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Review Article

The Ecological Significance of Plant Growth Promoting Rhizobacteria in Tropical Soil Kalimantan: A Narrative Review

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ABSTRACT

The diversity of flora in Kalimantan influences the presence of microbe-associated with rhizosphere on their activities and functions in ecosystems. However, abiotic stress such as acidification, drought, and toxic soil residues negatively impacted soil health and plant growth in some regions of Kalimantan's soil. The Plant-growth promoting rhizobacteria (PGPR) can alternate by producing phytohormone, solubilizing phosphate, nitrogen fixation, and biofilm production. Rhizobacteria will be beneficial for plant growth, soil aggregation, and bioremediation. Those benefit of rhizobacteria is essential to investigate. However, the study of the role of plant-rhizobacteria interaction in soil Kalimantan was limited. Therefore, this review focused on the presence of indigenous rhizobacteria and their mechanism to adapt and be tolerant in harsh environments.

Keywords: Acidic soil, Ammonia, IAA hormone, Rhizobacteria

Introduction

The biodiversity of Indonesian flora and fauna is the highest in global ecoregions[1]. One of the islands, Kalimantan, contributes various endemic flora and fauna, of which 54.9% of the area is covered by forest, and 23 million ha contains global biodiversity with the most remarkable plant diversity and complex ecosystem[1]. Because of the highest flora and fauna variety, Kalimantan (Borneo) is one of 24 hotspot regions in the world[2] in the category of tropical forest[1]. The tropical forest along Indonesia-Malaysia (Indo-Malay region) is known for its largest tropical forest ecosystem in the world[3]. The type of Kalimantan tropical forests include mangrove forests, peat swamp forests, freshwater non-peaty swamp forests, lowland Dipterocarp forests, forests on limestone, and various mountain forests[4]. In addition, Kalimantan has a variety of topography across the region that causes significant diversity in ecosystems. Due to this variety of landscape, Kalimantan plant species in the lowland forest have a high tree species diversity on mineral soils [5].

Most tropical forest interacts with soil associated with the microbiome[6]. The microbe could influence the diversity of soil microbiome, biotic (Rachman et al. 2021), and abiotic [7] in the ecosystem. The aboveground and belowground soil microbes affect soil carbon storage and cycle [4]. The most dominant microbe is bacteria which is

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present around the soil rhizosphere[8] and associated with plant type, plant age [9], and stage of plant growth[10]. The bacteria interacted with soil fauna, including the macroinvertebrates (larger size > 2mm) such as earthworms [11], soil-dwelling insects, myriapods, and isopods, which breakdown the litter and accelerate plant residue absorption into the soil[12]. The rhizosphere bacteria (rhizobacteria) and root exudates can synergize to increase carbon uptake into the bacteria community[13] and depict soil health and quality. The rhizobacteria associated with plants have a significance on plant growth[14], such as mediating direct and indirect plant growth by producing phytohormones, mineral solubilizing, and inhibiting plant growth pathogens[7]. Because of its potency, the rhizobacteria is well-known as plant growth-promoting rhizobacteria[10].

Regarding the relationship between plant and rhizobacteria diversity, we recognize that tropical soil in Kalimantan might generate an abundance of indigenous rhizobacteria associated with local plants and soil types. However, generally, acidic soil is dominant in Kalimantan soil, including acid peatland [10], acid sulphate [11, 12, 13, 14], tidal swamp [16], and sandy and clay soil texture [19, 25] that could be changed and improved the mechanism of rhizobacteria to survive in the extreme environment.

The research gap is that rhizobacteria studies in Kalimantan's tropical soil are rare; hence the exploration of indigenous rhizobacteria community, benefits, and their mechanism to adapt to abiotic stress are still unrecognized. Thus, in this study, we examine the significance of rhizobacteria role play in the soil in Kalimantan, including (a) how the presence of indigenous rhizobacteria spread in four regions of Kalimantan, (b) how rhizobacteria impact soil health and plant growth, and (c) how do rhizobacteria to restore the degraded soil. In addition, this review will compile a comprehensive overview of harsh environments. Therefore, this study is necessary to investigate and develop.

Material and Methods

This narrative review followed PRISMA guidelines (Petro)[15]. Relevant studies were retrieved from Google scholar, ScienceDirect, and PubMed with time restriction in 2005-2021 based on the availability of the rhizobacteria studies in Kalimantan. Therefore, the sorting article used keywords *'Rhizobacteria Kalimantan'*, *'Rhizosphere Kalimantan,' 'Nitrogen-fixing bacteria Kalimantan,' 'IAA producing bacteria Kalimantan'* and *'Phosphate-solubilizing bacteria Kalimantan.'* The total identified articles were 8085 articles. Those articles were screened to remove the double articles and continue to filter based on the title and abstract information. After the screening step, the

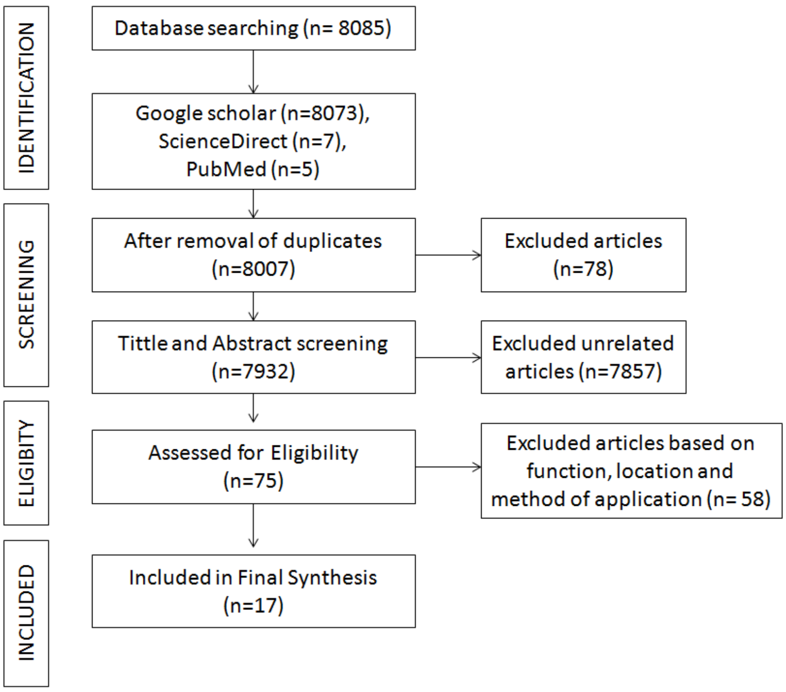

Figure 1. Flow diagram of the narrative review process

relevant topic (75 articles) was selected for further review. The articles were selected based on the comprehensive report, such as diversity, habitat, host plant, soil type, isolation and identification methods, beneficial rhizobacteria in the soil, and species names discovered from several provinces in Kalimantan. After filtering the purposive literature, seventeen articles that met the criteria were included in this systematic review flowchart (Figure 1).

Results and Discussion

The distribution of rhizobacteria in Kalimantan

The distribution of rhizobacteria in Kalimantan spread in various regions (Figure 2). For example, in the South Kalimantan, the distribution comes from several sources: acid peatland soil, sulfuric acid soil, sandy clay soil, grazing and ungrazing areas, sterile soil from critical land, and tidal swamp soil, sulfuric acid soil. However, all existing distributions are dominated by sources derived from sulfuric acid soil. Mubarik [16] stated that the soil has a low pH (pH 5-5.5), causing reduced soybean production. Hence, Tenggamus and Anjasmoro (the soybean cultivars) could be associated with symbiosis rhizobacteria such as *Bradyrhizobium japonicum* for the alternative. Hashidoko[17] reported the sulfuric acid soils used to shift agricultural land release most of the Al^{3+} with a low pH. The utilization of local rice was tolerant to acid-sulfuric soil and promoted rice growth such as *Sphingomonas rose*, *S. adhaesiva*, *S. parapaucimobilis*, *S. melonis*, *Sphingomonas* sp., and *Alcaligenes* spp.

Interestingly, Su [18] revealed that rice cultivation without fertilizers showed that the nitrogen-fixing bacteria increase local rice productivity. The most common species found in the rhizosphere and rhizoplane is *Burkholderia* spp. In addition, Purnomo [19] reported that local rice varieties were used due to rhizobacteria's capability to adapt to acidic soil conditions and unpredictable water levels. The isolates from local rice rhizosphere, such as the variety of Siam Ubi, identified the *Streptocidrophilus jiangxiensis*, *Streptomyces* sp. *Curtobacterium flaccumfaciens*, *Ralstonia picketsii, and Microbacterium esteroromaticum* as indigenous rhizobacteria. Meanwhile, *Nitrosospira* sp. was identified as a rhizobacteria-Siam Puntal interaction from Siam Ubi. The rhizobacteria group, *Burkholderia* spp., can solubilize insoluble P in various rice varieties.

According to Yuniarti [20], sulfuric acid soil's sulphide impacts soil health, plant growth, and productivity. Therefore, rhizobacteria resistant to acidification soil level was applied to enhance rice growth. The rhizobacteria were isolated from various plant rhizosphere and roots, such as *Melastoma* sp., *Eleocharis dulas, Stochlaenapacistris* sp., *Melaleuca leucadendra*, and local rice. As a result, the rice can grow properly in acidic soil with rhizobacteria as a mediator. These acidic soils sometimes had *Sphingomonas rosa* in the rhizosphere and rhizoplane, such as *Sphingomonas*

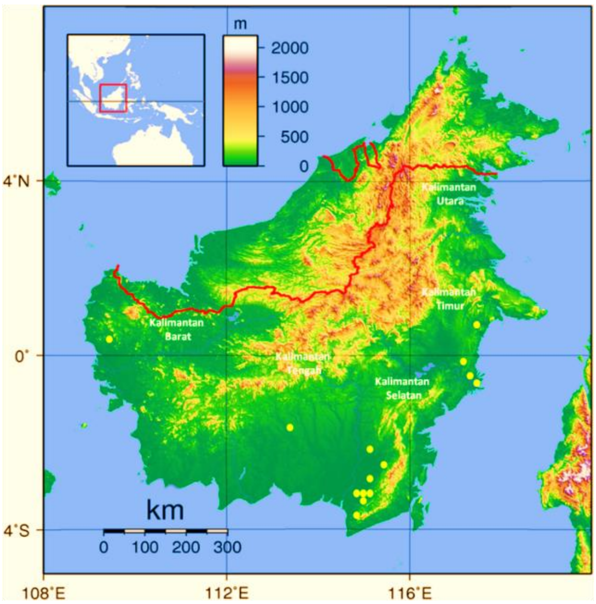

Figure 2. In the map of rhizobacteria distribution study, the yellow spots were the site of rhizobacteria sampling in East, West, Center, North, and South Kalimantan

rosa EC-K013[21]. Another one is *Burkholderia cepacia* isolated from *Melastoma malabathricum* rhizosphere. Another soil type, a tidal swamp land, also had low pH and was composed of high sulphur; applying *Azotobacter* sp. and *Azospirium* sp. was to improve rice cultivation. That method was effective in increasing rice production and reducing the risk of pesticide residues [22].

Soil acidification with low-level influences plant productivity. For instance, palm oil plantation management needs to rearrange soil health. According to Sulastri [23], palm oil production decreased due to soil fertility changes affected by the utilization of chemical pesticides. After finding the main problem, the way to tackle the issue was to improve the rhizobacteria colony, nitrogen-fixing and phosphate-solubilizing rhizobacteria. Both rhizobacteria can assist the palm root in absorbing the ammonia and phosphate with ease. The research showed the relationship between rhizobacteria altered the dynamic of soil characteristics, microbe communities, and functional properties and remediated pollutant contamination in the soil [24]. For example, reforestation was implemented by mediating plants and rhizobacteria. The vast grass (Elephant grass) synergizes with phosphate-solubilizing rhizobacteria to reduce the metal contamination in soil. In the case of the mineralization process in soil, Sato[25] also revealed that *Melastoma malabathricum* L., as a local plant, was able to accumulate the aluminium-contaminated soil; they can adapt in nutrient-poor and tolerant in sulfuric acid soil. Those plant potentials can interact with indigenous rhizobacteria due to their capability to supply the fixation nitrogen and mineralization in soil.

The distribution in West Kalimantan comes from grasslands and tropical peat soils. Kusumawati [26] reported that greens have a wide distribution area, *Imperata cylindrical*, which grows on low organic matter content, acid, and poor soil fertility, limited nutrients such as phosphate and nitrogen. Mining nitrogen fertilizers were used to improve land productivity, but they damaged the environment in the long term. Otherwise, indigenous rhizobacteria can increase soil productivity, such as *Rhizobium*-like strains, *Azotobacter*-like strains, *Azospirillum*-like strains, and phosphate solubilizer strains. In other soil types, peat soil is significantly dominant in tropical swamp forests. However, that forest was occurred by deforestation and forest fires, decreasing the organism diversity. Rahman [27] isolated the rhizobacteria around the peat soil to stabilize the soil nutrients and help grow tree nurseries and saplings using dipterocarp tree seeds. The species, such as *Serratia* sp. CKG7, *Burkholderia* spp. CK28 and CK43, and *Citrobacter* sp. CK49 enhanced soil nutrient input and solubilized some secondary minerals in the soil.

The rhizobacteria spreading in East Kalimantan was isolated from several sources, for instance, on hills, near rivers, and in the oil palm plantation. According to Anggrainy [28], investigating the nitrogen-fixing bacteria (NFB) in several ecosystems resulted in the development of soil health and could provide nutrients for maize growth. Hence, utilizing biological fertilizers containing microbes provided certain nutrients for plants. On the other hand, Anggrainy [29] reported that many factors affected soil health, such as the mineralization of organic matter and the amount of SBM (Soil Beneficial Microbes). Moreover, Suliasih[30] revealed rhizobacteria identification as an agent of biofertilizers, bioremediation, and biopesticides. In contrast, in West Kalimantan, the rhizobacteria were isolated from rubber, secondary forest, and shrub. Exopolysaccharide (EPS)-producing rhizobacteria was higher in sandy soil. According to Harahap[22], those EPS-producing rhizobacteria can assist soil aggregation and fulfil soil nutrients. This research reported the rhizobacteria were *Klebsiella* sp., *Klebsiella pneumonia*, and *Burkholderia anthina*.

The plant-beneficial Rhizobacteria role in critical land

Rhizobacteria can associate with roots in plants, forming a symbiotic relationship that significantly helps the plant's growth. Various species of rhizobacteria can carry out many metabolic processes. Their role plays were reported from 2005 until 2021 (Table 1), showing that nitrogen-fixing rhizobacteria were found in most study areas. This group of rhizobacteria can fix nitrogen using nitrogenous enzymes. Hence, the ammonia can be absorbed quickly to transport to another cell system in the plant's shoot. According to Hashidoko[17][21], the nitrogen-fixing bacteria (NFB) can investigate through a sphingomonad-detecting DNA array to monitor *Sphingomonas* sp. and discover their gene (*nif*H) using cloning-sequencing in the acid sulphate soil[25]. The NFB, such as *Sphingomonas* sp., inoculates or bio augments plants by binding to N_2 in the surrounding environment [17]. It is an attractive alternative to replace traditional nitrogen fertilization practices with low-cost and eco-friendly[31]. Regular nitrogen fertilization leads to the cause of the abundance of rhizobacteria changing[32]. On the other hand, free-living NFBs were also investigated from degraded and tidal swamp soil[14][20], enhancing grazing oil palm plantations and detecting the bacteria abundance on various phytomicrobiome. Meanwhile, Razie [22] and Su [18] reported that the NFB could improve rice cultivar production in acid-sulphate soil. The NFB had a high density in natural forest and oil palm plantations (nonproduction, 2009 year and 2011 year) which improved maize growth and biomass[28].

The second group of rhizobacteria was IAA-producing bacteria, which can primarily promote plant growth by increasing hair roots and elongating lateral roots to enhance water and nutrients in the soil. In the dipterocarp rhizosphere, an endemic plant in East Kalimantan, IAA-producing rhizobacteria were abundant[27]. Moreover, the inoculant, such as *Bradhyrhyzobium japonicum*, was treated on soybean in an acid peatland soil, showing that *B. japonicum* improved soybean growth and yield [16]. It was related to *B. japonicum* could be a growth regulator, such as natural *indole 3-acetic acid* (IAA), that can stimulate a rapid response to cell elongation and cell division and differentiation in plants[33]. Besides, IAA-producing bacteria also was applied to rice as biofertilizer in acid soil sulphate [20].

The third group was mineralizing or solubilizing bacteria. The rhizosphere's mineralization was categorized into primary and secondary minerals (Figure 3). Based on this review, the bacteria can mineralize or soluble the P, Ca, $CaPO_4$ and $C_6H_6(OPO_3H_2)_6$. The rhizobacteria were isolated from local rice such as siam Ubi and siam Puntal [19], elephant grass [24], *Imperata cylindrica* [26], dipterocarp and seedling [34, 27], degraded soil from natural forests and oil palm plantations [28] and local plant *Mimosa pudica* [30]. Khan [35] reported phosphate solubilizing rhizobacteria enhancing nutrient uptake and solubilizing plants' P-availability. In the natural environment, most bacteria can release phosphorus effectively through the mineralization process [36]. Phosphate solubilizing rhizobacteria also provide micronutrients (Fe, Ca, and Pb). This micronutrient is obtained from the impact of orthophosphate metabolism in rhizobacteria by releasing lead into the environment and making high pH and low alkalinity water [37][38].

The minor rhizobacteria groups were ACC deaminase-producing, exopolysaccharideproducing, and cellulose-degrading. However, each gro up has an essential function in the rhizosphere and plants. For instance, ACC deaminase-producing bacteria and EPS-producing bacteria were pro cesses with IAA-production that contributed to rootelongation and maintained soil aggregation,

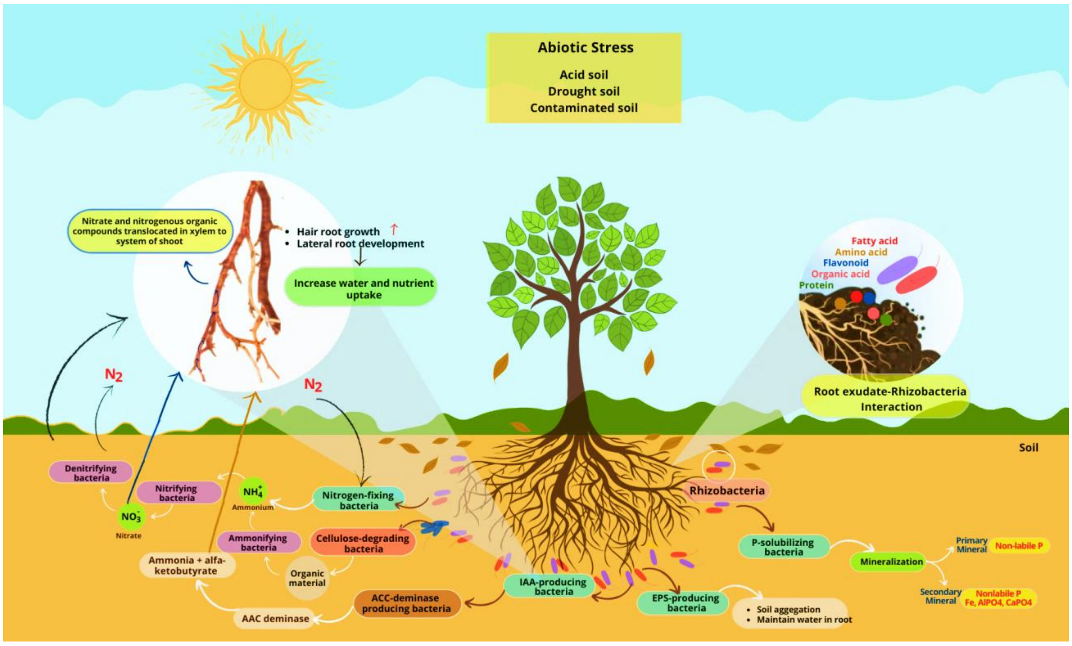

Figure 3. The mechanism of the rhizobacteria group in enhancing plant growth and nutrient inputs

Table 1. The rhizobacteria from several plant rhizosphere in Kalimantan

Kalimantan	Source	Host plant/ Vegetation	Objectives	Identified *Rhizobacteria*	Plant-beneficial rhizobacteria	Result	References
South	Acid Peatland soil	Soybean	To determine the influence of acid-Al tolerant *B. japonicum* formula using peat as a carrier on soybean.	*B. japonicum*.	IAA Production	The inoculant of acid-aluminium tolerant *B. japonicum* improved the soybean growth and yield in acid soil.	[16]
South	Acid sulphate soil	*Melastoma malabathricum*	To investigate the rhizosphere microflora of local rice and its ecological role.	*Sphingomonas* sp.	Nitrogen-fixing	The investigation of microfloral succession in the rhizosphere through a sphingomonad-detecting DNA array made it possible to monitor *Sphingomonas* sp. as a mediator in acid-tolerant plants	[17]
South	Acid sulphate soil	*Melastoma* sp., *Eleocharis-dulcis* *Stochlaenpalutris* sp., and *Melalauca leucadendra*	To determine rhizobacteria effectiveness and dark septa endophytic (DSE) improve swamp rice growth	Not Available	IAA Production	The rhizobacteria and DSE improved rice yields; hence they could be used as biofertilizers to improve swamp rice growth in acid sulphate soil.	[20]
South	Acid sulphate soil	Local rice 1. Siam Ubi 2. Siam Puntal	To identify microorganisms involved in solubilizing insoluble phosphate	1. *Burkholderia* spp. 2. *Streptacidiophils jiangxienis* 3. *Streptomyces* sp. 4. *Nitrosospira* sp. 5. *Curtobacterium falccumfaciens* 6. *Ralstonia pickettii* 7. *Microbacterium esteraromaticum*	P-solubilizing	*Burkholderia* spp. was common rhizobacteria, and rhizobacteria from local rice had specific species that could dissolve aluminium phosphate and tricalcium phosphate.	[19]
South	Acid sulphate, peat, and sandy clay	*Melastoma malabatrichum*	To investigate the diversity of diazotroph bacteria through cloning-sequencing of the *nifH* gene	Not Available	Nitrogen-fixing Diazotroph	The *nifH* gene in acid sulphate was shifted between the rhizosphere and bulk soil.	[25]

(continued)

Kalimantan	Source	Host plant/ Vegetation	Objectives	Identified *Rhizobacteria*	Plant-beneficial rhizobacteria	Result	References
South	Grazing and under-grazing area	Oil palm plantation	To determine the influence of grazing in an oil palm plantation on bacteria involved in the soil nitrogen cycle	Not Available	Diazotroph Nitrifying Denitrifying	The organic material from the cattle dung influenced the N-transforming bacteria in the grazing area of the oil palm plantation	[23]
South	Sterile soil from critical land	Elephant Grass	To examine the potential phosphate solubilizing bacteria and IAA production fungi from critical land	*Humicola* sp.	Phosphate-solubilizing	The consortium of phosphate-solubilizing bacteria and IAA-producing fungi could increase elephant grass growth	[24]
South	Tidal swamp land	Rica seedlings	To evaluate the amount of NFB (*Azotobacter* and *Azospirillum* sp.) found in tidal rice fields, the ability to fix nitrogen, and increase rice yields.	*Azotobacter* sp. and *Azospirillum* sp.	Nitrogen-fixing	The *Azotobacter* sp. and *Azospirillum* spp. Inoculation to rice cultivars could alternate the synthetic N fertilizer and improve the rice yields.	[22]
South	Tropic acid sulphate soil	Local rice	To determine the contribution of nitrogen-fixing bacteria in acid sulphate paddy soil in rice fields without fertilizer	*Burkholderia*	Nitrogen-fixing	The beneficial interaction of rice and free-living nitrogen-fixing bacteria was reduced due to acid soil (pH<3.5) with an additional 500 µM Al.	[18]
Central and South	Acid-tolerant local rice	*Melastoma malabahricum*	To investigate the productivity and diversity of free-living N_2-fixing bacteria	*Sphingomonas rosa* *Burkholderia cepacia*	Nitrogen-fixing	*Sphingomonas rosa* was acid-susceptible or highly absorbed into the soil particles.	[21]
Central	Grassland	*Imperata cylindrica*	To isolate beneficial microbe using direct and enrichment methods on specific media and screen these isolates for PGPR traits of Rhizobium-like strains	Rhizobium-like strains *Azotobacter-like strains* *Azospirillum-like strains* *Phosphate solubilizer-like strains*	IAA Production Ca-P solubilizing Releasing orthophosphate Nitrogen-fixing Cellulose-degrading	The enrichment method on specific media screened for IAA, phosphate solubilizing, nitrogen-fixing and cellulolytic activity was effective.	[26]
Central	Peat soil	Dipterocarp	To determine the rhizobacteria isolated from dipterocarp to solubilize and mineralize P and its potency to support plant growth in degraded land	*Erwinia* sp. *Rhizobium* sp. *Roseateles* sp. *Enterobacter* sp.	$Ca_3(PO_4)_2$ inorganic solubilizing $C_6H_6(OPO_3H_2)_6$ mineralizing	The quantification of P-solubilizing and mineralizing was important for primary screening. The potential P-solubilizer was height in the lowland dipterocarp forest	[34]

(continued)

Kalimantan	Source	Host plant/ Vegetation	Objectives	Identified *Rhizobacteria*	Plant-beneficial rhizobacteria	Result	References
Central	Tropical peat soil	Dipterocarp seedling	To examine polyphenol-degrading and Fe-chelating, and IAA-producing rhizobacteria	*Serratia* sp.CK67 *Burkholderia* spp. CK28 and CK43 *Citrobacter* sp. CK42	IAA production Fe-solubilizing	Salkowski's reagent test could screen functional rhizobacteria in peatland ecosystems.	[27]
East	De-graded land	Natural forest Oil palm plantation	To examine the soil health and soil microbes' richness in the conversion of land	Not Available	Phosphate-solubilizing Nitrogen-fixing	The natural forest showed a higher rhizobacteria population, indicating the soil's fertility. Otherwise, the low population of rhizobacteria due to the soil ecosystem degraded.	[28]
East	Hill and near river	*Mimosa pudica*	To characterize the activity of PGPR bacteria isolates, determine their potency to stimulate soybean growth, and identify the species of bacteria	*Klebsiella* sp. InaCC B833 *Mangrovibacter plantisponsor* InaCC B841	Nitrogen-fixing ACC deaminase IAA Production Cellulolytic activity Phosphate Solubilizing PME-ase *nifH*-gene	The rhizobacteria characterized and screened increased the plant yields in the greenhouse assay.	[30]
East	Upper ground surface	Primary forest Secondary forest Fallow land Palm oil plantation (2009-2011)	To evaluate the ability of nitrogen-fixing bacteria to produce nitrogenase, phytohormone, and nitrogen-fixing test using maize as plant indicator.	Not Available	Nitrogen-fixing IAA production Nitrogenase	The nitrogen-fixing bacteria were able to produce different nitrogenase and phytohormone. Five selected isolates were assessed and applied to maize which showed significantly increased growth and dry weight.	[29]
West	Sandy soil	Rubber Secondary forest Shrubs	To gain the bacteria that have a high potential for exopolysaccharide-producing bacteria	*Klebsiella* sp., *Klebsiella pneumonia*, and *Burkholderia anthina*	Exopolysaccharide-producing	The group of rhizobacteria isolates increased oil aggregate stability from 30.611% to 47.87%	[64]

respectively (Figure 3). Meanwhile, the cellulose-degrading bacteria broke down the organic material, such as fresh or dry litter and fire residues in the soil used for plant nutrients. Moreover, rhizobacteria also affect the growth and division of plant cells[26], such as *Azetobacter* sp. and *Azospirillium* sp., which also degrade cellulose. Cellulose degradation is a biological process controlled and processed by enzymes of the cellulase system. As a result of this cellulolysis process can release bioethanol or natural biofuels[39].

The rhizobacteria-plant rhizosphere interaction mechanism

The rhizosphere is a complex microhabitat that integrates a network of soil, plant roots, microbes[37], and earthworms[11]. This zone surrounding the plant's root is directly influenced by plant exudates[9][40] that have a direct impact on plant growth[37] plant health, and productivity[41]. The rhizosphere is also influenced by plant roots that produce several compounds, including amino acids, unrefined sugars, organic acids, flavonoids, proteins, and fatty acids[42] [43]. Those rhizobacteria activities can mediate plant nutrient uptake, growth, and production [44].

The rhizobacteria can convert various plant-unavailable essential nutrients such as nitrogen, phosphorus, zinc, calcium, and others into easily absorbed by plants[37]. Nutrient availability depicts the rhizosphere as a micro-ecosystem in which all residents compete to colonize and develop an ecological niche to inhabit. This condition triggered the rhizobacteria to survive in several biological strategies to succeed in extreme conditions[40]. These rhizobacteria activities contribute to root exudates' composition, quality, and quantity changes that reconstruct their structure community in the rhizoshere[7]. The beneficial rhizobacteria not only stimulate plant growth but also inhibit the pathogen from spreading to the plant[45], mineralize the organic pollutants[46], and remediate the heavy metal[47].

In environmental stress, the rhizobacteria can accumulate the heavy metal in specific mechanisms such as nitrogen fixation and the formation of a siderophore. In addition, those rhizobacteria can solubilize and restore ions in the soil by producing metal chelating to enhance soil-bound bioavailability of iron; hence the plant can survive and grow in heavy metal-contaminated soil[48]. Meanwhile, rhizobacteria assist plant growth in drought stress, height salinization, and low pH by biofilm formation such as EPS[49]. Furthermore, the EPS-producing rhizobacteria influence the aggregation of soil formation, humification, increasing water capacity for retaining, root nodulation, enrichment of microbial diversity[50][51], and improving rhizobacteria colonization[52].

This review showed several problems with soil pH, the drought of soil, and contaminated soil by pesticides or heavy metals. Some researchers observed the indigenous rhizobacteria from the soil in Kalimantan on various vegetation and found the primary forest showed the rhizobacteria population more abundance than other soil sources[29]. It was indicated that the diversity and richness of rhizobacteria were influenced by either biotic or abiotic factors in the soil environment[53]. Generally, based on this study, the rhizobacteria could be mediated to tackle soil acidification, drought stress, and removing pesticides and heavy metal compounds.

Unstable soil health is crucial to improve plant growth. For example, three significant toxicities in acidic soil are Al^{3+}, $Mn^{2+,}$ and H^{+}. The Al toxicity affects the plant, such as root growth and cell division are inhibited, the cytoskeleton is changed [54], and nutrient uptake is reduced[55]. In another case, plant deficiency of P shows the symptoms such as stunting, dark green leaves, late maturity, and purpling of stems[55]. Moreover, the drought soil is caused insufficient water to leach the salt solubilization, which has a high HCO_3^- concentration. This phenomenon may result in organic acid accumulation in root cells to stop the elongations[55]. Meanwhile, the contaminated soil of pesticides consists of xenobiont, organophosphate, and carbamate that contribute to reducing rhizobacteria activity, influencing the supplying nutrient to the plant to be not optimum. On the other hand, the pesticide residue might translocate inside the cell plant through a systemic mechanism.

Generally, the soil characteristics of Kalimantan are dominated by acidification soil due to swamp and peat soil. That soil type is high in sulphate, low pH (3.5), C/N ratio height, and rainfall. According to Badan Pusat Statistik of Kalimantan, the rainfall frequency level was moderate until high at 100.0-485.5 mm in 2002-2019[57][58][59][60]. Forest fires in the same year range highly occurred[61] that caused acid rain in the West, South, and Center of Kalimantan containing toxic compounds such as CO_2, N_2O, NO_X, and CO[62]. Meanwhile, the West and East of Kalimantan soil were affected by pesticide utilization; hence, regions contained low pH and drought soil performance. Unlocking the role of rhizobacteria is a promising strategy to alternate this problem. Plant-beneficial rhizobacteria are classified based on their roles, such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and IAA-producing bacteria. Since they can provide several nutrients for recovering soil immunity, plant fitness, and improving plant production, because of their positive effects on the soil environment, including crop residue degradation, soil organic matter synthesis, breakdown of soil organic matter, nutrient fixation, and solubilization are considered to assess their natural product to apply on plants [63]. The rhizobacteria's beneficial plant mechanism can be illustrated (Figure 3).

This review has already portrayed the presence of rhizobacteria with substantial potential to discover the natural product. Moreover, the diversity and abundance of rhizobacteria can change dependent on the rhizosphere of host plants, soil sources, and other biotic and abiotic factors in the environment. According to this review, the rhizobacteria have been studied in Kalimantan's soil for almost twenty years to explore rhizobacterial residence and function. Overall the research showed the unique characterization and diversity of the bacteria; however, using the metagenomic approach is necessary to gain a comprehensive understanding rather than only using the conventional technique. In the future, advanced technologies such as nanoparticle, proteomic, metabolomic, and engineering rhizobacteria can contribute to explaining the rhizobacteria-rhizosphere-plant interaction. Hence, the complexity of rhizobacteria's crucial roles can easily be explained.

Conclusion

The exploration of rhizobacteria on several plants in Kalimantan's soil described the extraordinary potency of beneficial rhizobacteria. However, their activities in the environment were dependent on biotic and abiotic factors. Most of the region of Kalimantan soil occurred by acidic soil, while other zones suffered from drought stress and the long-term effect of contaminated soil. This overview of studies concluded that the PGPR as beneficial rhizobacteria could tackle the main abiotic problems in Kalimantan soil. Consequently, the bacteria of fixation nitrogen, solubilizing phosphorus, and IAA production were discovered by conventional isolation on a molecular approach. Hence researchers applied indigenous rhizobacteria inoculant to improve plant growth and enrich nutrient uptake in the soil. Further, regarding these advantages, developing rhizobacteria as a natural product, such as a biofertilizer, is needed; however, there are many steps to achieve that goal. Therefore, the potency of consortium from indigenous rhizobacteria species is necessary to investigate deeply through advanced technology.

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