239.4 trillion, also to note that it opens up employment opportunities. Based on BPS RI (2020), the area of oil palm plantations in Indonesia has almost reached 15–16 million hectares. Palm oil is the leading vegetable oil used for food in Indonesia, consumed at double the rate of soybean oil. Since 2011, domestic consumption of palm oil for food has risen by 20%, reaching the number of 5.5 million tonnes in 2014. This demand is projected to keep growing alongside the population increase and gross domestic product (GDP) in Indonesia (Khatiwada *et al.* 2018).

With palm oil being a vital commodity in many aspects, maintaining high yields becomes increasingly critical, especially due to the persistent problem of weeds in oil palm plantations. Controlling weed growth in oil palm fields is a crucial factor in maintaining the productivity and also the sustainability of oil palm plantations. One of the major problems during the early stage of oil palm plantation is weed invasion, where competitive and invasive weeds such as *Imperata cylindrica, Mikania cordata, Cyperus rodontus,* and *Lantana camara,* compete for resources (nutrients, moisture, and light) that is necessary for the growth of oil palm (Thongjua and Thongjua 2016). A study conducted by Prasetyo & Zaman (2016) showed that in Jambi Province, losses in palm oil plantation due to weeds such as *Mikania micrantha* (locally known as *sembung rambat*) reached IDR 38,110,550 with an infestation area up to 757.5 ha, losses due to *Imperata cylindrica* (locally known as *alang-alang*) reached IDR 59,971,500 with an infestation area of 1086 ha, and losses due to *Paspalum conjugatum* (locally known as *rumput kerbau*) reached IDR 43,416,599 with an infestation area of 1149.9 ha. The damage caused by weeds is often not immediately visible. Several factors contribute to these losses, including stunted plant growth, which leads to longer production times, a decrease in both the quantity and quality of harvests, disruptions in work productivity, the potential for weeds to serve as breeding grounds for pests and diseases, and the high costs associated with weed control (Dahlianah 2019).

Therefore, to meet the high demand for palm oil, whether in its raw form or as CPO, effective weed management is essential. In its implementation to suppress weeds, plantations generally use chemical herbicides because they are relatively cheap. However, the use of chemical herbicides has disadvantages and side effects if used continuously and in the long term. Long-term herbicide application can also kill species of bacteria, fungi, and protozoa that combat disease-causing microorganisms, disrupting the balance between harmful pathogens and beneficial organisms (Latha and Gopal 2010). Apart from weeds, oil palm plantations also encounter problems in the form of macronutrient deficiencies in the soil, especially phosphorus, where phosphorus deficiency can lead to the inhibition of palm oil growth. Phosphorus in soil is a non-mobile nutrient, which can be defined as its tendency to bind mostly to soil particles and partly present as organic phosphorus, with only a little available in a form that can be taken up directly by plants (Ibrahim *et al.* 2022). In addition, to increase and meet the basic phosphorus needs for palm oil, chemical phosphorus (P) fertilizers are usually used to meet needs (Supriatna *et al.* 2023), where this is highly hypocritical on the principles of sustainable agriculture, due to its negative impact. Excessive use of P fertilizers increases the risk of nutrients percolating into deeper soil layers, leading to the loss of essential minerals, which can reduce soil fertility (Dubos *et al.* 2016).

Given these challenges, an effective and rapid solution must be developed that is environmentally friendly and cost-effective. The use of biocontrol plant-growth-promoting rhizobacteria (PGPR) has been demonstrated to be environmentally friendly, and proven to enhance plant growth and control diseases and weed infestation (Zainab *et al.* 2021). One of the most prominent potentials is the use of P. fluorescens, a gram-negative-bacteria, to compete with common weeds in palm oil plantations while increasing the supply of phosphorus for palm oil growth. *P. fluorescens* can enhance plant growth through increase of antioxidant enzymes, and converting P into available forms for palm oil (usually known as orthophosphates) (Linu *et al.* 2019). While the application of PGPR as biocontrol has proven to be both eco-friendly and cost-effective in enhancing plant growth, its specific role in weed control and phosphate solubilization in palm oil plantations remains under-explored. Addressing this gap can provide valuable insights for sustainable agriculture practices. Thus, the objectives of this review study are: 1) To identify the potential of *P. fluorescens* as a weed control agent at palm oil plantations; 2) To elucidate the interaction between *P. fluorescens* and common weeds at palm oil plantation; 3) To identify the potential of *P. fluorescens* on increasing the availability of phosphate in the soil of palm oil plantations; lastly, 4) To determine effective application strategies to optimize the role of *P. fluorescens* in weed control and increasing soil phosphate in palm oil plantations.

MATERIALS AND METHODS

This study employed a qualitative methodology through a systematic literature review to investigate the role of *Pseudomonas fluorescens* in weed control and phosphate availability in oil palm plantations. We performed the literature search across three major databases: Google Scholar, ScienceDirect, and Scopus. The search was limited to articles published from 2010 onward, with the following keywords: "*Pseudomonas fluorescens*", "biocontrol of weed", "palm oil", and "phosphate solubilization". Articles were included if they specifically discussed *P. fluorescens* as a biofertilizer or biopesticide or its use as a biofertilizer in palm oil cultivation. Studies were excluded if they didn't focus on weed control or phosphate supply, or if they were not related to agricultural settings. The initial screening process was conducted by a team of four reviewers, who independently reviewed the abstracts to determine their relevance. Articles that passed this initial screening underwent full-text review. While this review does not include a formal quality assessment of the studies, it focuses on presenting the main trends and current findings from the literature on the use of *P. fluorescens* as weed control and phosphate supply on palm oil plantations.

RESULTS AND DISCUSSION

Scientific studies have proven the effectiveness of *Pseudomonas fluorescens* in controlling weed populations, including in oil palm plantations. Research conducted by Kim *et al.* (2017) found that the application of

P. fluorescens significantly reduced the growth of weeds such as *Imperata cylindrica* and *Mikania micranth*a in agricultural soils. In addition, research by Verma *et al.* (2020) concluded that *Pseudomonas fluorescens* can inhibit the growth of weeds such as *Echinochloa colona* and *Cyperus rotundus* by increasing the competitiveness of the main crop against weeds. In oil palm plantations, commonly encountered weed types include *Imperata cylindrica* (locally known as alang-alang), weeds, and *Cyperus rotundus*. Thus, the application of *P. fluorescens* has the potential to be an effective tool in weed management in oil palm plantations, helping to improve the productivity and quality of oil palm crops by reducing competition from noxious weeds.

Research conducted in the field has shown significant differences between weed populations in plots treated with *P. fluorescens* and control plots (without *P. fluorescens*). For example, research conducted by Smith *et al.* (2019) in oil palm plantations found that *P. fluorescens* application consistently resulted in a significant reduction in weed numbers and density compared to control plots. The results included significant reductions in weeds commonly encountered in oil palm plantations, such as *Imperata cylindrica* (commonly known as alang-alang), weeds, and *Cyperus rotundus*. In addition, the study also noted that the difference in weed populations between the plots treated with *P. fluorescens* and the control plots remained significant over the long observation period, indicating a sustained effect of the treatment (Smith *et al.* 2019). These findings provide strong evidence of the effectiveness of *Pseudomonas fluorescens* as a potential biological control agent in reducing weed populations in oil palm plantations, with positive implications for weed management and overall farmland productivity.

P. fluorescens has promising potential as a biological alternative in weed control when compared to the use of chemical herbicides. The use of chemical herbicides is often effective in controlling weeds, but can cause several problems, including weed resistance to chemicals and negative impacts on the environment and human health (Rani *et al.* 2019). In contrast, the use of P*. fluorescens* as a biological control agent offers a more environmentally frindly and sustainable approach. This bacterium works by inhibiting weed growth through several mechanisms, such as nutrient competition, production of antibacterial compounds, and stimulating plant defense systems. In addition, the use of *P. fluorescens* does not leave harmful chemical residues in soil and water, and does not cause weed resistance (Mehmood *et al.* 2023). Thus, the use of *P. fluorescens* as a biological alternative in weed control can help reduce reliance on chemical herbicides and promote a more sustainable approach in weed management in the agricultural sector. The interaction between *P. fluorescens* and oil palm (*Elais guineensis*) serves as a crucial mechanism driving the growth and development of plants. *P. fluorescens* forms a mutualistic relationship with the oil palm by colonizing the rhizosphere and adhering to the root surfaces, forming a biofilm. Such colonization significantly enhances nutrient availability for the plant by facilitating the solubilization and mineralization of essential nutrients like phosphorus and iron. This process will promote robust root growth and strengthen the overall vigor of the plant. Additionally, *P. fluorescens* produces plant growth promoting hormons, such as auxins and cytokinins. This hormons will stimulate root elongation and branching, further optimizing nutrient uptake and fostering improved plant growth.

Beyond direct growth enhancement, *P. fluorescens* also exerts an indirect influence on oil palm health by bolstering the plant’s defense mechanisms against pathogens. The bacterium accomplishes this through the production of antimicrobial compounds, such as antibiotics and lytic enzymes which inhibit the proliferation of phytopathogens in the rhizosphere. This suppression of harmful microbes effectively reduces the incidence of diseases such as Fusarium and basal stem rot in oil palm plantations. Moreover, *P. fluorescens* triggers systemic resistance in the oil palm, fortifying the plant's immune system and enabling it to mount a more effective defensive response against pathogen attacks. The symbiotic interaction between *P. fluorescens* and oil palm underscores the importance of this bacterium as a bioinoculant for promoting plant growth and health in agricultural systems. By improving nutrient availability, fostering root development and strengthening the plant's defense mechanisms, *P. fluorescens* offers substantial benefits for sustainable oil palm cultivation, significantly contributing to increased productivity and resilience against environmental stress and pathogenic threats.

Utilizing microorganisms like *P. fluorescens* for weed management give a promising approach in agriculture. This bacterium offers several mechanisms to suppress weeds, primarily through the production of allelochemicals and competition for resources. The allelochemicals that are released will inhibit the germination and growth of weed seeds, which will effectively reduce weed populations in agricultural fields. Additionally, the bacterium competes with weeds for essential nutrients and space in the rhizosphere further limiting weed establishment and growth. Therefore, by harnessing the natural antagonistic properties of *P. fluorescens*, farmers can lessen their reliance on synthetic herbicides and reduce environmental pollution and promote soil health.

P. fluorescens play a crucial role in enhancing phosphate (P) availability for the growth of oil palm. The bacterium employs various mechanisms to solubilize and mobilize phosphate from both organic and inorganic sources in soil, making it easier for plants to access. These bacterium work by secreting organic acids, phosphatases, and siderophores so it will increase the solubility of insoluble phosphorus compounds, such as phosphate rock. *P. fluorescens* will convert them into forms that can be readily assimilated by oil palm roots. With better phosphate nutrition, oil palms will become more competitive against weeds, allocating more resources toward growth and development, thereby reducing their susceptibility to weed invasion.

Despite its potential of the use of *P. fluorescens* as a weed control agent and a provider of phosphate, it faces several limitations about effectiveness, flexibility, and compatibility with existing agriculture practices. A significant challenge is the inconsistent performance of *P. fluorescens* in controlling weed populations across different soil types and environmental conditions. Variability in microbial activity and phosphate-solubilizing efficiency has hindered its widespread application as a weed control agent and phosphate provider. Furthermore, integrating *P. fluorescens* into existing weed management and fertilization strategies requires careful consideration of compatibility with agrochemical inputs and other farming practices, leading to logistical and economic challenges in its implementation. Despite all the challenges, there ares some significant opportunities for advancing the application of *P. fluorescens* in weed management and phosphate provisioning within agricultural systems. Developments in microbial ecology, biotechnology, and formulation science offer potential for improving the efficacy, consistency, and scalability of *P. fluorescens* based products. By elucidating the mechanisms of action and optimizing formulations, it is possible to develop tailored solutions that maximize the weed control and phosphate solubilization in different agricultural environments. As agricultural practices continue to evolve towards sustainability, harnessing the natural capabilities of beneficial microorganisms such as *P. fluorescens* offers a promising way to reduce chemical use, improve soil health and ensure the long-term productivity and resilience of agricultural ecosystems.

Phosphorus is the second most important macronutrient after nitrogen (N) for plant growth and development. Most of the phosphorus in the soil is in insoluble form and therefore cannot be absorbed by plants. P availability in soil is generally low especially in palm oil. This is because P is bound into Fe-phosphate and Al-phosphate in acid soils or $Ca_3(PO_4)^2$ in alkaline soils. Plants cannot absorb P in its bound form and it must be converted into a plant-available form (Suliasih and Rahmat 2007). The interaction between *Pseudomonas fluorescens* and oil palm plants could yield significant benefits for plant growth, including the possibility of increased phosphate uptake. These bacteria can increase phosphate availability in the soil by producing organic acids or phosphatase enzymes, which break down insoluble phosphate compounds into forms that are more easily absorbed by plants. In addition, *P. fluorescens* can also play a role in soil pathogen control, helping oil palm plants to grow healthier and more efficiently absorb nutrients, including phosphate. By stimulating the plant's defense system and accelerating nutrient cycling in the soil through organic matter decomposition, this bacterium can also help increase phosphate uptake by oil palm plants.

P. fluorescens affects oil palm plant growth and development through a complex mechanism of action. It increases nutrient availability by producing organic acids and enzymes that helps in the dissolution of nutrients in the soil, allowing plants to absorb nutrients more efficiently. In addition, *P. fluorescens* acts as a biological control agent against soil pathogens, maintaining plant health and preventing diseases that can inhibit growth. The bacterial strain can also stimulate the plant's defense system, increasing resistance to pathogen attack and environmental stress. In addition, these bacteria increase the ability of plants to absorb water and nutrients from the soil by improving the root system and nutrient absorption efficiency. *P. fluorescens* has a significant ability to increase phosphate availability in soil, either through phosphate solubilization or other mechanisms. One of the main mechanisms is the production of organic acids, such as citric acid and gluconic acid, which can reduce the pH around plant roots. This decrease in pH increases the solubility of phosphate compounds that are generally less soluble in neutral or alkaline soil pH, thus making phosphate more easily taken up by plants. In addition, *P. fluorescens* also produces phosphatase enzymes that can convert organic phosphate compounds into inorganic forms that can be absorbed by plants. Through this combination of mechanisms, *P. fluorescens* plays an important role in increasing phosphate availability in the soil, making a significant contribution to plant growth and development as well as overall farmland productivity. With sufficient phosphate availability, oil palm plants can experience faster and healthier growth, producing leaves that are more vigorous. This is demonstrated in a study by Suliasih and Rahmat (2007), which explains that the addition of *P. fluorecens* to phosphate-rich picovskaya agar, shows the results of the formation of a wide clear zone. This shows that Pseudomonas is a phosphate solubilizing bacteria that can help the absorption and availability of phosphate in plants. As the palm oil industry increasingly shifts towards sustainable cultivation practices, *P. fluorescens* as bioagent has gained significant attention, due to its potential to enhance plant growth and its ability to control harmful weeds and pathogens. Nevertheless its application specifically in oil palm plantations remains limited by several factors that impede its widespread adoption. Several characteristics of *Pseudomonas* species allow them to function as plant growth promoters and biocontrol agents. These features include their strong ability to compete in the rhizosphere, rapid colonization, production of various root elongation, bioactive compounds and their responses to environmental stress (Mehmood *et al.* 2023).

On the current trends, *Pseudomonas* studies are more focused on horticulture crops for daily foods, such as tomato and artichoke. On a study done by Ullah *et al.* (2022), the bacterial strains applied notably enhanced the transfer of potassium (K), calcium (Ca), magnesium (Mg), and zinc (Zn) from the soil to the plant shoots at wheat and rice cultivation. In another study done by Isma *et al.* (2015), the pure culture of Pseudomonas GanoEB3 has demonstrated the ability to inhibit the growth of G. Boninense in vitro and has proven effective in controlling *G. Boninense* infection in oil palm seedlings; *Pseudomonas* GanoEB3 has the capability to decrease the incidence of *G. Boninense* disease by reducing the number of dead seedlings in oil palm. Study done by Kalbuadi *et al.* (2024) investigates the effect of beneficial microbes on macronutrient uptake on oil palm seedling growth, one of the macronutrients being phosphorus. The results show that a significant difference on the nutrient uptake increased due to the influence of *P. fluorescens.* Another benefit is that after 3–4 years of consistent use, biofertilizers are no longer needed, as the initial inocula are sufficient to sustain growth and multiplication on their own (Bumandalai and Tserennadmid 2019).

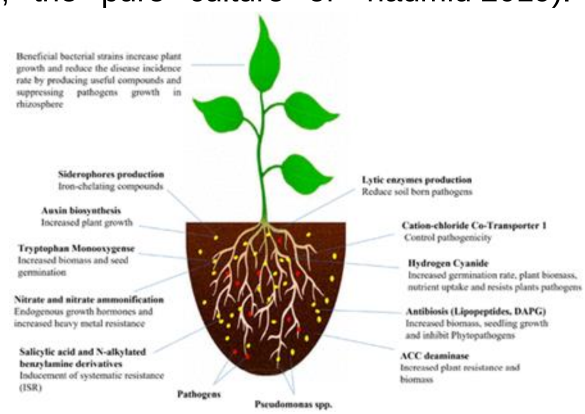

Figure 1 Systematic explanation of multifaceted *Pseudomonas* roles on plant growth.

Table 1 Macronutrient content in oil palm seedlings leaves at 6 MAP (Kalbuadi *et al.* 2024)

Treatments	**P (%)**
P0	0.50 b
P1	0.55 b
P2	0.66 a
P3	0.68 a
P4	0.68 a
P5	0.70 a
P6	0.68 a
P7	0.74 1
CV (%)	7.9

*) The Duncan's new multiple range test at = 0.05 finds no statistically significant difference between means in the same column and following the same letter.

Despite these promising findings on the effectiveness of *Pseudomonas* as a biofertilizer, there are still notable challenges that need to be addressed to fully realize its benefits in agricultural systems. The ability of *Pseudomonas* species to solubilize phosphate, a key point on bioagent, can differ due to genetic variability. Not all strains possess the ideal genetic mechanisms for consistent phosphate solubilization (Ou *et al.* 2022). The widespread use of *Pseudomonas* biofertilizers in large-scale agricultural systems may require significant optimization efforts. These include the development of appropriate formulations and efficient delivery methods to ensure the biofertilizer's effectiveness under diverse field conditions. However, such advancements can be resource-intensive, potentially driving up production and distribution costs. As a result, the overall expense for farmers may increase, posing an economic challenge for those looking to adopt biofertilizers as part of their sustainable farming practices. Balancing cost-effectiveness with optimization is therefore crucial for the broader adoption of *Pseudomonas* biofertilizers in large-scale agriculture (Yaashikaa *et al.* 2020).

Future studies should focus on genetically engineering *P. fluorescens* strains that specifically target weed growth in oil palm plantations, offering a tailored solution to one of the major challenges in this industry. These engineered strains could greatly improve weed management, reducing reliance on chemical herbicides while promoting a more sustainable agricultural practice. To make such innovations practical, researchers must also investigate methods for large-scale production of these bioagents, ensuring that they are cost-effective and easily accessible to palm oil farmers. Cost-efficiency is especially critical in this context, as high production and application costs could deter adoption in commercial plantations. Furthermore, more research should be conducted on the role of *P. fluorescens* as a biocontrol agent, with particular emphasis on its allelopathic potential to suppress weed growth through competition in the rhizosphere. Given the significant need for sustainable weed control in oil palm cultivation, this bio agent's ability to outcompete weeds presents a promising alternative to chemical solutions. Addressing these scientific and economic aspects will be key to integrating *P. fluorescens* into the future of sustainable palm oil production.

CONCLUSION

The use of *Pseudomonas fluorescens* in oil palm plantations can significantly boost crop productivity and quality by mitigating competition from detrimental weeds. The bacterium employs several mechanisms, including nutrient competition, the production of antibacterial substances, and the stimulation of the plant’s defense system to suppress weed growth. Furthermore, *P. fluorescens* enhances soil phosphate availability by producing organic acids or phosphatase enzymes that convert insoluble phosphate compounds into more plant-absorbable forms. To maximize its effectiveness, it is essential to evaluate the environmental conditions and specific weed problems in the plantation, and to select the *P. fluorescens* strains that are most compatible with the unique conditions and challenges present in the field.

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