

Supplementary figures

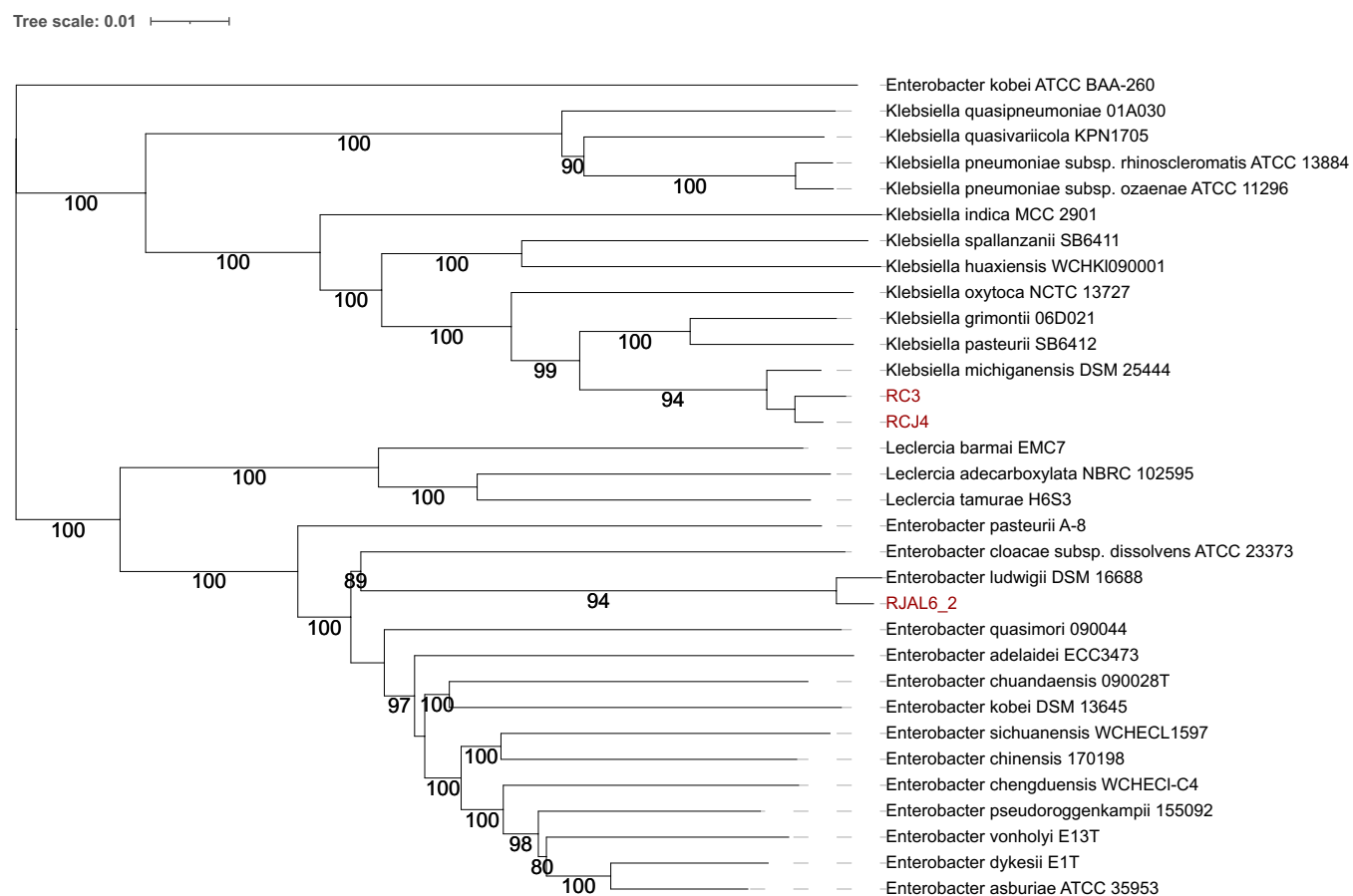


Figure 1S. Phylogenetic tree based on whole-genome sequences of the bacterial isolates RC3, RCJ4, and RJAL6_2, constructed using TYGS and visualized with iTOL. Numbers at the nodes indicate bootstrap support values (>70).

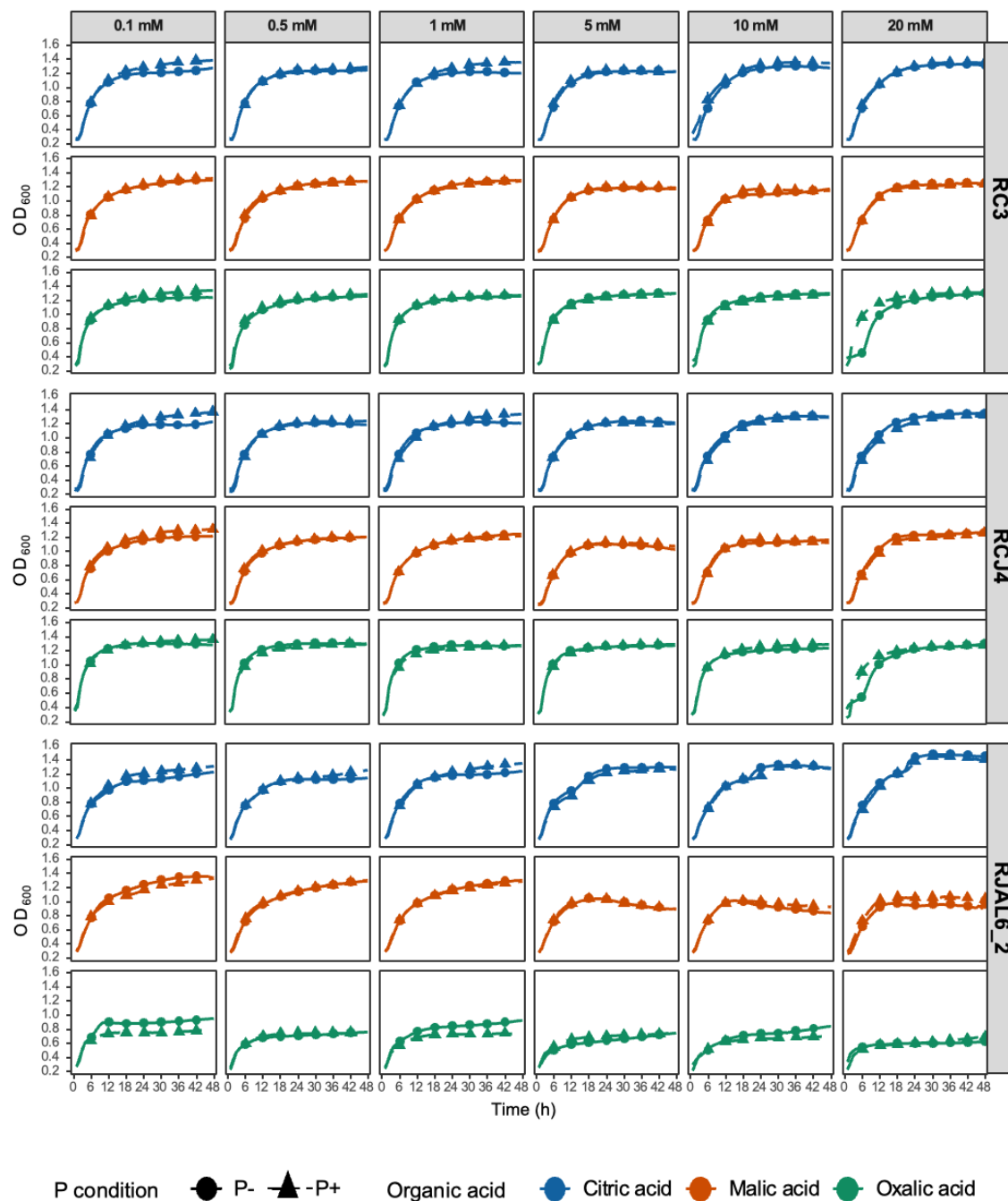


Figure S2. Growth kinetics of *K. michiganensis* RC3, *K. michiganensis* RCJ4 and *E. ludwigii* RJAL6_2 exposed to increasing concentrations of citric, malic, and oxalic acids under soluble (P+) and low soluble (P-) phosphorus conditions. Bacterial growth was monitored by OD₆₀₀ measurements over 48 h.

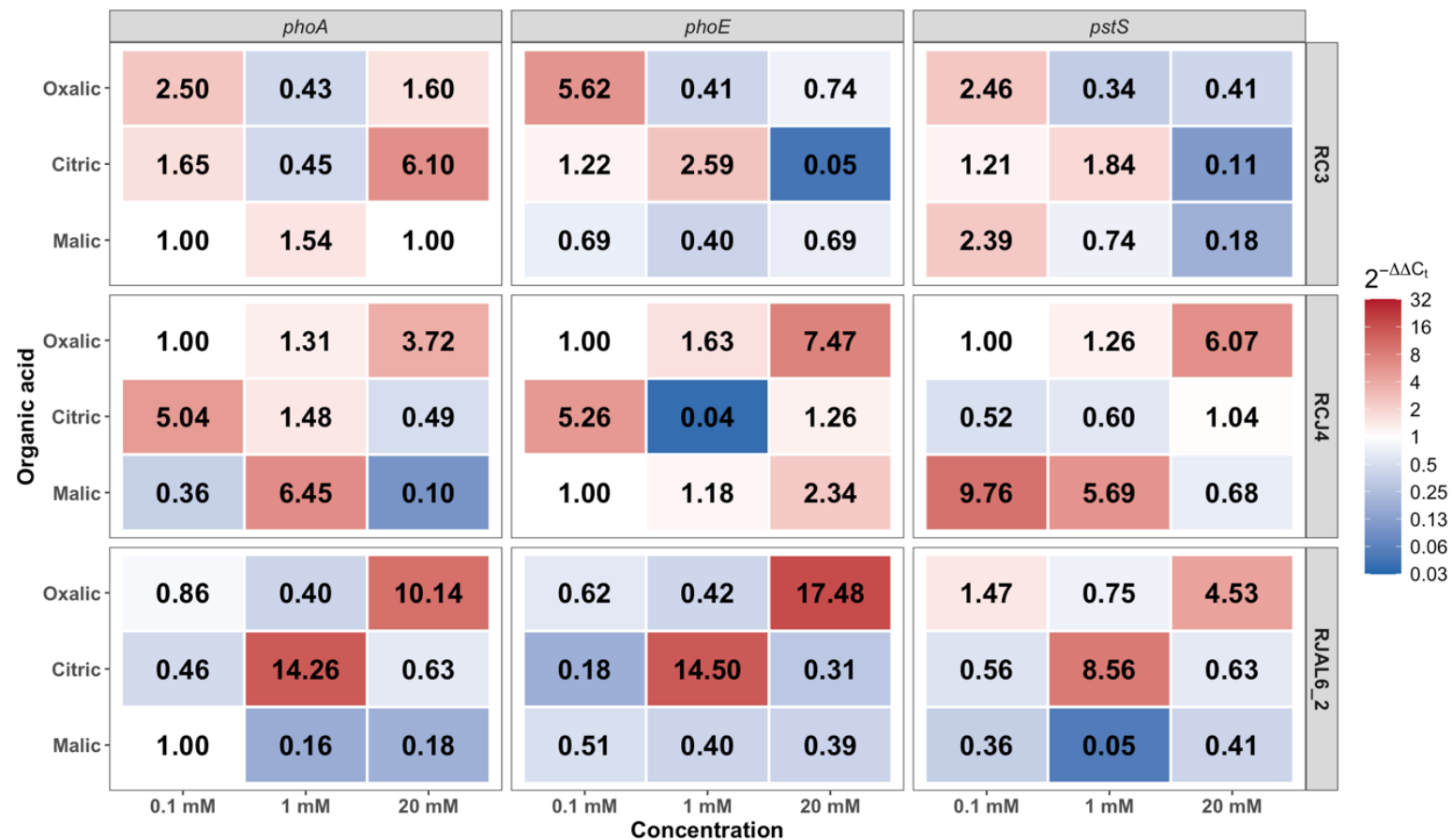


Figure S3. Heatmap showing the relative expression ($2^{-\Delta\Delta C_t}$) of the *phoA*, *phoE*, and *pstS* genes in the bacterial isolates RC3, RCJ4, and RJAL6_2 exposed to citric, malic, and oxalic acids at three concentrations under low-phosphorus (P⁻) conditions. Heatmap colors represent the relative expression values, and hierarchical clustering was performed to identify similarities among treatments. Statistical differences were determined using estimated marginal means (emmeans) following one-way ANOVA with Tukey-adjusted pairwise comparisons ($p < 0.05$).

Table 1S. Assigned codes and taxonomic identification of phosphate-solubilizing bacterial isolates based on preliminary classification, MALDI-TOF analysis, and 16S rRNA gene sequencing.

Internal Code	Previous identification	Identification with MALDI-TOF	Identification with 16S (Sager sequencing)	Whole genome Nanopore sequencing
RC3	<i>Klebsiella</i> sp.	<i>Klebsiella oxytoca</i>	<i>Klebsiella oxytoca</i>	<i>Klebsiella michiganensis</i>
RCJ4	<i>Klebsiella</i> sp.	<i>Klebsiella oxytoca</i>	<i>Klebsiella oxytoca</i>	<i>Klebsiella michiganensis</i>
RJAL6_2	<i>Enterobacter</i> sp.	<i>Enterobacter ludwigii</i>	<i>Enterobacter ludwigii</i>	<i>Enterobacter ludwigii</i>

Table S2. Growth parameters (area under the curve (AUC), maximum specific growth rate (μ), and maximum optical density (OD_{max}) of phosphate-solubilizing bacterial strains grown under different organic acid concentrations in soluble (P+) and insoluble (P-) phosphorus media.

Strain	P source	Treatment	AUC	μ	OD_{max}
RC3	P-	Citric 0.1 mM	51.62a $\pm$ 0.54	0.109b $\pm$ 0.005	1.227a $\pm$ 0.019
		Citric 0.5 mM	52.33ab $\pm$ 0.52	0.111b $\pm$ 0.006	1.243a $\pm$ 0.020
		Citric 1 mM	51.21a $\pm$ 0.37	0.107b $\pm$ 0.004	1.222a $\pm$ 0.016
		Citric 5 mM	51.65a $\pm$ 0.50	0.103b $\pm$ 0.001	1.240a $\pm$ 0.017
		Citric 10 mM	52.98bc $\pm$ 0.34	0.093a $\pm$ 0.001	1.297b $\pm$ 0.004
		Citric 20 mM	53.65c $\pm$ 0.00	0.089a $\pm$ 0.000	1.327b $\pm$ 0.002
		Malic 0.1 mM	52.93c $\pm$ 0.32	0.087a $\pm$ 0.001	1.271c $\pm$ 0.007
		Malic 0.5 mM	52.13bc $\pm$ 1.13	0.084a $\pm$ 0.001	1.267c $\pm$ 0.031
		Malic 1 mM	52.32c $\pm$ 0.80	0.081a $\pm$ 0.001	1.277c $\pm$ 0.022
		Malic 5 mM	50.23b $\pm$ 0.72	0.104b $\pm$ 0.005	1.190b $\pm$ 0.025
		Malic 10 mM	48.14a $\pm$ 0.63	0.104b $\pm$ 0.005	1.132a $\pm$ 0.019
		Malic 20 mM	52.22c $\pm$ 0.18	0.098b $\pm$ 0.004	1.254c $\pm$ 0.002
		Oxalic 0.1 mM	53.40ab $\pm$ 0.75	0.133c $\pm$ 0.011	1.230a $\pm$ 0.025
		Oxalic 0.5 mM	52.45ab $\pm$ 0.08	0.106b $\pm$ 0.005	1.235a $\pm$ 0.004
		Oxalic 1 mM	53.94ab $\pm$ 0.46	0.131c $\pm$ 0.009	1.246a $\pm$ 0.017
		Oxalic 5 mM	55.30b $\pm$ 0.54	0.127c $\pm$ 0.007	1.284a $\pm$ 0.018
		Oxalic 10 mM	54.80b $\pm$ 0.41	0.120bc $\pm$ 0.006	1.274a $\pm$ 0.017
		Oxalic 20 mM	50.60a $\pm$ 3.09	0.069a $\pm$ 0.001	1.296a $\pm$ 0.078
RCJ4	P-	Citric 0.1 mM	50.40a $\pm$ 0.57	0.107c $\pm$ 0.004	1.192a $\pm$ 0.012
		Citric 0.5 mM	50.90ab $\pm$ 0.12	0.106c $\pm$ 0.000	1.206ab $\pm$ 0.003
		Citric 1 mM	51.30b $\pm$ 0.06	0.104c $\pm$ 0.002	1.218b $\pm$ 0.004
		Citric 5 mM	51.27b $\pm$ 0.40	0.094b $\pm$ 0.003	1.238c $\pm$ 0.006
		Citric 10 mM	53.21c $\pm$ 0.26	0.085a $\pm$ 0.001	1.305d $\pm$ 0.006
		Citric 20 mM	54.21d $\pm$ 0.08	0.086a $\pm$ 0.000	1.337e $\pm$ 0.001
		Malic 0.1 mM	49.85d $\pm$ 0.13	0.087b $\pm$ 0.001	1.196cd $\pm$ 0.002
		Malic 0.5 mM	48.97bc $\pm$ 0.46	0.086b $\pm$ 0.002	1.184c $\pm$ 0.010
		Malic 1 mM	49.58cd $\pm$ 0.38	0.078a $\pm$ 0.002	1.214d $\pm$ 0.006
		Malic 5 mM	46.19a $\pm$ 0.31	0.104d $\pm$ 0.001	1.096a $\pm$ 0.011
		Malic 10 mM	48.33b $\pm$ 0.17	0.109e $\pm$ 0.001	1.142b $\pm$ 0.004
		Malic 20 mM	51.48e $\pm$ 0.28	0.092c $\pm$ 0.002	1.256e $\pm$ 0.006
		Oxalic 0.1 mM	57.17b $\pm$ 0.74	0.171de $\pm$ 0.001	1.294b $\pm$ 0.018
		Oxalic 0.5 mM	57.12b $\pm$ 0.13	0.160c $\pm$ 0.001	1.298b $\pm$ 0.004
		Oxalic 1 mM	56.19b $\pm$ 0.63	0.174e $\pm$ 0.003	1.272b $\pm$ 0.016

RJAL6_2	P-	Oxalic 5 mM	55.85b ± 1.63	0.165cd ± 0.004	1.269b ± 0.032
		Oxalic 10 mM	53.48a ± 0.52	0.152b ± 0.002	1.220a ± 0.013
		Oxalic 20 mM	51.25a ± 0.36	0.069a ± 0.001	1.289b ± 0.006
		Citric 0.1 mM	49.10b ± 0.69	0.075a ± 0.007	1.173b ± 0.030
		Citric 0.5 mM	48.03a ± 0.38	0.088b ± 0.003	1.133a ± 0.006
		Citric 1 mM	51.16c ± 0.02	0.098b ± 0.005	1.205b ± 0.004
		Citric 5 mM	53.03d ± 0.09	0.068a ± 0.001	1.311c ± 0.005
		Citric 10 mM	53.33d ± 0.02	0.075a ± 0.002	1.325c ± 0.005
		Citric 20 mM	58.59e ± 0.17	0.073a ± 0.001	1.497d ± 0.003
		Malic 0.1 mM	54.36d ± 0.51	0.073a ± 0.001	1.343d ± 0.011
		Malic 0.5 mM	50.18c ± 0.11	0.063a ± 0.000	1.254c ± 0.007
		Malic 1 mM	51.15c ± 0.74	0.066a ± 0.000	1.273c ± 0.024
		Malic 5 mM	43.12b ± 0.99	0.114b ± 0.013	0.986b ± 0.018
		Malic 10 mM	41.15a ± 0.57	0.134c ± 0.001	0.928a ± 0.014
		Malic 20 mM	41.57ab ± 0.04	0.103b ± 0.001	0.965ab ± 0.003
		Oxalic 0.1 mM	40.35e ± 0.07	0.112d ± 0.003	0.913d ± 0.001
		Oxalic 0.5 mM	32.35c ± 0.53	0.076c ± 0.006	0.730b ± 0.016
		Oxalic 1 mM	37.88d ± 0.00	0.061b ± 0.005	0.884d ± 0.005
		Oxalic 5 mM	29.51b ± 0.08	0.026a ± 0.006	0.721b ± 0.024
		Oxalic 10 mM	32.94c ± 0.37	0.035a ± 0.002	0.799c ± 0.007
		Oxalic 20 mM	27.75a ± 0.92	0.071bc ± 0.007	0.607a ± 0.020
RC3	P+	Citric 0.1 mM	55.44bc ± 0.58	0.095ab ± 0.002	1.350b ± 0.014
		Citric 0.5 mM	52.62ab ± 0.06	0.105bc ± 0.012	1.260a ± 0.018
		Citric 1 mM	54.37abc ± 0.22	0.086a ± 0.001	1.340b ± 0.005
		Citric 5 mM	52.29a ± 0.45	0.117c ± 0.002	1.240a ± 0.010
		Citric 10 mM	56.22c ± 2.49	0.086a ± 0.003	1.357b ± 0.030
		Citric 20 mM	54.64abc ± 0.08	0.085a ± 0.001	1.353b ± 0.004
		Malic 0.1 mM	53.35d ± 0.70	0.083a ± 0.001	1.297d ± 0.023
		Malic 0.5 mM	52.30cd ± 1.01	0.092b ± 0.002	1.251bcd ± 0.030
		Malic 1 mM	51.84bcd ± 0.14	0.079a ± 0.002	1.269cd ± 0.011
		Malic 5 mM	50.52ab ± 0.76	0.101c ± 0.002	1.201ab ± 0.023
		Malic 10 mM	48.86a ± 0.36	0.101c ± 0.003	1.161a ± 0.013
		Malic 20 mM	51.28bc ± 0.23	0.093b ± 0.000	1.234bc ± 0.006
		Oxalic 0.1 mM	55.99b ± 0.60	0.111a ± 0.001	1.303a ± 0.017

RCJ4	P+	Oxalic 0.5 mM	53.78a ± 0.92	0.112ab ± 0.003	1.250a ± 0.027
		Oxalic 1 mM	54.30ab ± 0.85	0.130ab ± 0.016	1.253a ± 0.033
		Oxalic 5 mM	54.55ab ± 0.61	0.121ab ± 0.006	1.265a ± 0.022
		Oxalic 10 mM	53.58a ± 0.66	0.117ab ± 0.010	1.247a ± 0.024
		Oxalic 20 mM	55.84b ± 0.56	0.135b ± 0.008	1.287a ± 0.019
		Citric 0.1 mM	53.31d ± 0.14	0.081b ± 0.003	1.327c ± 0.000
		Citric 0.5 mM	51.22ab ± 0.04	0.102c ± 0.001	1.232a ± 0.000
		Citric 1 mM	52.76cd ± 0.31	0.080b ± 0.000	1.317bc ± 0.009
		Citric 5 mM	50.67a ± 0.38	0.104c ± 0.001	1.213a ± 0.008
		Citric 10 mM	51.80bc ± 0.33	0.078b ± 0.001	1.294b ± 0.007
		Citric 20 mM	51.94bc ± 0.78	0.072a ± 0.002	1.314bc ± 0.015
		Malic 0.1 mM	52.85d ± 0.05	0.088b ± 0.001	1.280e ± 0.001
		Malic 0.5 mM	49.62bc ± 0.15	0.092c ± 0.000	1.187c ± 0.005
		Malic 1 mM	49.40bc ± 0.84	0.083a ± 0.001	1.199c ± 0.021
		Malic 5 mM	47.05a ± 0.19	0.100d ± 0.000	1.121a ± 0.004
		Malic 10 mM	48.75b ± 0.34	0.107e ± 0.002	1.158b ± 0.005
		Malic 20 mM	49.96c ± 0.31	0.083a ± 0.000	1.233d ± 0.011
		Oxalic 0.1 mM	58.14c ± 0.26	0.137ab ± 0.001	1.329c ± 0.006
		Oxalic 0.5 mM	55.81b ± 0.30	0.140b ± 0.006	1.277b ± 0.000
		Oxalic 1 mM	54.81ab ± 0.40	0.143b ± 0.005	1.252a ± 0.007
RJAL6_2	P+	Oxalic 5 mM	55.72b ± 0.60	0.146b ± 0.002	1.275ab ± 0.012
		Oxalic 10 mM	55.21b ± 0.33	0.138ab ± 0.002	1.269ab ± 0.007
		Oxalic 20 mM	53.95a ± 0.56	0.129a ± 0.000	1.254ab ± 0.014
		Citric 0.1 mM	52.51c ± 0.48	0.081b ± 0.003	1.267b ± 0.009
		Citric 0.5 mM	49.73a ± 0.54	0.073ab ± 0.018	1.204a ± 0.019
		Citric 1 mM	53.43c ± 0.36	0.074ab ± 0.001	1.318c ± 0.010
		Citric 5 mM	50.99ab ± 0.72	0.058a ± 0.003	1.290bc ± 0.011
		Citric 10 mM	52.28bc ± 0.12	0.069ab ± 0.000	1.303c ± 0.002
		Citric 20 mM	56.69d ± 0.45	0.072ab ± 0.002	1.457d ± 0.004
		Malic 0.1 mM	51.79d ± 0.16	0.060a ± 0.000	1.286d ± 0.003
		Malic 0.5 mM	50.81c ± 0.27	0.065b ± 0.000	1.252c ± 0.005
		Malic 1 mM	50.44c ± 0.35	0.065b ± 0.001	1.243c ± 0.013
		Malic 5 mM	43.22a ± 0.65	0.122d ± 0.001	0.983a ± 0.016
		Malic 10 mM	43.07a ± 0.23	0.121d ± 0.003	0.979a ± 0.005

Malic 20 mM	46.06b ± 0.02	0.108c ± 0.001	1.065b ± 0.001
Oxalic 0.1 mM	34.26e ± 0.32	0.096c ± 0.006	0.766d ± 0.005
Oxalic 0.5 mM	33.30de ± 0.43	0.077b ± 0.001	0.751cd ± 0.010
Oxalic 1 mM	32.53cd ± 0.82	0.073b ± 0.005	0.736cd ± 0.023
Oxalic 5 mM	31.69c ± 0.60	0.056a ± 0.000	0.725bc ± 0.016
Oxalic 10 mM	30.25b ± 0.55	0.058a ± 0.003	0.691b ± 0.012
Oxalic 20 mM	28.09a ± 0.14	0.045a ± 0.009	0.641a ± 0.004

Values are presented as mean ± standard deviation (n = 3). Different superscript letters indicate significant differences among organic acid concentrations within each bacterial strain, organic acid, and phosphorus condition (P+ or P-) according to Tukey's HSD test ($p < 0.05$). Growth was evaluated using the area under the growth curve (AUC), maximum specific growth rate (μ), and maximum optical density (OD_{max}).

Supplementary Table S3. Two-way ANOVA evaluating the effects of organic acid identity, concentration, and their interaction on the expression of *phoA*, *phoE*, and *pstS* in the three bacterial isolates.

Strain	Gene	Effect	F	p value
RC3	<i>phoA</i>	Organic acid	6.76	0.0088
		Concentration	196.71	<0.0001
		Organic acid x concentration	36.99	<0.0001
	<i>phoE</i>	Organic acid	245.32	<0.0001
		Concentration	943.22	<0.0001
		Organic acid x concentration	844.83	<0.0001
	<i>pstS</i>	Organic acid	1.19	0.3280
		Concentration	462.36	<0.0001
		Organic acid x concentration	79.12	<0.0001
RCJ4	<i>phoA</i>	Organic acid	91.07	<0.0001
		Concentration	137.12	<0.0001
		Organic acid x concentration	243.03	<0.0001
	<i>phoE</i>	Organic acid	506.6	<0.0001
		Concentration	1698.13	<0.0001
		Organic acid x concentration	296	<0.0001
	<i>pstS</i>	Organic acid	160.28	<0.0001
		Concentration	14.44	0.0003
		Organic acid x concentration	119.51	<0.0001
RJAL6_2	<i>phoA</i>	Organic acid	201.22	<0.0001
		Concentration	68.61	<0.0001
		Organic acid x concentration	190.97	<0.0001
	<i>phoE</i>	Organic acid	20.78	<0.0001
		Concentration	15.56	0.0001

	Organic acid x concentration	51.66	<0.0001
	Organic acid	244.6	<0.0001
<i>pstS</i>	Concentration	11.53	0.0006
	Organic acid x concentration	123.37	<0.0001

Values are presented as F statistics and corresponding *p* values obtained from two-way ANOVA. Pairwise comparisons among treatments were performed using estimated marginal means (EMMs) with Tukey's multiple-comparison adjustment. Gene expression analyses excluded samples with no detectable amplification.

Table S4. Summary of statistical comparisons for soluble phosphorus concentrations across strains, organic acids, concentrations, and sampling times.

Strain	Treatment	Sampling time	Strain comparison	Concentration comparison	Organic acid comparison	Sampling time comparison
Control	Citric 0.1 mM	Ti	a	A	A'	***
RC3		Ti	b	A	A'	ns
RCJ4		Ti	b	A	A'	ns
RJAL6_2		Ti	a	A	A'	**
Control		Tf	a	A	A'	***
RC3		Tf	a	A	A'	ns
RCJ4		Tf	a	A	A'	ns
RJAL6_2		Tf	a	A	A'	**
Control	Citric 1 mM	Ti	a	B	A'	ns
RC3		Ti	b	B	A'	***
RCJ4		Ti	a	A	A'	ns
RJAL6_2		Ti	a	A	A'	ns
Control		Tf	a	B	A'	ns
RC3		Tf	a	A	AB'	***
RCJ4		Tf	b	A	A'	ns
RJAL6_2		Tf	a	B	A'	ns
Control	Citric 20 mM	Ti	a	C	A'	*
RC3		Ti	b	C	A'	ns
RCJ4		Ti	c	B	A'	ns
RJAL6_2		Ti	c	B	A'	***
Control		Tf	a	C	A'	*
RC3		Tf	a	B	A'	ns
RCJ4		Tf	a	B	A'	ns
RJAL6_2		Tf	a	C	A'	***
Control	Malic 0.1 mM	Ti	a	A	A'	**
RC3		Ti	b	A	B'	ns
RCJ4		Ti	bc	A	A'	ns
RJAL6_2		Ti	ac	A	A'	ns

Control		Tf	a	A	B'	**
RC3		Tf	b	A	A'	ns
RCJ4		Tf	b	A	A'	ns
RJAL6_2		Tf	ab	A	A'	ns
Control		Ti	a	B	B'	**
RC3		Ti	b	A	A'	ns
RCJ4		Ti	ab	A	A'	ns
RJAL6_2		Ti	ab	A	A'	ns
Control		Tf	a	B	B'	**
RC3		Tf	a	A	A'	ns
RCJ4		Tf	a	A	A'	ns
RJAL6_2	Malic 1 mM	Tf	a	A	A'	ns
Control		Ti	a	C	B'	**
RC3		Ti	b	B	B'	ns
RCJ4	Malic 20 mM	Ti	c	B	B'	ns
RJAL6_2		Ti	ac	B	B'	**
Control		Tf	a	C	B'	**
RC3		Tf	b	B	B'	ns
RCJ4		Tf	ab	B	B'	ns
RJAL6_2		Tf	a	B	B'	**
Control		Ti	a	A	B'	***
RC3		Ti	b	A	B'	*
RCJ4	Oxalic 0.1 mM	Ti	ab	A	A'	ns
RJAL6_2		Ti	a	A	A'	ns
Control		Tf	a	A	C'	***
RC3		Tf	b	A	A'	*
RCJ4		Tf	b	A	A'	ns
RJAL6_2		Tf	b	A	A'	ns
Control		Ti	ab	B	C'	***
RC3		Ti	a	B	B'	*
RCJ4	Oxalic 1 mM	Ti	a	A	B'	ns
RJAL6_2		Ti	b	B	B'	**
Control		Tf	a	A	C'	***
RC3		Tf	a	A	B'	*
RCJ4		Tf	a	A	A'	ns
RJAL6_2		Tf	a	B	B'	**
Control		Ti	a	C	A'	ns
RC3	Oxalic 20 mM	Ti	b	C	A'	ns
RCJ4		Ti	b	B	A'	**
RJAL6_2		Ti	ab	C	A'	ns
Control		Tf	a	B	C'	ns
RC3		Tf	a	B	A'	ns
RCJ4		Tf	a	B	A'	**

RJAL6_2

Tf

a

C

A'

ns

Different lowercase letters indicate significant differences among strains within each organic acid, concentration, and sampling time. Different uppercase letters indicate significant differences among concentrations within each strain, organic acid, and sampling time. Different uppercase letters followed by a prime symbol (') indicate significant differences among organic acids within each strain, concentration, and sampling time. Asterisks indicate significant differences between Ti and Tf for each strain, organic acid, and concentration (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; ns, not significant).
