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Isolation, characterization, and field evaluation of Lactic Acid Bacteria (LAB) as plant growth promoting agents in tomato (*Solanum lycopersicum* L.) Cultivation

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Abstract
The present study explored the isolation, characterization, and functional evaluation of lactic acid bacteria (LAB) from curd samples collected from four villages of Rahuri Taluka, Ahmednagar, Maharashtra. Four distinct LAB strains (CRD-I, CRD-II, CRD-III, CRD-IV) were purified and subjected to morphological, biochemical, and phenotypic characterization, confirming typical Lactobacillus spp. traits, including Gram-positive rods, fermentative metabolism, and broad carbohydrate utilization. Functional screening revealed significant variation among isolates, with CRD-II (Rahuri) demonstrating the highest lactic acid production (7.40%), superior phosphate solubilization, and enhancement of tomato seed germination. A field trial under a randomized block design assessed the effect of LAB inoculation combined with graded NPK levels and foliar application. Integrated treatments significantly improved plant survival, height, branching and yield.

Keywords: Lactic acid bacteria, *Lactobacillus* spp., Tomato, Biofertilizer, Phosphate solubilization, Seed germination, NPK integration, Sustainable agriculture

Introduction
Tomato (*Solanum lycopersicum* L.) is a globally significant horticultural crop valued for its nutritional and economic importance. Its high nutrient demand often necessitates intensive chemical fertilizer use, which can lead to soil degradation, environmental pollution, and rising production costs. The use of beneficial microorganisms, particularly lactic acid bacteria (LAB), offers a promising strategy to enhance nutrient availability, promote plant growth, and improve soil health. LAB are Gram-positive, fermentative bacteria widely recognized for their role in food fermentation; recent studies have highlighted their potential as plant growth-promoting organisms due to lactic acid production, phosphate solubilization, and production of growth-stimulating compounds. Integrating LAB with mineral fertilizers may optimize nutrient use efficiency, reduce chemical input, and support sustainable agricultural practices. Despite their promise, systematic evaluation of LAB strains from local sources and their field-level impact on tomato growth remains limited. This study aims to isolate and characterize LAB strains from curd samples, evaluate their functional properties *in vitro*, and assess their efficacy under field conditions.

Methodology
Isolation and characterization of LAB strains
Curd samples were collected from four villages of Taluka Rahuri, District Ahmednagar, Maharashtra, namely Deolali Pravara (CRD-I), Rahuri (CRD-II), Wambori (CRD-III) (CRD-III) and Digras (CRD-IV). Isolation of lactic acid bacteria was carried out by serial dilution and pour plating on Man, Rogosa and Sharpe (MRS) agar medium (De Man *et al*., 1960) [6]. Colonies with distinct mucoid, circular morphology were purified and maintained as separate isolates.

The purified cultures were subjected to morphological characterization (colony form, elevation, colour, texture, and margin) and microscopic studies including Gram staining to determine cell shape and arrangement. Biochemical profiling was performed following

the methods of Harrigan and McCance (1976) [8], including tests for acid production, citrate utilization, catalase, oxidase, urease, starch hydrolysis, gelatin liquefaction, H_2S production, motility, indole, and oxidative/fermentative metabolism. Phenotypic characterization involved growth under different stress conditions, namely temperature (15-60 °C), pH (2-8), NaCl concentration (1-6%), and bile salts (0.5-2%), as per the protocols of Axelsson (2004) [4]. Carbohydrate fermentation ability was tested against lactose, glucose, fructose, sucrose, starch, and galactose (Cappuccino & Sherman, 2008) [5].

Functional screening of LAB strains

The functional efficiency of isolates was examined through lactic acid production, phosphate solubilization, and seed germination assays. Lactic acid production was determined titrimetrically (AOAC. 1990). Phosphate solubilization was tested on three different media MRS, National Botanical Research Institute's Phosphate (NBRIP) medium (Nautiyal, 1999) [10], and Pikovskaya agar (Pikovskaya, 1948) [12] by recording the diameter of the solubilization zone around colonies.

For germination studies, tomato (*Solanum lycopersicum* L.) seeds were treated with individual isolates, and germination percentage was calculated after seven days of incubation under controlled conditions. Seeds without microbial treatment served as control.

Field experiment

A field experiment was carried out at the Instructional Farm, MPKV, Rahuri, during the *kharif* season on tomato variety *Phule Surya*. The trial was laid out in a Randomized Block Design (RBD) with eight treatments and three replications. The treatments included:

- **T_1:** Seedling inoculation with LAB + Soil application
- **T_2:** Seedling inoculation with LAB + Soil application + Foliar application
- **T_3:** 25% NPK + Seedling inoculation with LAB + Soil application + Foliar application
- **T_4:** 50% NPK + Seedling inoculation with LAB + Soil application + Foliar application
- **T_5:** 75% NPK + Seedling inoculation with LAB + Soil application + Foliar application
- **T_6:** 100% NPK + Seedling inoculation with LAB + Soil application + Foliar application
- **T_7:** 100% Recommended Dose of Fertilizer (RDF) only
- **T_8:** Untreated control

All standard agronomic practices for tomato cultivation were followed (Jackson, 1973) [9]. Observations were recorded on plant survival percentage, plant height and branching at 30, 60 and 90 days after transplanting (DAT). Yield was calculated both on a per-plot basis and extrapolated to per hectare. Soil nutrient status (N, P, K in kg/ha) was determined after harvest using standard protocols (Subbiah & Asija, 1956 [14]; Olsen *et al*., 1954; Jackson, 1973) [9, 11].

Statistical analysis

All experimental data were subjected to analysis of variance (ANOVA) as per Gomez and Gomez (1984) [7]. Treatment means were compared at a 5% level of significance, and results were expressed as mean values along with standard error (SEm).

Results and Disscussion

Efficiency of LAB strains under *in vitro* conditions

Morphological characterization

Four LAB strains isolated from curd collected from different villages of Tal. Rahuri were characterized for morphological traits (Table 1.1). Colonies of all strains were circular in form, mucoid in texture and showed entire margins. CRD-I (Deolali Pravara), CRD-II (Rahuri), and CRD-IV (Digras) produced white colonies, whereas CRD-III (Wambori) produced creamy white colonies. Colony elevation was raised in all isolates except CRD-IV (Digras), which was flat. Microscopic observations revealed that all isolates were Gram positive rods occurring in chains. Thus, all isolates were morphologically similar, with only minor variation in colour and elevation.

Table 1.1: Morphological characterization of LAB strains.

LAB Strain	Colony Form	Colour	Elevation	Margin	Texture	Cell Shape andArrangement	Gram's Reaction
CRD I	Circular	White	Raised	Entire	Mucoid	Rod in chains	Gram +
CRD II	Circular	White	Raised	Entire	Mucoid	Rod in chains	Gram +
CRD III	Circular	Creamy white	Raised	Entire	Mucoid	Rod in chains	Gram +
CRD IV	Circular	White	Flat	Entire	Mucoid	Rod in chains	Gram +

Biochemical characterization

As presented in Table 1.2, biochemical profiling of the isolates revealed uniform characteristics across all four strains. All isolates were positive for acid production and milk coagulation, while negative for urease, citrate utilization, catalase, oxidase, gelatin liquefaction, H_2S production, starch hydrolysis, motility and indole production. The oxidative/fermentative test showed that all isolates were fermentative in nature. Hence, biochemical features confirmed the isolates to be typical lactic acid bacteria, with no differentiation among them.

Phenotypic characterization: The phenotypic characterization of LAB strains is given in Table 1.3. All four isolates exhibited growth at 15 °C and 30 °C, with dense (+++) growth at 30 °C. Moderate to dense growth was observed at 45 °C, while no growth occurred at 60 °C. With respect to pH tolerance, isolates grew well between pH 4.0 and 8.0, showing dense growth at pH 5.0 to 7.0. NaCl tolerance was observed up to 6% (w/v), with dense growth recorded at 2-4% NaCl. All isolates also tolerated bile salt concentrations up to 1.5%, while growth at 2.0% bile was weak or absent. Slight differences were noticed wherein CRD-II (Rahuri) and CRD-III (Wambori) showed marginally better tolerance to 2% bile compared to CRD-I (Deolali) and CRD-IV (Digras). Overall, the

Table 1.2: Biochemical characterization of LAB strains.

LAB Strains	Acid Production	Urease	Citrate	Catalase	Oxidase	Milk Coagulation	Gelatin Liquefaction	H_2S Production	Starch Hydrolysis	Motility	Indole	Oxidative/ Fermentive
CRD I	+	-	-	-	-	+	-	-	-	-	-	F+ive
CRD II	+	-	-	-	-	+	-	-	-	-	-	F+ive
CRD III	+	-	-	-	-	+	-	-	-	-	-	F+ive
CRD IV	+	-	-	-	-	+	-	-	-	-	-	F+ive

+ = Positive, - = Negative, F+ive - Fermentive

Table 1.3: Phenotypic characterization of LAB strains.

Strains	Temperature in °C				pH							NaCl Tolerance Test in % (w/v)						Bile Salt Tolerance Test (%) (w/v)			
	15	30	45	60	2	3	4	5	6	7	8	1	2	3	4	5	6	0.5	1	1.5	2
CRD I	+	+++	++	-	-	-	++	+++	+++	+++	+	+++	+++	+++	++	++	-	+++	++	-	-
CRD II	+	+++	+	-	-	+	++	+++	+++	+++	+	+++	+++	+++	++	++	+/-	+++	++	+	-
CRD III	+	+++	+	-	-	+	++	+++	+++	+++	+	+++	+++	+++	++	+	-	+++	+	+	-
CRD IV	+	+++	+	-	-	+	++	+++	+++	+++	+	+++	+++	+++	++	+	-	+++	+	-	-

= No growth (negative); + = slight growth (positive); ++ = moderate growth (positive); +++ = dense growth (positive);
+/- = ambiguous/undecided. Isolates showed broad adaptability to temperature, pH, NaCl and bile stress, with Rahuri and Wambori isolates performing marginally better under stress conditions.

Carbohydrate fermentation

As shown in Table 1.4, all isolates were able to ferment lactose, glucose, fructose, sucrose, starch and galactose positively. Carbohydrate fermentation patterns were identical across isolates, indicating no variability in utilization of tested sugars.

Table 1.4: Carbohydrate fermentation test of LAB strains.

LAB Strains	Lactose	Glucose	Fructose	Sucrose	Starch	Galactose
CRD I	+	+	+	+	+	+
CRD II	+	+	+	+	+	+
CRD III	+	+	+	+	+	+
CRD IV	+	+	+	+	+	+

+ = Positive, - = Negative

As shown in Table 1.4, all isolates were able to ferment lactose, glucose, fructose, sucrose, starch and galactose positively. Carbohydrate fermentation patterns were identical across isolates, indicating no variability in utilization of tested sugars.

Lactic acid production

Significant variation was recorded among isolates for lactic acid production as presented in Table 1.5, with graphical representation in Figure 1. The Rahuri isolate CRD-II (7.40%) was significantly superior to all other isolates. The Deolali isolate CRD-I (6.02%), Wambori isolate CRD-III (6.11%) and Digras isolate CRD-IV (5.80%) were statistically at par, but significantly inferior to CRD-II. Hence, CRD-II (Rahuri) emerged as the most efficient lactic acid producer among the tested strains.

Phosphate solubilization on various Medias

As shown in Table 1.6 and figure 2, the four LAB isolates differed significantly in their ability to solubilize phosphate on three different media, namely MRS, NBRIP and Pikovskaya agar.

Table 1.5: Lactic acid production by LAB strains isolated from curd.

LAB Strains	Lactic acid produced (%)
CRD-I	6.02 ^{b}
CRD-II	7.40 ^{a}
CRD-III	6.11 ^{b}
CRD-IV	5.80 ^{b}
SE m±	0.27
CD @ 1%	0.84

Table 1.6: Phosphate solubilization by LAB strains on different media.

LAB Strains	MRS (Diameter of zone in mm)	NBRIP (Diameter of zone in mm)	Pikovskaya (Diameter of zone in mm)
CRD-I	19.35 ^{c}	5.18 ^{d}	12.23 ^{c}
CRD-II	23.44 ^{a}	11.12 ^{a}	19.25 ^{a}
CRD-III	21.47 ^{b}	10.10 ^{b}	16.22 ^{b}
CRD-IV	17.48 ^{d}	6.33 ^{c}	9.05 ^{d}
SE m±	0.45	0.25	0.31
CD @ 1%	1.41	0.78	0.97

Note- MRS= Man, Rogosa and Sharpe medium; NBRIP= National Botanical Research Institute's Phosphate Medium.

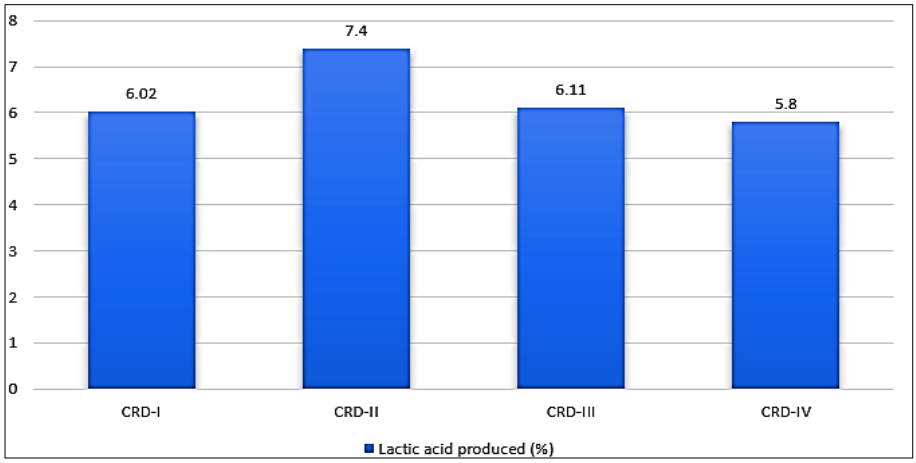

Fig 1: Lactic acid produced by different strains of Lactobacillus.

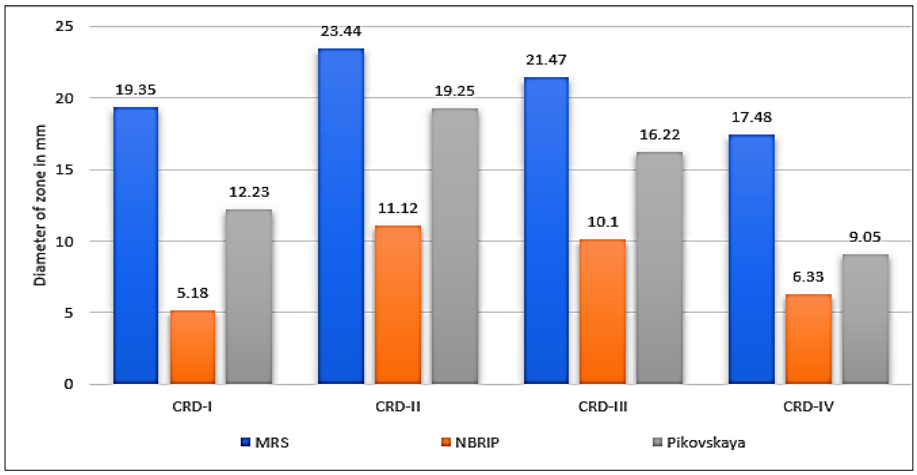

Fig 2: Solubilization of Phosphate by different LAB strains on MRS, NBRIP and Pikovskaya media

On MRS medium, the Rahuri isolate CRD-II produced the maximum solubilization zone of 23.44 mm, which was significantly superior to all other strains. The Wambori isolate CRD-III (21.47 mm) ranked second and was significantly higher than both CRD-I (Deolali, 19.35 mm) and CRD-IV (Digras, 17.48 mm). The latter two isolates were statistically at par with each other, but significantly inferior to CRD-II and CRD-III. This clearly indicated that Rahuri and Wambori isolates possessed stronger phosphate solubilizing capacity on MRS medium compared to the Deolali and Digras isolates.

On NBRIP medium, a similar trend was observed though the absolute zone diameters were smaller. Here again, the Rahuri isolate CRD-II (11.12 mm) recorded the significantly highest zone diameter, followed closely by the Wambori isolate CRD-III (10.10 mm). The Digras isolate CRD-IV (6.33 mm) and the Deolali isolate CRD-I (5.18 mm) exhibited considerably smaller zones, and were significantly inferior to CRD-II and CRD-III. The difference between CRD-IV and CRD-I was non-significant, showing that both these isolates had weak phosphate solubilizing ability on this medium.

On Pikovskaya medium, which is widely used as a standard test medium for phosphate solubilization, the same ranking pattern was evident. The Rahuri isolate CRD-II (19.25 mm) again proved to be significantly superior to all other isolates, followed by the Wambori isolate CRD-III (16.22 mm). The Deolali isolate CRD-I (12.23 mm) and the Digras isolate CRD-IV (9.05 mm) recorded much smaller solubilization zones and were significantly inferior to both CRD-II and CRD-III.

Across all three-test media, a consistent superiority of the Rahuri isolate CRD-II was established, while the Wambori isolate CRD-III always ranked second. The Deolali isolate CRD-I and the Digras isolate CRD-IV, though capable of solubilization, were markedly less effective and statistically at the lower end of performance.

Seed germination percentage under laboratory conditions

Significant differences were observed among treatments for germination percentage as shown in Table 1.7. The Rahuri isolate CRD-II (87.33%was significantly superior, followed by the Wambori isolate CRD-III (85.33%). The untreated control (83.33%) was significantly higher than the Deolali isolate CRD-I (81.66%, 64.67 arcsine) and the Digras isolate CRD-IV (80.33%), which were statistically at par and lowest.

Table 1.7: Effect of LAB strains on germination percentage of tomato *in vitro*

LAB Strains	Germination percentage
CRD-I	81.66 (64.67)^{d}
CRD-II	87.33 (69.17)^{a}
CRD-III	85.33 (67.49)^{b}
CRD-IV	80.33 (63.67)^{e}
Control	83.33 (65.93)^{c}
SE m±	0.18
CD @ 1%	0.54

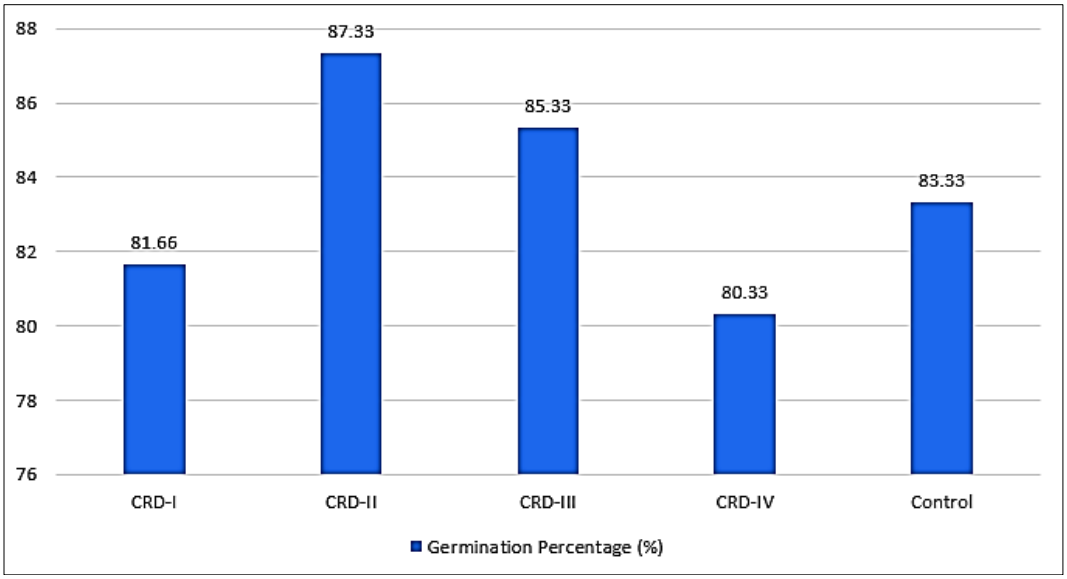

Fig 3: *In vitro* efficacy of LAB strains of seed germination of Tomato

Effect of different treatments on growth parameters of Tomato under field conditions

The results presented in Table 2.1 and Table 2.2, along with graphical representation in Figure 4 and 5 respectively, revealed that different treatments exerted significant effects on plant survival percentage, plant height, and the number of branches of Tomato at successive growth stages as well as yield and its effect on fertilizer levels of soil.

Plant survival percentage

The results presented in Table 2.1 revealed that different treatments exerted significant effects on plant survival percentage, plant height, and the number of branches of tomato at successive growth stages.

The observation that survival is highest in treatments with 100% and 75% NPK combined with LAB inoculation highlights the potential of microbial inoculants to improve nutrient-use

Table 2.1: Effect of different treatments on growth parameters of Tomato under field conditions

Treatment No.	Treatment details	Plant survival (%)*	Plant Height (cm)			Number of Branches #		
			30 DAT	60 DAT	90 DAT	30 DAT	60 DAT	90 DAT
T_1	Seedling inoculation with LAB +Soil application.	90.50 (72.08)^{c}	35.30 ^{d}	67.20 ^{e}	82.03 ^{e}	2.00 (1.55)^{bcd}	2.33 (1.67)^{cd}	3.33 (1.95)^{cd}
T_2	Seedling inoculation with LAB +Soil application + Foliar application.	90.50 (72.05)^{c}	36.57 ^{c}	67.67 ^{e}	82.23 ^{e}	1.33 (1.34)^{d}	2.33 (1.67)^{cd}	4.00 (2.11)^{cd}
T_3	25% NPK+ Seedling inoculation with LAB + Soil application+ Foliar application.	91.33 (72.89)^{c}	36.97 ^{c}	70.03 ^{d}	84.47 ^{d}	2.33 (1.67)^{abc}	2.67 (1.77)^{bcd}	4.33 (2.19)^{c}
T_4	50% NPK+ Seedling inoculation with LAB + Soil application+ Foliar application.	92.00 (73.57)^{c}	37.10 ^{c}	72.60 ^{c}	87.13 ^{c}	2.33 (1.67)^{abc}	3.00 (1.85)^{bcd}	5.67 (2.48)^{b}
T_5	75% NPK+ Seedling inoculation with LAB + Soil application+ Foliar application.	93.83 (75.65)^{b}	40.40 ^{a}	76.43 ^{a}	92.40 ^{a}	2.67 (1.77)^{ab}	3.67 (2.02)^{ab}	7.33 (2.79)^{a}
T_6	100% NPK+ Seedling inoculation with LAB + Soil application+ Foliar application	95.16 (77.34)^{a}	41.33 ^{a}	77.13 ^{a}	93.70 ^{a}	3.00 (1.87)^{a}	4.66 (2.27)^{ab}	7.66 (2.85)^{a}
T_7	Only 100% RDF.	88.50 (70.18)^{d}	38.30 ^{b}	74.63 ^{b}	90.20 ^{b}	2.33 (1.67)^{abc}	3.33 (1.95)^{abc}	6.33 (2.61)^{ab}
T_8	Untreated control.	87.00 (68.88)^{d}	34.23 ^{d}	64.50 ^{f}	79.43 ^{f}	1.66 (1.46)^{cd}	2.00 (1.58)^{d}	3.00 (1.85)^{d}
SE m±		0.53	0.39	0.58	0.58	0.09	0.10	0.09
CD @ 5%		1.58	1.20	1.77	1.79	0.27	0.32	0.28

*= Values in Parenthesis are Arcsine transformed.
#= Values in Parenthesis are Squareroot Transformed

efficiency, allowing for reduced fertilizer input without compromising plant establishment. This reduction in fertilizer requirement has practical significance for sustainable agriculture, offering economic benefits and lowering environmental impacts associated with excessive fertilizer use. Conversely, treatments with LAB inoculation but without mineral fertilizers showed moderate survival, which was better than the untreated control but lower than integrated treatments. This suggests that while LAB inoculants improve soil health and plant resilience, they cannot fully substitute for the essential nutrients supplied by fertilizers but serve best as complementary inputs (Alori and Babalola, 2018) [2]; Shahwar *et al*., 2023 [13].

Plant height

At 30 DAT, plant height was significantly influenced by treatments. The highest plant height (41.33 cm) was recorded in T_6, followed closely by T_5 (40.40 cm). These were significantly superior to T_7 (38.30 cm) and T_4 (37.10 cm). Minimum plant height (34.23 cm) was noted in

untreated control (T_8), which was significantly inferior to all other treatments.

At 60 DAT, the superiority of integrated treatments became more evident. T_6 (77.13 cm) and T_5 (76.43 cm) recorded significantly greater plant height compared to RDF alone (T_7: 74.63 cm) and reduced NPK levels. Treatments T_1 and T_2 (67.20-67.67 cm) remained significantly lower. The untreated control (64.50 cm) recorded the least plant height.

At 90 DAT, the same trend persisted with T_6 (93.70 cm) producing the tallest plants, followed by T_5 (92.40 cm). Both these treatments were significantly superior to RDF alone (T_7: 90.20 cm). The untreated control (79.43 cm) and seedling inoculation alone (T_1: 82.03 cm) recorded significantly shorter plants, demonstrating that synergism of LAB with recommended NPK levels enhanced vegetative growth more than individual components alone.

The integration of microbial inoculants like LAB with NPK fertilizers significantly improves plant growth and development, which is supported by numerous studies. Microbial inoculants contribute to plant height enhancement by producing plant growth regulators such as indole acetic acid and gibberellins that promote cell division and elongation, leading to increased shoot length. Additionally, these inoculants improve nutrient uptake efficiency, which further supports vegetative growth, explaining why plants treated with LAB and partial or full doses of fertilizer are taller than those with fertilizer alone or untreated controls (Adnan *et al*., 2016) [1]; Alori and Babalola, 2018 [2].

Number of branches: The branching pattern of tomato plants was significantly influenced by the treatments at different growth stages. At 30 DAT, the maximum number of branches (3.00) was recorded in treatment T_6 (100% NPK + LAB), which was significantly superior over the untreated control (T_8: 1.66). Treatments T_4 (2.33), T_5 (2.67) and T_7 (2.33) were found statistically at par with each other, though markedly lower than T_6. The lowest number of branches was observed in T_2 (1.33) and T_8 (1.66).

At 60 DAT, a similar trend was observed where T_6 (4.66) registered the maximum number of branches, followed by T_5 (3.67) and T_7 (3.33), both of which were at par with each other but significantly lower than T_6. The untreated control (T_8: 2.00) remained the poorest performer, recording significantly fewer branches compared to all other treatments.

At 90 DAT, the superiority of integrated treatments became more evident. The highest number of branches (7.66) was again recorded in T_6, closely followed by T_5 (7.33), both of which were statistically superior over T_7 (6.33). In contrast, the untreated control (T_8: 3.00) and seedling inoculation alone (T_1: 3.33) produced the minimum number of branches, which were significantly inferior to all other treatments.

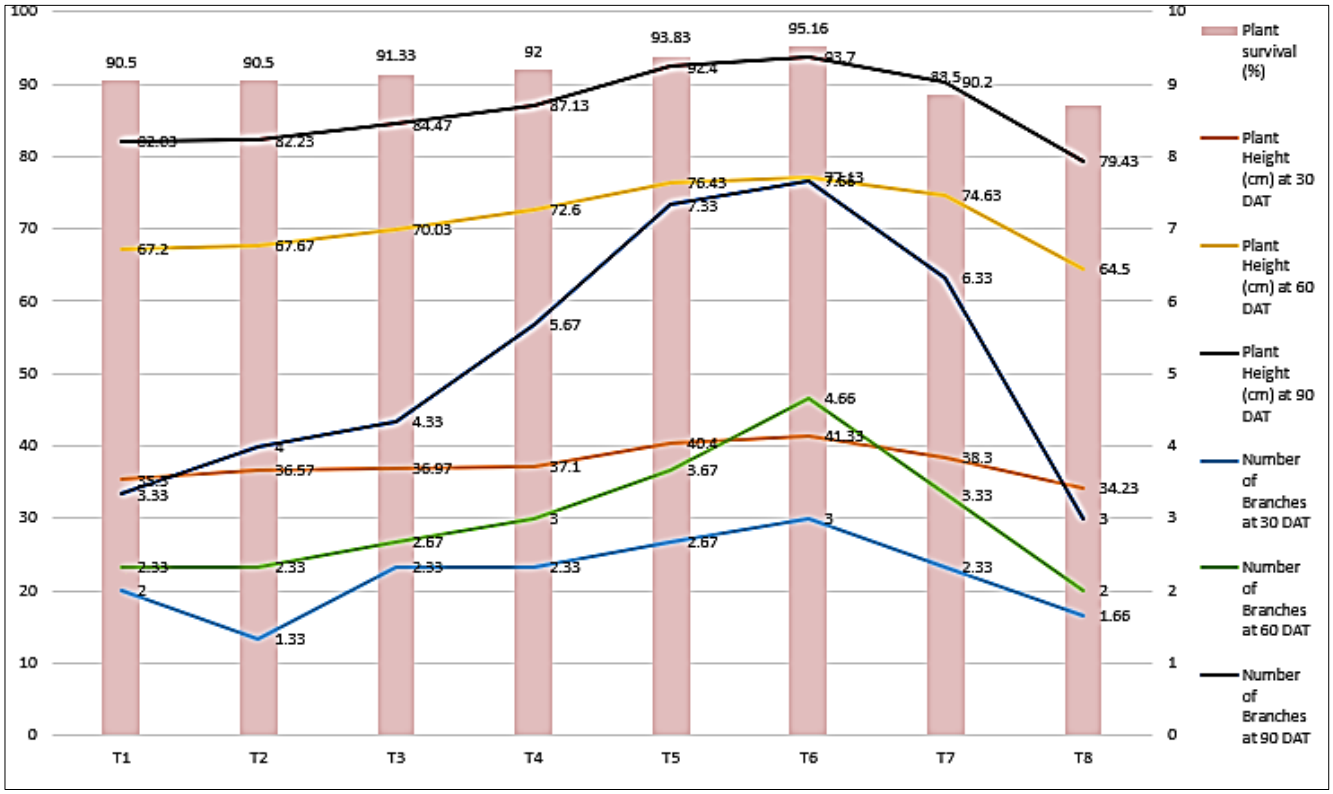

Fig 4: Efficacy of different treatments on Plant Survival, Plant height and Number of Branches on Tomato under field condition

Table 2.2: Effect of different treatments on yield of Tomato and its effects on soil fertilizer levels of NPK under field conditions

Treatment No.	Treatment details	Yield		Soil Fertilizer Levels After Harvest		
		Kg/plot	t/ha	N	P	K
T_1	Seedling inoculation with LAB +Soil application.	63.33 ^{e}	53.31 ^{e}	219.52 ^{c}	14.24 ^{d}	352.58 ^{de}
T_2	Seedling inoculation with LAB +Soil application + Foliar application.	63.67 ^{e}	53.59 ^{e}	221.61 ^{b}	14.49 ^{a}	353.32 ^{cde}
T_3	25% NPK+ Seedling inoculation with LAB + Soil application+ Foliar application.	68.33 ^{d}	57.52 ^{d}	221.94 ^{b}	14.94 ^{c}	353.82 ^{cd}
T_4	50% NPK+ Seedling inoculation with LAB + Soil application+ Foliar application.	71.00 ^{c}	59.76 ^{c}	222.70 ^{b}	15.19 ^{bc}	354.14 ^{cd}
T_5	75% NPK+ Seedling inoculation with LAB + Soil application+ Foliar application.	73.67 ^{a}	62.01 ^{a}	225.47 ^{a}	15.58 ^{ab}	355.86 ^{ab}
T_6	100% NPK+ Seedling inoculation with LAB + Soil application+ Foliar application	74.66 ^{a}	62.85 ^{a}	226.63 ^{a}	15.84 ^{a}	356.94 ^{a}
T_7	Only 100% RDF.	72.33 ^{b}	60.89 ^{b}	223.35 ^{b}	15.22 ^{bc}	354.89 ^{bc}
T_8	Untreated control.	62.66 ^{e}	52.75 ^{e}	219.19 ^{c}	14.15 ^{d}	351.85 ^{e}
SE m±		0.38	0.32	0.62	0.13	0.48
CD @ 5%		1.17	0.98	1.90	0.41	1.45

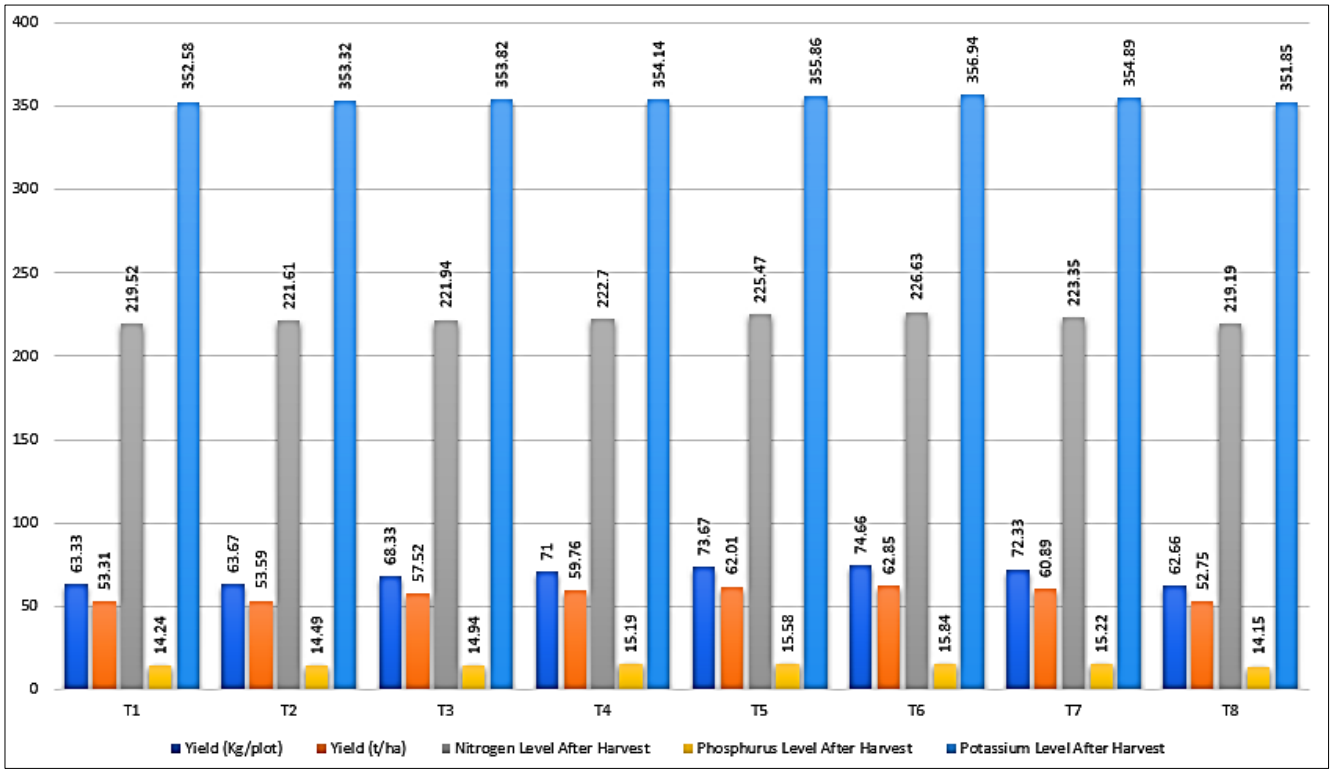

Fig 5: Efficacy of different treatments on Yield of Tomato and Soil Fertilizer levels after harvest

The integration of microbial inoculants like LAB with NPK fertilizers significantly improves plant growth and development, which is supported by numerous studies. Microbial inoculants contribute to plant height enhancement by producing plant growth regulators such as indole acetic acid and gibberellins that promote cell division and elongation, leading to increased shoot length. Additionally, these inoculants improve nutrient uptake efficiency, which further supports vegetative growth, explaining why plants treated with LAB and partial or full doses of fertilizer are taller than those with fertilizer alone or untreated controls (Adnan *et al*., 2016) [1]; Alori and Babalola, 2018 [2].

Yield

The results indicate that different treatments significantly affected tomato yield. The highest yields were recorded in T_6 (100% NPK + LAB inoculation with soil and foliar application) and T_5 (75% NPK + LAB inoculation with soil and foliar application), producing 62.85 and 62.01 t/ha respectively. These treatments were significantly superior to the recommended dose fertilizer alone (T_7) and untreated control (T_8), showing the clear efficacy of combining microbial inoculants with fertilizer to improve productivity.

The increased yield under integrated treatments can be attributed to the ability of LAB inoculants to enhance nutrient availability through solubilization of phosphorus and potassium and production of growth-promoting substances. This creates a more favorable rhizosphere environment that supports better plant growth and fruiting. The comparable yields of 75% NPK + LAB and 100% NPK + LAB treatments demonstrate the potential for substantial fertilizer reduction without compromising yield, aligning with studies that report biofertilizers improving nutrient use efficiency and promoting sustainable production (Adnan *et al*., 2016) [1]; Alori and Babalola, 2018 [2]. These findings are reinforced by the lower yield values observed in inoculation or fertilizer alone treatments, emphasizing the synergistic role of microbial inoculants.

Soil fertilizer levels after harvest

Post-harvest soil nutrient analysis showed significant differences among treatments for nitrogen, phosphorus, and potassium levels. The highest residual N, P, and K were maintained in T_6 (100% NPK + LAB), followed closely by T_5 (75% NPK + LAB), which had significantly better nutrient status than the sole recommended dose fertilizer (T_7) and inoculation-only treatments (T_1 and T_2). This indicates that LAB inoculation improves nutrient retention and cycling in the soil, likely through enhanced microbial activity and nutrient mineralization.

The improved soil nutrient levels in integrated treatments suggest more efficient fertilizer utilization and reduced nutrient losses, which contribute to sustaining soil fertility over time. This conservation of soil nutrients is crucial for long-term crop productivity and environmental sustainability. Lower residual nutrients in treatments without microbial inoculation or fertilizer demonstrate the necessity of combined nutrient management approaches to optimize fertilizer efficiency and maintain soil health (Shahwar *et al*., 2023) [13].

Conclusion

The present investigation demonstrated that lactic acid bacteria (LAB) strains isolated from curd samples of Rahuri taluka villages (CRD-I to CRD-IV) exhibited characteristic morphological, biochemical, and phenotypic traits typical of *Lactobacillus* spp. (Table 1.1-1.3). All isolates were Gram-positive, fermentative rods in chains, with uniform ability to ferment a wide range of carbohydrates (Table 1.4). Functional screening revealed significant variation among isolates: CRD-II consistently produced the highest lactic acid (7.40%) and showed superior phosphate solubilization on NBRIP and Pikovskaya's medium (Table 1.5, 1.6), while germination studies indicated that CRD-II and CRD-III enhanced seedling vigor *in vitro* compared to the control (Table 1.7). These results confirmed the potential of LAB strains, particularly CRD-II, as effective plant growth promoting organisms.

Field evaluation under tomato cultivation further established the efficacy of integrated applications (Table 2.1). Seedling inoculation with LAB in combination with graded levels of NPK and foliar supplementation significantly improved plant survival, height, and branching, with maximum values consistently recorded under 100% NPK + LAB (T_6), closely followed by 75% NPK + LAB (T_5). Untreated control and seedling inoculation alone remained the least effective.

Yield performance mirrored the growth trends (Table 2.2). The highest yields (62.85 t/ha) were obtained under 100% NPK + LAB (T_6), statistically at par with 75% NPK + LAB (T_5: 62.01 t/ha), indicating that a 25% reduction in chemical fertilizer requirement was possible without yield penalty when LAB was applied.

In summary, the study concludes that LAB strains, particularly CRD-II, possess strong plant growth promoting traits and when integrated with NPK fertilizers can enhance tomato growth, yield. Importantly, 75% NPK + LAB application sustained yields at par with 100% NPK + LAB, thereby highlighting the possibility of reducing chemical fertilizer use through microbial integration.

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