Int.J.Curr.Microbiol.App.Sci (2026) *15*(3): 85-97

International Journal of Current Microbiology and Applied Sciences
ISSN: 2319-7706 **Volume 15 Number 3 (2026)**
Journal homepage: http://www.ijcmas.com

Original Research Article https://doi.org/10.20546/ijcmas.2026.1503.009

Microbial Solubilization of Iron and Zinc Minerals for Enhancement of Sugarcane Yield and Quality in Micronutrient-Deficient Soils

Sudha Devendra Ghodke*, A. D. Kadlag, Preeti S. Deshmukh, D. S. Jadhav and K. B. Kamble

Agricultural Microbiology and Soil Science Section, Vasantdada Sugar Institute, Manjari (Bk), Pune – 412307, Maharashtra, India

*Corresponding author

Keywords

Sugarcane, Bioinoculant, Iron solubilizing microbes, Zinc solubilizing microbes, Micronutrient deficiency.

Article Info

Received: 15 January 2026
Accepted: 26 February 2026
Available Online: 10 March 2026

ABSTRACT

Micronutrient deficiencies, especially iron (Fe) and zinc (Zn), pose a major challenge to sugarcane productivity in alkaline soils. This study comprehensively evaluated the application of a liquid bioinoculant containing Fe and Zn solubilizing microbes (FeZnSM) in combination with varying levels of micronutrient fertilizers. Field trials were conducted across three sugarcane factories in Maharashtra, India, employing a split plot design to assess effects on crop growth, yield, nutrient uptake, juice quality, soil fertility, and economic returns. Results demonstrated that integrating FeZnSM with 100% recommended Fe + Zn fertilizer produced the highest cane yield (123.81 t ha^{-1}) and CCS yield (17.95 t ha^{-1}), as well as substantial improvements in nutrient uptake, microbial populations, and soil micronutrient availability. Notably, combining FeZnSM with 50% of the recommended fertilizer dose delivered comparable yields and profitability, highlighting the potential to partially substitute chemical fertilizers with microbial bioinoculants. The findings underscore the value of integrating microbial and chemical micronutrient management for sustainable sugarcane cultivation in deficient soils.

Introduction

Sugarcane (*Saccharum officinarum* L.) is one of the most important commercial crops cultivated in tropical and subtropical regions of the world. India is the second largest producer of sugarcane after Brazil, contributing significantly to the sugar industry and rural economy. The crop requires balanced nutrition for optimum growth, yield and juice quality. Although macronutrient fertilization has received considerable attention, micronutrient deficiencies have increasingly emerged as a major constraint limiting sugarcane productivity, particularly in intensively cultivated and alkaline soils.

Among micronutrients, iron (Fe) and zinc (Zn) play critical roles in plant metabolism. Iron is essential for chlorophyll synthesis, photosynthesis, respiration and enzyme activation, whereas zinc is involved in protein synthesis, growth regulation and auxin metabolism. Deficiency of these nutrients leads to reduced chlorophyll content, poor plant growth, decreased cane yield and deterioration of juice quality. Iron deficiency chlorosis is commonly observed in calcareous soils, while zinc deficiency is widespread in many agricultural soils due to high pH, excessive phosphorus fertilization and continuous cropping (Alloway, 2008).

In India, several studies have reported widespread micronutrient deficiencies in cultivated soils. Zinc deficiency alone affects nearly 40–50% of Indian agricultural soils, while iron deficiency is common in calcareous and alkaline soils of many sugarcane-growing regions. In such soils, applied micronutrients often become unavailable due to precipitation and fixation reactions, resulting in low nutrient use efficiency.

Microorganisms play a vital role in nutrient cycling and improving nutrient availability in soil. Certain soil microorganisms possess the ability to solubilize insoluble forms of micronutrients such as iron and zinc through the production of organic acids, siderophores and other metabolites. These microbial processes convert unavailable mineral forms into plant-available forms, thereby enhancing nutrient uptake by crops (Gadd, 2010). Iron solubilizing microorganisms produce siderophores that chelate Fe^{3+} and make it available to plants, while zinc solubilizing microorganisms release organic acids that dissolve zinc minerals such as zinc oxide, zinc carbonate and zinc phosphate.

Several bacterial and fungal species have been identified as efficient solubilizers of micronutrients. Species such as *Bacillus polymyxa*, *Pseudomonas striata*, *Thiobacillus ferrooxidans*, *Aspergillus niger* and *Trichoderma viride* have been reported to enhance the availability of iron and zinc in soil. These microorganisms improve plant growth not only through micronutrient solubilization but also by producing growth promoting substances, improving root development and increasing nutrient uptake efficiency (Ramesh *et al.,* 2014).

In recent years, bioinoculants containing micronutrient solubilizing microorganisms have gained considerable attention as an eco-friendly alternative to chemical fertilizers. Application of such biofertilizers can reduce the requirement of chemical micronutrient fertilizers while improving soil health and crop productivity. Several studies have demonstrated the beneficial effects of zinc solubilizing bacteria and iron mobilizing microorganisms on crop growth and yield under field conditions (Singh and Prasad, 2014).

Despite the potential benefits of microbial inoculants, limited information is available regarding their combined use with micronutrient fertilizers for improving sugarcane productivity under micronutrient-deficient soils. Therefore, the present investigation was undertaken to evaluate the effect of iron and zinc solubilizing microbial liquid bioinoculant (FeZnSM) on sugarcane growth, yield, nutrient uptake, soil microbial population and soil fertility status under field conditions.

Materials and Methods

A field experiment was conducted during the sugarcane growing season at three different sugar factory command areas in Maharashtra, India to evaluate the effect of iron and zinc solubilizing microbial liquid bioinoculant (FeZnSM) on growth, yield and quality of sugarcane under micronutrient deficient soils. The experimental locations were: Bhimashankar Sahakari Sakhar Karkhana Ltd., Pune district, Sahakar Maharshi Bhausaheb Thorat Sahakari Sakhar Karkhana Ltd., Ahmednagar district, Sahakar Maharshi Shankarrao Mohite Patil Sahakari Sakhar Karkhana Ltd., Akluj, Solapur district.

The soils of the experimental fields were alkaline in reaction with moderate organic carbon content and were deficient in available iron and zinc. Initial soil samples were collected before planting and analyzed for physicochemical properties including pH, electrical conductivity (EC), organic carbon, and available nutrients. The experiment was laid out in a split plot design with three replications at each location. Three levels of iron and zinc fertilizers were used as main plot treatments: F1: No iron and zinc application (control), F2: Iron @ 25 kg ha^{-1} + Zinc @ 20 kg ha^{-1} (100% recommended dose) and F3: Iron @ 12.5 kg ha^{-1} + Zinc @ 10 kg ha^{-1} (50% recommended dose). Four levels of iron and zinc solubilizing microbial liquid bioinoculant were used as sub plot treatments (FeZnSM bioinoculant application): M1: Control (no bioinoculant), M2: FeZnSM @ 2.5 L ha^{-1}, M3: FeZnSM @ 3.75 L ha^{-1} and M4: FeZnSM @ 5.0 L ha^{-1}. A total of 12 treatment combinations were evaluated under field conditions.

The sugarcane variety Co 86032, a widely cultivated commercial variety, was used for planting in all experimental plots. Healthy three-budded setts were planted in furrows following recommended spacing. Farmyard manure (FYM) was applied uniformly at the rate of 20 t ha^{-1} before planting to improve soil fertility and organic matter content. The recommended dose of NPK fertilizers was applied uniformly to all treatments according to regional agronomic recommendations for sugarcane cultivation. Nitrogen fertilizer was applied in split doses, while phosphorus and potassium were applied as basal dose at the time of planting. Standard agronomic practices including irrigation, intercultivation, earthing up, and plant protection measures were carried out uniformly in all plots throughout the crop growth period. The iron and zinc solubilizing microbial liquid bioinoculant (FeZnSM) contained beneficial microorganisms capable of solubilizing insoluble iron and zinc minerals in soil. The bioinoculant consisted of microbial strains such as: *Acetobacter diazotrophicus, Bacillus polymyxa, Pseudomonas striata, Thiobacillus ferroxidans, Aspergillus awamori, Trichoderma viride, Aspergillus niger* and *Thiobacillus thiooxidans* The required quantity of FeZnSM was applied as soil treatment at the time of planting along the furrows according to the respective treatment doses. Composite soil samples were collected from each plot before planting and after harvest of the crop. The samples were air dried, ground and passed through a 2 mm sieve for analysis. The following soil parameters were determined using standard analytical methods: Soil pH (1:2.5 soil-water suspension), Electrical conductivity (EC) using conductivity meter, Organic carbon by Walkley and Black method, Available nitrogen by alkaline permanganate method, Available phosphorus by Olsen method, Available potassium by flame photometer and Available iron and zinc by DTPA extraction method.

Observations on growth and yield parameters were recorded at appropriate stages of crop growth and at harvest: Number of millable canes (NMC) per hectare, Cane height (cm), Cane girth (cm), Number of internodes per cane, Germination percentage, Tillering ratio, Cane yield (t ha^{-1}), Commercial cane sugar (CCS) yield (t ha^{-1}), Cane yield was calculated by harvesting the entire plot area and converting the yield into tonnes per hectare.

At harvest, representative cane samples were collected from each treatment and crushed in a crusher to extract juice. The juice samples were analyzed for quality parameters including: Sucrose percentage, Brix percentage, Commercial Cane Sugar (CCS) percentage and Juice purity percentage. These parameters were determined using standard procedures followed in sugar factories. Plant samples were collected at harvest to determine iron and zinc uptake by the crop. The samples were washed, oven dried, ground and digested using suitable acid digestion procedures. Iron and zinc concentrations in the digested plant samples were determined using atomic absorption spectrophotometer (AAS). Nutrient uptake was calculated by multiplying nutrient concentration with dry matter yield.

Soil samples collected from the rhizosphere were analyzed for the population of iron and zinc solubilizing microorganisms using standard serial dilution and plate count techniques. Specific culture media were used for enumeration of microbial count. Microbial population was expressed as colony forming units (CFU) per gram of soil.

Economic analysis of the treatments was carried out to evaluate the profitability of different nutrient management practices. A Gross monetary return (Rs ha^{-1}), Cost of cultivation (Rs ha^{-1}), Net profit (Rs ha^{-1}) and Benefit-cost (B:C) ratio were calculated. Costs of fertilizers, micronutrients, bioinoculants and agronomic operations were considered while calculating the total cost of cultivation. The experimental data were subjected to statistical analysis using analysis of variance (ANOVA) appropriate for split plot design. Significance of treatment effects was tested using the F-test at 5% probability level. Standard error of mean (SEm) and critical difference (CD) values were calculated to compare treatment means.

Results and Discussion

Effect of Iron and Zinc Solubilizing Microbial Bioinoculant on Growth and Yield of Sugarcane

The application of iron and zinc solubilizing microbial liquid bioinoculant (FeZnSM) along with micronutrient fertilizers significantly influenced growth and yield parameters of sugarcane (Table 2). The pooled results from three locations indicated considerable improvement in cane yield, CCS yield, number of millable canes, cane height, girth, and other growth attributes compared to the control treatment.

Among all treatment combinations, the application of Fe + Zn (100%) along with FeZnSM @ 5.0 L ha^{-1} (F2M4) recorded the highest cane yield (123.81 t ha^{-1}) and CCS yield (17.95 t ha^{-1}). This treatment also produced the highest number of millable canes (81,213 ha^{-1}), greater cane girth (11.17 cm), and improved millable cane height (200.55 cm). The increase in cane yield in this treatment was about 26% higher than the control treatment (F1M1).

Similarly, the treatment Fe + Zn (50%) with FeZnSM @ 5.0 L ha^{-1} (F3M4) also produced higher cane yield (121.23 t ha^{-1}) and CCS yield (18.21 t ha^{-1}), indicating that bioinoculant application can partially substitute chemical micronutrient fertilizers without reducing productivity.

The improvement in growth and yield attributes may be attributed to increased availability of iron and zinc in the rhizosphere due to microbial solubilization of these nutrients. Iron plays an essential role in chlorophyll formation and photosynthesis, while zinc is involved in enzyme activation and growth hormone synthesis.

Adequate availability of these micronutrients enhances physiological processes leading to better vegetative growth and higher yield.

Similar results were reported by several researchers who observed significant increases in crop growth and productivity due to application of micronutrient solubilizing microorganisms. Zinc solubilizing bacteria have been reported to improve nutrient uptake and yield in various crops through enhanced micronutrient availability in soil.

Effect on Juice Quality Parameters

The application of FeZnSM along with micronutrient fertilizers had a positive effect on sugarcane juice quality parameters (Table 4). Treatments receiving bioinoculant showed improvement in sucrose content, Brix percentage, CCS percentage and juice purity compared with control.

The highest sucrose content (18.54%) and Brix value (20.40%) were observed in the treatment Fe + Zn (50%) + FeZnSM @ 3.75 L ha^{-1}, while the highest CCS percentage (16.01%) was also recorded in the same treatment combination. The increase in CCS percentage indicates improved sugar recovery from cane juice.

Juice purity also improved in bioinoculant treated plots, with values ranging from 90 to 92%. Although statistical analysis showed non-significant differences for some parameters, the overall trend indicated improvement in juice quality due to micronutrient management.

The improvement in juice quality parameters may be attributed to better nutrient balance in plants resulting from increased availability of iron and zinc. These micronutrients play an important role in carbohydrate metabolism and enzymatic activities associated with sugar synthesis and accumulation in sugarcane stalks.

Economic Analysis

The economic evaluation of treatments revealed that the application of FeZnSM along with micronutrient fertilizers significantly improved economic returns (Table 5). The highest net profit (Rs. 215,371 ha^{-1}) and benefit-cost ratio (2.64) were recorded with the treatment Fe + Zn (100%) + FeZnSM @ 5.0 L ha^{-1}. Similarly, the treatment Fe + Zn (50%) + FeZnSM @ 5.0 L ha^{-1} also recorded higher net profit (Rs. 208,697 ha^{-1}) with a benefit-cost ratio of 2.60. The control treatment recorded the lowest benefit-cost ratio of 2.12. The increased profitability under bioinoculant treatments may be attributed to higher cane yield and improved CCS yield, which ultimately increased gross monetary returns. The cost of bioinoculant application was relatively low compared with the yield benefits obtained, making this technology economically viable for farmers.

Effect on Iron and Zinc Uptake

Application of FeZnSM significantly increased iron and zinc uptake by sugarcane plants (Table 6). The highest mean iron uptake (5.58 kg ha^{-1}) and zinc uptake (2.05 kg ha^{-1}) were recorded with the treatment Fe + Zn (50%) + FeZnSM @ 5.0 L ha^{-1}. This treatment recorded considerably higher nutrient uptake compared with the control treatment which showed iron uptake of 1.93 kg ha^{-1} and zinc uptake of 0.35 kg ha^{-1}. The increased uptake of micronutrients may be due to microbial production of organic acids, siderophores and chelating compounds which solubilize insoluble iron and zinc minerals in soil. These processes convert unavailable forms of nutrients into plant-available forms, thereby enhancing nutrient absorption by plant roots. Similar findings have been reported in earlier studies where microbial inoculants significantly increased micronutrient uptake and improved plant growth.

Effect on Soil Microbial Population

The population of beneficial microorganisms in soil increased considerably with the application of FeZnSM (Table 7). The microbial counts of species such as *Bacillus polymyxa*, *Pseudomonas striata*, *Thiobacillus ferrooxidans*, *Aspergillus niger* and *Trichoderma viride* increased significantly in bioinoculant treated plots compared with the initial soil population.

The highest microbial populations were observed in treatments receiving higher doses of FeZnSM, particularly FeZnSM @ 5.0 L ha^{-1}, indicating successful establishment and multiplication of introduced microorganisms in the soil environment.

The increase in microbial population enhances nutrient cycling and improves soil biological activity, which ultimately contributes to improved soil fertility and crop productivity.

Effect on Soil Nutrient Status after Harvest

Post-harvest soil analysis showed improvements in soil nutrient status due to application of FeZnSM (Table 8). Although soil pH, electrical conductivity, organic carbon, and macronutrient levels did not show significant differences among treatments, the availability of micronutrients such as iron and zinc increased significantly.

The highest available iron (4.52 mg kg^{-1}) and zinc (0.52 mg kg^{-1}) were recorded in treatments receiving Fe + Zn (100%) + FeZnSM @ 5.0 L ha^{-1}. The increase in available micronutrients may be attributed to microbial solubilization of iron and zinc minerals through production of organic acids and chelating substances. These microbial processes help in maintaining a continuous supply of micronutrients to plants and improve soil fertility.

Overall Performance of Treatments

Overall results indicated that combined application of micronutrient fertilizers and iron and zinc solubilizing microbial bioinoculant significantly improved sugarcane productivity, nutrient uptake, microbial population and economic returns. Among all treatments, Fe + Zn (100%) combined with FeZnSM @ 5.0 L ha^{-1} proved to be the most effective treatment for enhancing cane yield, CCS yield, and profitability. However, the treatment Fe + Zn (50%) + FeZnSM @ 5.0 L ha^{-1} also produced comparable yield and economic returns, indicating the potential of microbial bioinoculants to reduce chemical micronutrient fertilizer requirements. These findings highlight the importance of integrating microbial biofertilizers with micronutrient fertilization for sustainable sugarcane production in micronutrient-deficient soils.

Table.1A Soil analysis at initial stage (before planting)

Locations	pH (1:2.5)	EC (dSm^{-1})	Organic carbon (%)	Soil Available Nutrients (kg ha^{-1})		
				N	P	K
Bhimashankar ssk	8.21	0.37	0.60	225.00	15.2	321.2
SMBT ssk, A'nagar	8.78	0.26	0.45	238.33	43.79	596.96
SMSMP ssk, Solapur	8.52	0.34	0.79	230.50	9.23	237.42

Table.1B DTPA extractable micronutrients of Soil at initial stage (before planting)

Locations	DTPA extractable micronutrients (mg kg^{-1})				$CaCO_3$ %
	Zn	Fe	Mn	Cu	
Bhimashankar ssk	0.46	3.30	18.32	1.62	17.36
SMBT ssk, A'nagar	0.37	3.89	-	-	17.50
SMSMP ssk, Solapur	0.37	4.05	18.50	2.42	13.41

Table.2 Effect of Iron& Zinc solubilizing microbial liquid bioinoculant on growth & yield of sugarcane.

(Pooled data of sugar mills)

Tr. No.	Cane Yield (t/ha)	CCS Yield (t/ha)	N.M.C. ('000/ha)	Millable Height (Cm)	Girth (Cm)	No. of internodes	B:C Ratio	Tillering ratio	Germi nation %	CCS %	Purity %
F1M1	98.03	13.53	59909.47	171.43	8.43	20.66	2.12	3.39	65.14	14.10	88.87
F1M2	102.07	14.73	65186.21	180.26	9.64	20.76	2.20	3.95	59.21	14.58	90.46
F1M3	104.52	14.80	64928.41	182.05	9.69	19.92	2.25	3.30	63.79	14.25	91.92
F1M4	103.98	14.68	64341.11	182.64	9.87	21.61	2.24	3.29	64.29	14.23	92.46
F2M1	113.13	16.15	69397.81	188.85	9.97	20.14	2.43	3.57	68.69	14.36	91.59
F2M2	112.49	16.88	70552.70	195.64	10.07	21.83	2.41	4.32	63.53	15.26	90.78
F2M3	111.95	15.79	69018.85	199.02	10.03	21.64	2.39	3.30	60.16	14.42	91.03
F2M4	123.81	17.95	81213.36	200.55	11.17	21.55	2.64	3.66	65.42	14.66	89.97
F3M1	105.44	15.40	69080.54	202.11	9.79	20.78	2.28	3.61	63.63	14.82	91.96
F3M2	106.94	15.70	68280.92	203.65	10.10	20.91	2.30	3.86	62.30	14.96	92.01
F3M3	111.35	16.88	70572.42	204.66	10.14	20.20	2.39	3.99	60.12	15.48	90.58
F3M4	121.23	18.21	79798.45	206.80	11.01	21.31	2.60	3.73	68.15	15.24	90.76

	Cane Yield		CCS Yield		N.M.C.		Millable Height		Girth		No. of internodes		B:C Ratio		Tillering ratio		Germination %		CCS %		Purity %	
	SE (m) ±	**CD at 5%**	**SE (m) ±**	**CD at 5%**	**SE (m) ±**	**CD at 5%**	**SE (m) ±**	**CD at 5%**	**SE (m) ±**	**CD at 5%**	**SE (m) ±**	**CD at 5%**	**SE (m) ±**	**CD at 5%**	**SE (m) ±**	**CD at 5 %**	**SE (m) ±**	**CD at 5%**	**SE (m) ±**	**CD at 5%**	**SE (m) ±**	**CD at 5%**
Main treatment	*1.09*	*3.54*	*0.16*	*0.51*	882.85	2879.13	*3.15*	*10.26*	*0.11*	*0.36*	*0.24*	*0.78*	-	-	*0.45*	***NS***	1.44	***NS***	*0.16*	***NS***	*0.49*	*NS*
Sub treatment	*1.28*	*3.66*	*0.26*	*0.74*	1093.37	3135.96	*3.87*	*11.10*	*0.08*	*0.22*	*0.26*	*0.73*	-	-	*0.43*	***NS***	2.04	***NS***	*0.18*	***NS***	*0.69*	*NS*
Interaction	*2.21*	*6.35*	*0.45*	*1.28*	1893.77	5431.64	*6.70*	*19.22*	*0.13*	*0.38*	*0.44*	*1.27*	-	-	*0.75*	***NS***	3.54	***NS***	*0.32*	***NS***	*1.20*	*NS*

Table.4 Effect of Iron& Zinc solubilizing microbial liquid bioinoculant on juice quality of sugarcane

(Pooled data of sugar mills)

Treatment Details	**Sucrose %**		**Brix %**		**CCS %**		**Purity %**	
Control	17.42		19.46		14.10		88.87	
FeZnSM @ 2.5 lit ha^{-1}	17.67		19.60		14.32		90.46	
FeZnSM @3.75lit ha^{-1}	17.40		19.43		13.71		91.92	
FeZnSM 5.0litha^{-1}	17.27		19.15		14.14		92.46	
Fe + Zn (100%)	17.87		19.52		14.69		91.59	
Fe + Zn (100%) + FeZnSM @ 2.5 litha^{-1}	18.06		19.82		15.78		90.78	
Fe + Zn (100%) FeZnSM @ 3.75lit/ha	17.17		19.23		14.02		91.03	
Fe + Zn (100%) FeZnSM @5.0 litha^{-1}	17.23		19.13		14.92		89.97	
Fe + Zn (50%)	17.97		19.74		14.49		91.96	
Fe + Zn (50%) + FeZnSM @2.5 litha^{-1}	17.87		19.68		15.54		92.01	
Fe + Zn (50%) FeZnSM @3.75litha^{-1}	18.54		20.40		16.01		90.58	
Fe + Zn 50%) FeZnSM @ 5.0 lit ha^{-1}	17.86		19.66		15.81		90.76	
	SE (m) ±	***CD at 5%***	***SE (m) ±***	***CD at 5%***	***SE (m) ±***	***CD at 5%***	***SE (m) ±***	***CD at 5%***
Main treatment	*0.18*	*NS*	*0.22*	*NS*	*0.16*	***NS***	*0.49*	*NS*
Sub treatment	*0.23*	*NS*	*0.29*	*NS*	*0.18*	***NS***	*0.69*	*NS*
Interaction	*0.41*	*NS*	*0.51*	*NS*	*0.32*	***NS***	*1.20*	*NS*

Table.5 Effect of Iron & Zinc solubilizing microbial liquid bioinoculant on Cost Benefit ratio

(Pooled data of sugar mills)

Treatment Details	Monetary returns (Rs/ha)	Cost of Agronomic cultivation (Rs.)	Cost of fertilizers	Cost of Fe source	Cost of Zn source	Cost of liquid FeZnS	Total cost of cultivation (Rs/ha)	Net Profit (Rs.)	Cost Benefit Ratio
Control	274498	113660	15578	0	0	0	129238	145260.0	2.12
FeZnSM @ 2.5 lit ha^{-1}	285782	113660	15578	0	0	500	129738	156044.0	2.20
FeZnSM @3.75lit ha^{-1}	292670	113660	15578	0	0	750	129988	162682.0	2.25
FeZnSM 5.0litha^{-1}	291158	113660	15578	0	0	1000	130238	160920.0	2.24
Fe + Zn (100%)	316764	113660	15578	225	820	0	130283	18648.1	2.43
Fe + Zn (100%) + FeZnSM @ 2.5 litha^{-1}	314972	113660	15578	225	820	500	130783	184189.0	2.41
Fe + Zn (100%) FeZnSM @ 3.75lit/ha	313446	113660	15578	225	820	750	131033	182413.0	2.39
Fe + Zn (100%) FeZnSM @5.0 litha^{-1}	346654	113660	15578	225	820	1000	131283	215371.0	**2.64**
Fe + Zn (50%)	295218	113660	15578	112.5	410	0	129760.5	165457.5	2.28
Fe + Zn (50%) + FeZnSM @2.5 litha^{-1}	299446	113660	15578	112.5	410	500	130260.5	169185.5	2.30
Fe + Zn (50%) FeZnSM @3.75litha^{-1}	311780	113660	15578	112.5	410	750	130510.5	181269.5	2.39
Fe + Zn 50%) FeZnSM @ 5.0 lit ha^{-1}	339458	113660	15578	112.5	410	1000	130760.5	208697.5	**2.60**

Table.6 Effect of Iron & Zinc solubilizing microbial liquid bioinoculant on Fe & Zn uptake

(Pooled data of sugar mills)

Treatments	Bhimashankar SSK	SMSMP SSK	Mean of Total Fe (kg ha^{-1})	Bhimashankar SSK	SMSMP SSK	Mean of Total Zn (kg ha^{-1})
	Total Fe (kg ha^{-1})	Total Fe (kg ha^{-1})		Total Zn (kg ha^{-1})	Total Zn (kg ha^{-1})	
Control	1.09	2.76	**1.93**	0.28	0.41	**0.35**
FeZnSM @ 2.5 lit ha^{-1}	1.58	2.99	**2.29**	0.32	0.45	**0.38**
FeZnSM @3.75lit ha^{-1}	1.65	3.35	**2.50**	0.34	0.47	**0.41**
FeZnSM 5.0litha^{-1}	1.67	3.91	**2.79**	0.34	0.49	**0.41**
Fe + Zn (100%)	1.87	4.21	**3.04**	0.42	0.53	**0.47**
Fe + Zn (100%) + FeZnSM @ 2.5 litha^{-1}	2.14	4.38	**3.26**	0.42	0.54	**0.48**
Fe + Zn (100%) FeZnSM @ 3.75lit/ha	2.19	4.44	**3.31**	0.45	0.62	**0.54**
Fe + Zn (100%) FeZnSM @5.0 litha^{-1}	2.77	4.87	**3.82**	2.82	0.65	**1.74**
Fe + Zn (50%)	2.49	4.75	**3.62**	2.40	0.61	**1.50**
Fe + Zn (50%) + FeZnSM @2.5 litha^{-1}	2.59	5.43	**4.01**	2.62	0.67	**1.64**
Fe + Zn (50%) FeZnSM @3.75litha^{-1}	2.99	7.24	**5.12**	2.74	0.77	**1.75**
Fe + Zn 50%) FeZnSM @ 5.0 lit ha^{-1}	3.47	7.69	**5.58**	3.27	0.84	**2.05**

Table.7 Effect of Iron & Zinc solubilizing microbial bioinoculant on iron and zinc solubilizing microbial count in soil

(Pooled data)

Treatments	*B. polymyxa*	*P. striata*	*Thio ferroxidanse*	*A. awamorie*	*T. thioxidance*	*A. niger*	*T. viride*
Initial (Before planting)	**1.0 X 10^{4}**	**1.0 X 10^{4}**	**2.0 X 10^{4}**	**1.0 X 10^{2}**	**1.0 X 10^{4}**	**1.0 X 10^{2}**	**1.0 X 10^{2}**
Control	2.0 X 10^{4}	2.0 X 10^{4}	4.0 X 10^{4}	2.0 X 10^{2}	3.0 X 10^{4}	1.0 X 10^{2}	3.0 X 10^{2}
FeZnSM @ 2.5 lit ha^{-1}	8.0 X 10^{4}	3.0 X 10^{4}	3.0 X 10^{6}	4.0 X 10^{2}	3.0 X 10^{4}	2.0 X 10^{2}	14.0 X 10^{2}
FeZnSM @3.75lit ha^{-1}	1.0 X 10^{6}	1.0 X 10^{6}	11.0X 10^{6}	6.0 X 10^{2}	11.0 X 10^{4}	1.0 X 10^{4}	3.0 X 10^{4}
FeZnSM 5.0litha^{-1}	4.0 X 10^{6}	2.0 X 10^{6}	15.0X 10^{6}	6.0 X 10^{2}	2.0 X 10^{6}	1.0 X 10^{4}	5.0 X 10^{4}
Fe + Zn (100%)	2.0 X 10^{6}	6.0 X 10^{4}	6.0 X 10^{4}	3.0 X 10^{2}	6.0 X 10^{4}	2.0 X 10^{2}	2.0 X 10^{2}
Fe + Zn (100%) + FeZnSM @ 2.5 lit ha^{-1}	2.0 X 10^{6}	7.0 X 10^{4}	12.0X 10^{6}	3.0 X 10^{4}	7.0 X 10^{4}	4.0 X 10^{2}	6.0 X 10^{2}
Fe + Zn (100%) FeZnSM @ 3.75lit/ha	8.0 X 10^{6}	12.0X 10^{4}	14.0X 10^{6}	4.0 X 10^{4}	7.0 X 10^{4}	1.0 X 10^{4}	4.0 X 10^{4}
Fe + Zn (100%) FeZnSM @5.0 litha^{-1}	10.0X 10^{6}	14.0X 10^{4}	18.0X 10^{6}	4.0 X 10^{4}	12.0 X 10^{4}	3.0 X 10^{4}	7.0 X 10^{4}
Fe + Zn (50%)	6.0 X 10^{4}	2.0X 10^{6}	2.0 X 10^{6}	2.0 X 10^{4}	2.0 X 10^{6}	2.0 X 10^{2}	2.0 X 10^{2}
Fe+Zn (50%)+FeZnSM@2.5 lit ha^{-1}	4.0 X 10^{6}	2.0X 10^{6}	2.0 X 10^{6}	3.0 X 10^{4}	2.0 X 10^{6}	4.0 X 10^{2}	2.0 X 10^{2}
Fe + Zn (50%) FeZnSM @3.75lit ha^{-1}	9.0 X 10^{6}	13.0X 10^{6}	11.0X 10^{6}	19.0X10^{2}	3.0 X 10^{6}	9.0 X 10^{2}	3.0 X 10^{2}
Fe + Zn 50%) FeZnSM @ 5.0 lit ha^{-1}	11.0X 10^{6}	14.0X 10^{8}	13.0X 10^{6}	4.0 X 10^{4}	18.0 X 10^{6}	11.0X10^{2}	1.0 X 10^{4}

Graph.1 Effect of Iron & Zinc solubilizing microbial liquid bioinoculant on yield of sugarcane

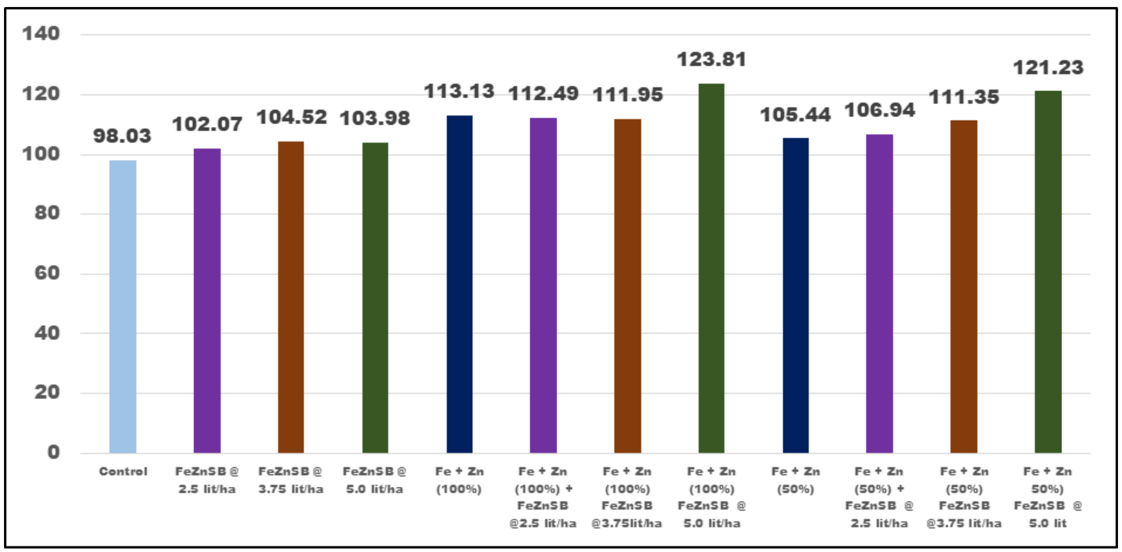

Table.8 Effect of Iron & Zinc solubilizing microbial liquid bioinoculant on soil nutrients at harvest

(Pooled data of sugar mills)

Treatments	pH (1:2.5	EC (dSm^{-1})	OC	Available N	Available P	Available K	Available Fe	Available Zn
Control	8.33	0.37	0.63	216.65	10.57	277.39	3.34	0.27
FeZnSM @ 2.5 lit/ha	8.31	0.40	0.66	213.37	11.05	291.51	4.09	0.32
FeZnSM @ 3.75 lit/ha	8.30	0.39	0.68	211.98	11.92	289.08	4.16	0.34
FeZnSM @ 5.0 lit/ha	8.30	0.33	0.68	206.85	10.97	341.67	4.21	0.38
Fe + Zn (100%)	8.30	0.34	0.71	214.30	12.35	368.87	4.47	0.41
Fe + Zn (100%) FeZnSM @ 2.50lit/ha	8.32	0.33	0.64	217.45	11.73	320.75	4.49	0.43
Fe + Zn (100%) FeZnSM @ 3.75lit/ha	8.28	0.38	0.73	222.03	10.52	284.02	4.51	0.48
Fe + Zn (100%) FeZnSM @ 5.0 lit	8.31	0.35	0.70	218.48	11.27	292.42	4.52	0.52
Fe + Zn (50%)	8.35	0.34	0.67	213.20	11.64	301.00	4.40	0.35
Fe+Zn (50%) +FeZnSM @ 2.5 lit/ha	8.39	0.30	0.63	223.71	11.82	276.83	4.45	0.37
Fe+Zn (50%) FeZnSM @3.75 lit/ha	8.32	0.32	0.68	215.36	11.01	270.84	4.46	0.39
Fe +Zn 50%) FeZnSM @5.0 lit	8.30	0.40	0.77	221.33	11.21	284.77	4.47	0.41

	SE (m) ±	***CD at 5%***	***SE (m) ±***	***CD at 5%***	***SE (m) ±***	***CD at 5%***	***SE (m) ±***	***CD at 5%***	***SE (m) ±***	***CD at 5%***	***SE (m) ±***	***CD at 5%***	***SE (m) ±***	***CD at 5%***	***SE (m) ±***	***CD at 5%***
Main treatment	*0.03*	*NS*	*0.01*	*NS*	*0.020*	*NS*	*1.91*	*NS*	*0.16*	*NS*	*8.87*	*NS*	*0.07*	*0.24*	*0.008*	*0.025*
Sub treatment	*0.02*	*NS*	*0.02*	*NS*	*0.023*	*NS*	*2.85*	*NS*	*0.28*	*NS*	*12.78*	*NS*	*0.05*	*0.16*	*0.012*	*0.035*
Interaction	*0.04*	*NS*	*0.03*	*NS*	*0.040*	*NS*	*4.93*	*NS*	*0.48*	*NS*	*22.13*	*NS*	*0.09*	*0.27*	*0.021*	*0.061*

Image.1 Effect of Iron yy& Zinc solubilizing microbial liquid bioinoculant on yield of sugarcane

In conclusion, the present investigation demonstrated that the combined application of iron and zinc fertilizers along with iron and zinc solubilizing microbial liquid bioinoculant (FeZnSM) significantly improved sugarcane growth, yield, nutrient uptake, soil microbial population and economic returns under micronutrient-deficient soils. The results clearly indicated that micronutrient management through both chemical and biological sources plays an important role in enhancing sugarcane productivity and improving soil fertility.

Among the various treatment combinations evaluated in the study, the application of Fe + Zn at 100% recommended dose along with FeZnSM @ 5.0 L ha^{-1} recorded the highest cane yield (123.81 t ha^{-1}), CCS yield (17.95 t ha^{-1}), and number of millable canes. This treatment also resulted in higher cane girth, improved plant height and better growth attributes compared to the control treatment. The improved growth performance may be attributed to enhanced availability and uptake of micronutrients, particularly iron and zinc, which play vital roles in photosynthesis, enzyme activation and metabolic activities of plants.

The application of FeZnSM also improved sugarcane juice quality parameters such as sucrose content, Brix percentage, CCS percentage and juice purity.

Improved sugar accumulation in the cane stalk may be associated with better micronutrient nutrition, which supports efficient carbohydrate metabolism and sugar synthesis in sugarcane.

A significant increase in iron and zinc uptake by the crop was observed in bioinoculant treated plots. The highest uptake values were recorded in treatments receiving FeZnSM at higher doses, indicating the efficiency of iron and zinc solubilizing microorganisms in mobilizing insoluble forms of micronutrients present in soil.

These microorganisms produce organic acids, siderophores and other metabolites that enhance the solubilization and availability of micronutrients in the rhizosphere, thereby facilitating greater nutrient absorption by plants.

The application of FeZnSM also increased the population of beneficial soil microorganisms including *Bacillus polymyxa*, *Pseudomonas striata*, *Thiobacillus ferrooxidans*, *Aspergillus niger* and *Trichoderma viride*. The increased microbial population indicates improved biological activity in the soil ecosystem, which contributes to enhanced nutrient cycling and better soil health.

Post-harvest soil analysis revealed improved availability of iron and zinc in treatments receiving bioinoculant along with micronutrient fertilizers. Although soil pH, EC, organic carbon and macronutrients did not show significant differences among treatments, the increase in available micronutrients highlights the role of microbial inoculants in maintaining micronutrient balance in soil.

Economic analysis showed that the treatment Fe + Zn (100%) + FeZnSM @ 5.0 L ha^{-1} produced the highest net profit and benefit–cost ratio (2.64), indicating that the technology is economically feasible for farmers. Interestingly, the treatment Fe + Zn (50%) + FeZnSM @ 5.0 L ha^{-1} also produced comparable yields and economic returns, suggesting that microbial bioinoculants can partially reduce the requirement of chemical micronutrient fertilizers without compromising productivity.

Overall, the findings of this study clearly demonstrate that the integration of iron and zinc solubilizing microbial bioinoculants with micronutrient fertilization is an effective and sustainable strategy for improving sugarcane productivity in micronutrient-deficient soils. The use of such bioinoculants not only enhances crop yield and quality but also improves soil microbial activity and nutrient availability, thereby contributing to long-term soil fertility and sustainable agricultural production.

Therefore, the application of FeZnSM @ 5.0 L ha^{-1} in combination with recommended micronutrient fertilizers can be recommended as an effective nutrient management practice for improving sugarcane yield and quality under micronutrient-deficient conditions. Further research on long-term field trials and multi-location testing would help in validating the technology for wider adoption by sugarcane growers.

Author Contributions

Sudha D. Ghodke: Conceptualization, Microbial Culture Development, Laboratory Analysis Experimental Design, Field Trial Supervision, Microbial Enumeration Data Analysis Statistical Analysis, Manuscript Writing. Dr. A.D. Kadlag: Data Interpretation, Critical Review of Manuscript. Dr. Preeti S. Deshmukh: Soil and Plant Analysis, Technical Support. D.S. Jadhav & K.B. Kamble: Field Implementation, Soil Sampling, Agronomic Management.

Acknowledgements

The authors thank the participating sugar mills and Vasantdada Sugar Institute for infrastructure and support. Special thanks to the Advisor, Director General, Principal Scientist and Agricultural Microbiology team and field staff for technical assistance.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

References

Adnan, M., Fahad, S., Zamin, M., Shah, S., Shah, T., Mian, I. A., & Arif, M. (2020). Integrated use of phosphate solubilizing bacteria and phosphorus fertilizer improves wheat productivity. Agronomy, 10(2), 178. https://doi.org/10.3390/agronomy10020178

Alloway, B. J. (2008). Zinc in soils and crop nutrition (2nd ed.). International Zinc Association and IFA.

Alloway, B.J. (2008). Zinc in soils and crop nutrition. International Zinc Association, Brussels.

Broadley, M., Brown, P., Cakmak, I., Rengel, Z., & Zhao, F. (2012). Function of nutrients: Micronutrients. In P. Marschner (Ed.), Marschner's Mineral Nutrition of Higher Plants (3rd ed., pp. 191–248). Academic Press. https://doi.org/10.1016/B978-0-12-384905-2.00007-8

Fageria, N.K., Baligar, V.C., and Clark, R.B. (2002). Micronutrients in crop production. Advances in Agronomy, 77: 185-268. https://doi.org/10.1016/S0065-2113(02)77015-6

Gadd, G.M. (2010). Metals, minerals and microbes: geomicrobiology and bioremediation. Microbiology, 156: 609-643. https://doi.org/10.1099/mic.0.037143-0

Khan, A., Khan, A. L., Waqas, M., Hussain, J., Al-Harrasi, A., Al-Rawahi, A., & Lee, I. J. (2018). Microbial strategies to improve the bioavailability and management of micronutrients in soil. Frontiers in Microbiology, 9, 2146. https://doi.org/10.3389/fmicb.2018.02815

Lucy, M., Reed, E., & Glick, B. R. (2004). Applications of free-living plant growth-promoting rhizobacteria. Antonie van Leeuwenhoek, 86(1), 1–25. https://doi.org/10.1023/B:ANTO.0000024903.10757.6e

Marschner, H. (2012). Marschner's Mineral Nutrition of Higher Plants (3rd ed.). Academic Press. https://doi.org/10.1016/C2009-0-63043-9

Rajkumar, M., Ae, N., Prasad, M. N. V., & Freitas, H. (2010). Potential of siderophore-producing bacteria for improving heavy metal phytoextraction. Trends in Biotechnology, 28(3), 142–149. https://doi.org/10.1016/j.tibtech.2009.12.002

Ramesh, A., Sharma, S. K., Sharma, M. P., Yadav, N., & Joshi, O. P. (2014). Inoculation of zinc solubilizing Bacillus aryabhattai strains for improved growth, mobilization and biofortification of zinc in soybean and wheat cultivated in Vertisols of central India. Applied Soil Ecology, 73, 87–96. https://doi.org/10.1016/j.apsoil.2013.08.009

Sharma, S. K., Ramesh, A., Joshi, O. P., & Sharma, M. P. (2012). Selection of plant growth-promoting bacteria and their influence on growth, yield and nutrient content in wheat. Journal of Plant Nutrition, 35(11), 1617–1633. https://doi.org/10.1080/01904167.2012.698347

Singh, A., Prasanna, R., Joshi, M., & Nain, L. (2016). Microbial bioresources for enhancing micronutrient availability in soil and plant systems. Frontiers in Microbiology, 7, 1664. https://doi.org/10.3389/fmicb.2016.01664

Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. Plant and Soil, 255(2), 571–586. https://doi.org/10.1023/A:1026037216893

Yadav, S. K., Verma, J. P., Tiwari, K. N. (2018). Effect of zinc-solubilizing bacteria on growth, yield and nutrient uptake of sugarcane. Sugar Tech, 20(6), 730–736. https://doi.org/10.1007/s12355-018-0600-1

How to cite this article:

Sudha Devendra Ghodke, Kadlag A. D., Preeti S. Deshmukh, Jadhav D. S. and Kamble K. B. 2026. Microbial Solubilization of Iron and Zinc Minerals for Enhancement of Sugarcane Yield and Quality in Micronutrient-Deficient Soils. *Int.J.Curr.Microbiol.App.Sci.* 15(3): 85-97. **doi:** https://doi.org/10.20546/ijcmas.2026.1503.009