



Review

From Lab to Farm: Elucidating the Beneficial Roles of Photosynthetic Bacteria in Sustainable Agriculture

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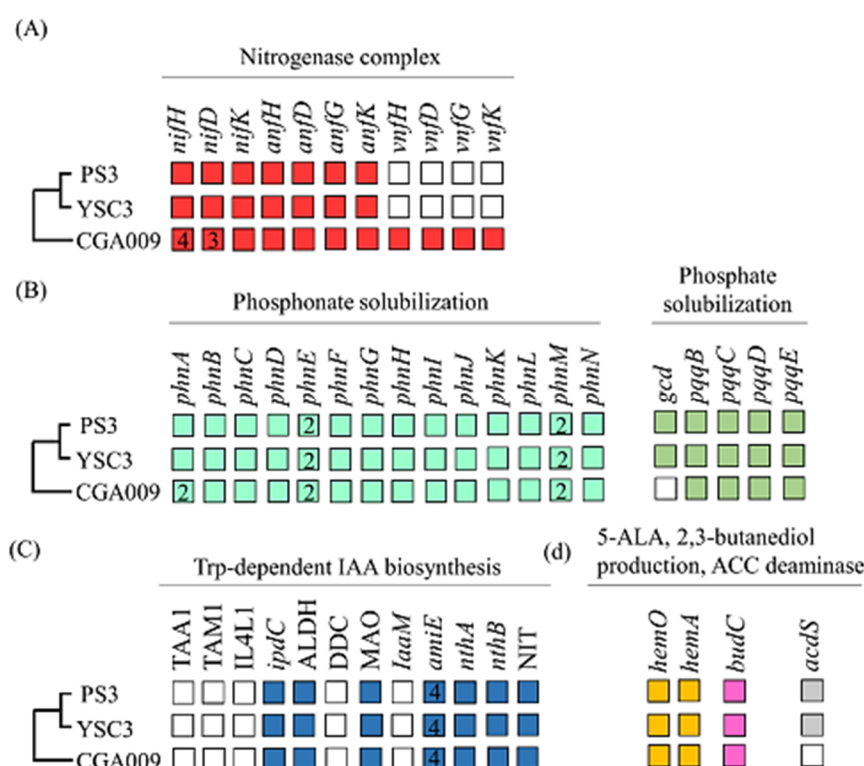
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Supplementary Materials



Supplementary Figure S1. Genes potentially related to plant growth promotion and biofilm formation in different strains of PS3, YSC3, and CGA009. An overview of 150 genes showing their presence (colored) and absence (empty) of (A) nitrogenases, (B) (C) phosphate solubilization, Trp-dependent IAA biosynthesis (D) 5-ALA, 2,3-butanediol production, ACC deaminase. Multicopies of genes are labeled by their copy number inside the filled squares. TAA1, tryptophan-pyruvate 155 aminotransferase; TAM1, tryptophan aminotransferase; IL4L1, amino-acid oxidase; 156 ALDH, aldehyde dehydrogenase; DDC, aromatic amino acid decarboxylase; TSO, 157 tryptophan side-chain oxidase; MAO, monoamine oxidase; NIT, nitrilase [40].

Supplementary Table S1. Beneficial effects of PNSB on different crops. Most of the information listed below was adapted from Table 1 and Table 2 of Sakarika et al., (2020) [39].

No.	Reference	Country	PNSB	Applica- tion Method	Dosage	Crop	Growth Conditions	Beneficial effect
1	Kobayashi and Haque (1971)	Japan	<i>R. capsulatus</i>	Irrigation	PNSB powder	Rice variety Kyoto Asahi	Pot	Enhanced grain number per ear by 32%
2	Kobayashi and Tchan (1973)	Japan, Australia	Phototrophic bacteria	Irrigation	Diluted solution	Citrus (10 years old)	Field	Increased fruit weight and sugar and carotenoid contents
3	Elbardy and El-banna (1999)	Egypt	<i>R. capsulatus</i> DSM155	Irrigation	2.2×10^8 CFU/mL of suspension into 60 mL nutrient solution	Rice cv. Giza 159, 171, 176, 181	Hydroponic	Improved aerial part by 47–100% Enhanced N content by 45–78%
4	Elbardy et al., 1999b	Egypt	<i>R. capsulatus</i> DSM155	Dipping	10^8 CFU/mL suspension mixed with 10% (w/v) gum arabic 0.05 M phosphate buffer (pH 7.0) mixed with 10% (w/v) gum arabic	Rice variety Giza 177	Pot	Increased straw yield and grain yield by 9–33% Increased panicle length, panicle weight, and panicle number
5	Harada et al., 2005	Japan	<i>R. palustris</i> KN122	Irrigation	10 g rice straw with 1.7×10^{11} MPN/pot (day 0) 5.0×10^9 MPN/pot (day 43) 5.1×10^{10} cells/pot (day 86)	Rice variety Nipponbare	Pot	Increasing grain yield per pot by 21–29% Increased plant height and tiller number
6	Koh and Song (2007)	China	<i>R. palustris</i> KL9 and BL6	Irrigation	4×10^9 cell suspension (daily for 8 weeks)	Tomato	Petri dish	Increased dry mass of seedlings Increased the root and shoot lengths of germinated seedlings by 123.5% and 54%, respectively
7	Lee et al., 2008	Korea	<i>R. capsulatus</i> KL9 and BL6	Dipping	One application of 5×10^7 cells	Tomato	Pot	Increased fresh weight by 97% compared with that of the control Increased lycopene content and vegetative growth (root and shoot)
8	Kondo et al., 2010	Japan	<i>R. sphaeroides</i>	Irrigation (split)	2.5–1.25 g cells	Tomato	Field	No significant difference in fruit weight but increased contents of ascorbic acid, malic acid and phosphoric acid in fruit
9	Eldin and El-banna (2011)	Egypt	<i>R. sphaeroides</i> DSM155	Irrigation	10^8 CFU/mL cell suspension with 10% of gum arabic	Rice cv. Giza 177	Field	Improved grain yield up to 66% Increased reproductive parameters in paddy

10	Yin et al., 2012	China	<i>PSB</i>	Foliar spraying	2.0×10^9 CFU/mL twice per week	Chinese dwarf cherry	Hydroponic (drought stress)	Significant accumulation of fresh weight, leaf area and photosynthetic rate Induced the activities of superoxide dismutase (SOD) and ascorbate peroxidase (APX)
11	Wu et al., 2013	China	<i>Rhodopseudomonas</i> sp. ISP-1	Foliar spraying Irrigation	Foliar spraying (F): 2.4×10^{12} CFU (total) Soil irrigation (S): 3.0×10^{12} CFU (total) Foliar spraying and soil irrigation (F+S): 2.7×10^{12} CFU (total)	Sweet leaves	Pot	Increased the plant yield in all treatments and increased the chlorophyll content, shoot biomass and stevioside content significantly in the foliar with spray treatment.
12	Kang et al., 2014	Korea	<i>R. sphaeroides</i> KE149	Irrigation	5-mL cell suspensions (1×10^6 CFU/mL)	Cucumber	Pot (water lodging stress)	Increased root length, shoot fresh weight, shoot dry weight, and chlorophyll content via secretion of indole acetic and organic acids Enhanced on gibberellin content in plant Reduction on abscisic acid content in cucumber
13	Wong et al., 2014	Taiwan	<i>R. palustris</i> PS3 and YSC3	Irrigation	10^6 CFU/g per week	Maruba santoh	Pot	PS3 and half the normal amount of fertilizer produced the same plant growth potential as 100% of the normal amount of fertilizer
14	Yang et al., 2014	China	<i>Ru. gelatinosus</i>	Irrigation	Adjust bacterial concentration to an OD ₆₀₀ of 0.5 and 10 mL inoculated into soil	Tomato	Field	Increased agricultural traits and antioxidant value of tomato
15	Miao et al., 2014	China	Photosynthetic bacteria (PSB)	Foliar spraying	1×10^9 – 4×10^9 CFU/mL	Yellow-skinned watermelon	Field (low temperature stress)	Decreased the decomposition of chlorophyll and antioxidant enzymes to protect the membrane system under low temperature stress
16	Ge and Zhang, 2015	China	PS21(<i>Rhodopseudomonas</i> sp., <i>Rhodospirillum</i> sp.)	Irrigation	1×10^7 CFU/mL	Wheat	Pot (tetrabromobisphenol A stress)	Increased soluble sugar content, soluble protein content, SOD, CAT and POD activities Decreased MDA content in wheat
17	Hsu et al., 2016	Taiwan	<i>R. palustris</i> PS3 and YSC3	Irrigation	10^6 CFU/mL per week	Maruba santoh Cuiyu cabbage	Hydroponic	Increased the number of consumable leaves by 28% and reduced the nitrate content in Chinese cabbage Increased the number of consumable leaves by 40% and reduced the nitrate content in Cuiyu cabbage

						Crinkle garden lettuce	Increased plant weight by 16% and reduced the nitrate content in lettuce
18	Kantha et al., 2015	Thailand	<i>R. palustris</i> TN114, PP803, and TK103	Irrigation	One application every two weeks of 10^8 cells/gram with rice husk ash and rice straw (vegetative growth)	Rice (Thai jasmine KDML105)	Saline field: Increased grain yield by 5–8% (inoculated with PP803 and TK103) Organic field: Increased grain yield by 30–48% when inoculated with TN114, TK103 and PP803 compared with the control
					One application per week of 10^8 cells/gram with rice husk ash and rice straw (reproductive and maturation stages)		
19	Kantachote et al., 2016	Thailand	<i>R. palustris</i> TN114 and PP803	Root dipping	Immerse seedlings in culture supernatant for 12 hours	Rice	Pot: Increased fresh and dry weights by up to 70% in both saline and normal conditions (inoculation treatment)
20	Xu et al., 2016	China	<i>R. palustris</i> sp.	Irrigation	Irrigate <i>Stevia</i> seedlings with 10^7 CFU/mL x 100 mL inoculant on 60th, 67th, 74th, and 81st day after emergence	Sweet leaf	Field: Increased biomass slightly but not significantly
21	Lee et al., 2016	Taiwan	<i>R. palustris</i> PS3	Irrigation	Storage formulated inoculant applied into 300 g of soil per week	Maruba santoh	Pot: Promoted fresh and dry weight of shoot by 40–56%
22	Batool et al., 2017	Pakistan	<i>R. palustris</i> CS2 and SS5	Seed bacterization	Adjust bacterial concentration to an OD ₆₀₀ of 0.5 and dip seeds in bacterial inoculum for 15–20 minutes	<i>Vigna mungo</i>	Pot (Arsenic stress): Beneficial bacteria help to remediate soil containing arsenic; plant shoot and root lengths increased up to 12–24%.
23	Su et al., 2017	China	<i>R. palustris</i> GJ-22	Foliar spraying	Apply 6×10^7 CFU/mL solution to the leaves	Tobacco	Pot: Improved on IAA production and ISR response Increased the number of first-class tobacco leaves by 27–40% Enhanced seed germination rate
24	Nookongbut et al., 2018	Thailand	<i>R. palustris</i> C1	Irrigation	1×10^8 cells/mL (inoculation every week for 30 days)	Rice (HomNil and PathumThani)	Hydroponic (Arsenic stress): Reduced rice seedling loss by 50% through amelioration of arsenic toxicity in water Improved vegetative growth and increased germination index by up to 10 times compared with that in other treatments
		Australia	<i>Ru. benzoatilyticus</i> C31				
25	Imsong et al., 2018	India	Photosynthetic bacteria	Irrigation	50–150 L/ hectare of cell suspension	Broccoli	Field: Increased yield, quality and growth parameters

26	Khuong et al., 2018	Vietnam	<i>R. palustris</i> TLS06, VNW02, NNW64, and VNS89	Irrigation	5.4 x 10 ⁴ cells/g DSW in 6 kg soil/pot	Rice	Pot (low available phosphorus soil)	Increased rice grain yield by 26.5% Improved plant height, panicle length, and the spikelet/panicle ratio
27	Luo et al., 2019	China	<i>R. palustris</i> PSB06 and CGA009	Irrigation	Soak seeds for 3 h + root irrigation (15 days after transplanting)	Rice (LiangYou number 7)	Pot	PSB treatment (Irrigation): Increased rice stalks by 6–17%; Increased peroxidase (POD), and superoxide dismutase (SOD) activities CGA009 treatment (seed inoculation): Increased rice stalks by approximately 5–30%; Increased SOD activity
				Seed inoculation	Soak seeds for 3 h			
28	Ge and Zhang (2019)	China	<i>R. palustris</i> G5	Irrigation	25 mL per pot (10 ⁸ CFU/mL)	Cucumber	Pot (salt stress)	Increased shoot height, root length, and plant fresh and dry weight
29	Nookongbut et al., 2020	Thailand, Vietnam	<i>R. palustris</i> KTSSR54	Irrigation	Suspend 10 ⁸ cfu/mL (OD = 0.5) of inoculum in 3 L of tap water every two weeks	Rice	Pot	Reduced grain loss (100-grain weight) by 15–40% under field conditions with biotic stress
30	Zhang et al., 2020	China	<i>R. palustris</i> GJ-22	Foliar spraying	6.79 x 10 ⁶ or 19 x 10 ⁷ CFU/mL on 3 rd to 4 th leaf, total volume is 50 mL per pot	Potato tuber Xingjia2	Pot	Reduced late blight disease through bio-control
31	Kang et al., 2020	Korea	<i>R. sphaeroides</i> KE149	Irrigation	50 mL of cell suspension (1 x 10 ⁸ CFU/mL) for 7 days	Adzuki bean	Pot (water stress)	Decreased stress-responsive endogenous abscisic acid and jasmonic acid and increased salicylic acid Increased the levels of calcium (Ca), magnesium (Mg), and potassium (K) Increased root length, shoot length, stem diameter, biomass, and higher chlorophyll content
32	Lo et al., 2020	Taiwan	<i>R. palustris</i> sp. PS3 and YSC3	Irrigation	250 mL of modified cell suspension medium (10 ⁸ CFU/mL) into 30 L of tank containing nutrient solution per week 2 mL of modified cell suspension medium (10 ⁸ CFU/mL) into 300 g of soil per week	Cuiyu cabbage	Hydroponic Pot	Promoted shoot and root weight by 12–48%

33	Xiao et al., 2021	China	<i>R. palustris</i> sp.	Irrigation	Apply 24 g/m ² of inoculum in the tillering stage	Rice	Pot	Increased rice yields by 9.84–17.73%
34	Kang et al., 2021		<i>R. sphaeroides</i> KE149	Irrigation	10 mL of cell suspension (10 ⁸ CFU/mL)	Soybean	Pot (water logging stress)	Improved plant morphological attributes, such as root length, shoot length, and fresh biomass. Increased jasmonic acid, phenolic and flavonoids contents Enhanced the levels of endogenous phytohormones (such as abscisic acid) under water lodging conditions Decreased the levels of endogenous phytohormones (such as abscisic acid) under normal conditions
35	Hsu et al., 2021	Taiwan	<i>R. palustris</i> sp. PS3 and YSC3	Irrigation	10 ⁶ CFU/mL per week	Maruba santoh	Hydroponic	Increased cabbage fresh weight by 50% compared with that of the control Increased consumable leaf expansion and cell plate number
36	Sakpirom et al., 2021	Thailand	<i>R. palustris</i> TN110 and <i>R. gelatinosus</i> TN414	Irrigation	1 × 10 ⁸ CFU/mL; 1 × 10 ⁷ CFU/mL	Paddy	Pot	Both liquid and solid formulations increased rice growth and parameters in paddy soil compared with controls.
37	Liu et al., 2021	China	<i>R. sphaeroides</i>	Irrigation	1 × 10 ⁷ CFU/g per pot	Oilseed rape	Pot	Increased the plant total N Recruit beneficial diazotrophic rhizobacteria
38	Wang et al., 2021	China	<i>R. palustris</i> ISP-1	Irrigation	Adjust to 10 ⁸ CFU/mL and 300 L/ha of suspensions for twice, sowing and pegging stage	Peanut	Field	Increased 12.5% of total peanut yield and nutrient content in soil

Highlighted in dark grey represent the updated references not included in Sarkarika et al., 2020: #10, #12, #14, #15, #16, #21, #25, #27, #28, #29, #31, #32, #33, #34, #35, #36, #37, #38.

Supplementary Table S2. Plant growth responses to PS3 inoculation under different experimental conditions and farming systems.

Farming System	Plant Species	Application Method	Dosage (CFU/g soil)	Instructions	Inoculations	Effects
Conventional	Heading Chinese cabbage	Irrigation	10^5 – 10^6	20 mL per plant	8	yield increased by ~39%
Organic	Chinese cabbage	Irrigation	10^5 – 10^7	200 L per hectare	1	yield increased by ~43%
	Lettuce	Irrigation	10^5 – 10^7	200 L per hectare	1	yield increased by ~30%
	Sesame leaves	Irrigation	10^5 – 10^7	200 L per hectare	1	yield increased by 25–30%
	Tomato	Irrigation	10^5 – 10^7	200 mL per plant	3	yield increased by ~25% and ~38% in fruit fresh and dry weights, respectively; sugar/acid ratio increased by 45%; vitamin C and lycopene contents increased by 25%
Conventional with organic amendment	Chinese flowering cabbage (choi sum)	Irrigation	10^5 – 10^7	200 L per hectare	1	yield increased by ~27%
	Pepper leaves	Irrigation	10^5 – 10^7	200 L per hectare	1	yield increased by ~26%

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