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Yield and economics of barley (*Hordeum vulgare* L.) as influenced by zinc biofortification and fertility levels under humid southern plains of Rajasthan

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Abstract

A field experiment was conducted during the *rabi* seasons of 2023–24 and 2024–25 at Udaipur, Rajasthan to study effect of fertility levels and zinc biofortification on yield and economics of barley (*Hordeum vulgare* L.). The experiment was laid out in split plot design comprising 16 combinations of 4 fertility levels in main plot and 4 zinc biofortification treatments in sub plot. The results showed that fertility levels significantly influenced productivity of barley. Application of 75% RDF + 25% FYM produced significantly higher yield (grain, straw and biological yield), net return (78165 ₹/ha) and benefit: cost ratio (2.39) which remained statistically at par with 100% RDF. Among zinc biofortification treatments, application of 2.5 kg Zn/ha + *Zinc Solubilising Bacteria* at 5.0 ml/kg seed obtained the maximum grain, straw and biological yield, net return (77063 ₹/ha) and benefit: cost ratio (2.38) comparable with 5 kg Zn/ha due to improved productivity and cost efficiency. The interaction effect revealed that the combination of 75% RDF + 25% FYM along with 2.5 kg Zn/ha + *Zinc Solubilising Bacteria* at 5.0 ml/kg produced the significantly highest grain yield (5608 kg/ha) and achieved maximum benefit: cost ratio (2.49) in barley cultivation under the agro-climatic conditions of southern Rajasthan.

Keywords: Barley, zinc biofortification, grain yield, fertility levels, economic analysis, integrated nutrient management

Introduction

Barley (*Hordeum vulgare* L.) is one of the earliest domesticated crops and continues to be a vital global crop due to its remarkable adaptability to diverse agro-ecological environments. Barley grains are nutritionally rich, containing carbohydrates, proteins, β -glucans, vitamins and minerals, making the crop valuable for food and feed purposes. In India, barley plays a significant role in food, feed and malt industries, particularly in semi-arid and arid regions where other cereals often fail (Jat *et al.*, 2023) [18]. Southern Rajasthan represents one such region, characterized by erratic rainfall, alkaline soils and declining soil fertility, which often restricts barley yield and profitability. Rajasthan is the largest state having more than 52 per cent in barley production and 46 per cent area followed by Uttar Pradesh. In Rajasthan, barley was cultivated on 0.40 million hectares area with the production of 1.43 million tonnes at an average productivity of 3657 kg ha⁻¹ in year 2023-24 (GoR, 2024). Balanced nutrient management is a key determinant of crop productivity and sustainability. Continuous use of chemical fertilizers alone has led to nutrient imbalance, deterioration of soil physical properties, and reduced nutrient use efficiency (Debbarma *et al.*, 2025) [13]. Integration of organic manures such as farmyard manure (FYM) with inorganic fertilizers improves soil structure, enhances microbial activity, and ensures a sustained release of nutrients, thereby improving crop growth and yield. Optimizing fertility levels through integrated nutrient management has been reported to increase cereal productivity while reducing input costs and improving economic returns (Tefera *et al.*, 2022) [19]. Among micronutrients, zinc (Zn) deficiency is widespread in Indian soils, particularly in calcareous and alkaline soils common in Rajasthan (Shukla *et al.*, 2019) [17]. Zinc plays a crucial role in enzyme activation, protein synthesis, chlorophyll formation, and carbohydrate metabolism in plants. Deficiency of zinc not only reduces crop yield but also lowers grain

nutritional quality, contributing to zinc malnutrition in human populations. Zinc biofortification through soil application, seed treatment, or use of *zinc-solubilizing bacteria* (ZnSB) has emerged as a promising strategy to enhance zinc availability, improve crop productivity, and increase grain zinc concentration (Bogale *et al.*, 2025) [2]. Economic viability is a major concern for farmers in semi-arid regions where rising input costs often limit adoption of improved nutrient management practices. Therefore, in view of the above facts, the present study has been undertaken to evaluate an economically viable treatment for enhancing barley productivity.

Materials and Methods

A field experiment was conducted during the *rabi* seasons of 2023–24 and 2024–25 at the Instructional Farm, Department of Agronomy, Rajasthan College of Agriculture, MPUAT, Udaipur (Rajasthan). The region falls under NARP agro-climatic zone IVa (Sub- Humid Southern Plain and Aravalli Hills) of Rajasthan at longitude 73°42'E and latitude 24°35'N with an altitude of 582.17 m above the mean sea level. Composite soil samples collected from 0–15 cm depth prior to sowing revealed that the soil of experimental site was clay-loam, alkaline (pH 7.8 and 8.1), low in available nitrogen (276.5 and 277.6 kg/ha), medium in available phosphorus (18.60 and 19.00 kg/ha), high in available potassium (371.9 and 372.8 kg/ha) and deficient in available zinc (0.582 and 0.589 mg/kg) during *rabi* 2023-24 and 2024-25, respectively. The experimental site is characterized by a subtropical climate with scorching summers and high relative humidity during the monsoon season. The region receives rainfall mainly from the south-western monsoon, with an average annual rainfall of 664.33 mm, most of which occurs between July and September.

Table 1: Treatment details with symbols

A. Fertility Levels (04)		Symbols
Absolute control		F ₀
50% RDF +50% FYM		F ₁
75% RDF +25% FYM		F ₂
100% RDF		F ₃
B. Zinc Biofortification (04)		
Control		Zn ₀
2.5 kg ha ⁻¹ Zn + Zinc Solubilising Bacteria @ 5.0 ml kg ⁻¹ seed		Zn ₁
5 kg ha ⁻¹ Zn		Zn ₂
Zinc Solubilising Bacteria @ 5.0 ml kg ⁻¹ seed (sole)		Zn ₃

The experiment comprised 16 treatment combinations involving 4 fertility levels (absolute control, 50% RDF + 50% FYM, 75% RDF + 25% FYM and 100% RDF) assigned to main plots and 4 zinc biofortification treatments (control, 2.5 kg Zn/ha + *Zinc Solubilising Bacteria* at 5.0 ml/kg seed, 5 kg Zn/ha and *Zinc Solubilising Bacteria* at 5.0 ml/kg seed) to subplots using barley variety “DWRB-137” in a split plot design. The recommended dose of fertilizers (RDF) for test crop was 60-30-20 kg N-P-K/ha used. Half dose of nitrogen and full dose of phosphorus, potassium and zinc were applied as basal while the remaining nitrogen was top dressed in two equal splits after first and second irrigations. The integrated nutrient management treatments were formulated on nitrogen equivalent basis. In the treatment comprising 50% RDF + 50% FYM, 50% of the recommended nitrogen was supplied through inorganic fertilizers, while the remaining 50% was supplied through FYM. Similarly, in 75% RDF + 25% FYM, 75% of nitrogen was applied through chemical fertilizers and 25% through FYM. The quantity of FYM required was calculated based on its nitrogen

content, assuming 0.5% N (5 kg N per tonne of FYM). Accordingly, FYM was applied @ 6.0 t ha⁻¹ and 3.0 t ha⁻¹ in 50% RDF + 50% FYM and 75% RDF + 25% FYM treatments, respectively. The FYM used in the experiment was well-decomposed and applied uniformly before sowing. Zinc was applied through zinc sulphate monohydrate (ZnSO₄·H₂O, containing 33% Zn) at the rates of 2.5 and 5.0 kg Zn ha⁻¹. The required quantity of zinc fertilizer was calculated on elemental Zn basis and applied as basal dose. *Zinc Solubilising Bacteria* obtained from Liquid Biofertilizer Production Laboratory, MPUAT, Udaipur was used for seed treatment at 5.0 ml/kg seed. Each treatment was replicated three times resulting in 48 plots. Gross plot size was 6.0 m × 2.4 m (14.40 m²) and net plot size was 5.0 m × 2.0 m (10.0 m²). The fertilizers and FYM was applied as per treatments. The crop was sown manually in furrows opened to a depth of 4–5 cm using a seed rate of 100 kg/ha with a row spacing of 20 cm on 04 November and 14 November and harvested on 10 March and 18 March during 2023-24 and 2024-25, respectively.

Grain, straw and biological yields were recorded from the net plot after harvest and threshing and expressed in kg/ha after conversion. Gross return were estimated using the prevailing minimum supporting price while cost of cultivation was calculated based on current input prices (₹/ha). Net return was obtained by deducting cost of cultivation from gross return and the benefit: cost ratio was computed accordingly. Experimental data were analyzed statistically using ANOVA with treatment significance tested at 5 per cent probability level.

Results and Discussion

Fertility levels

The pooled data indicate that fertility levels exerted a significant influence on grain, straw and biological yields of barley during both the years (Table 1). Application of 75% RDF + 25% FYM resulted in the highest grain yield which was found at par with 100% RDF and 50% RDF + 50% FYM. The barley crop fertilized with 75% RDF + 25% FYM registered a 24.54% increase over the absolute control. Further analysis of data showed that straw yield was maximized with 75% RDF + 25% FYM on pooled basis which was significantly higher than 50% RDF + 50% FYM and the control. A similar trend was observed for biological yield, where 75% RDF + 25% FYM recorded the highest pooled biological yield and statistically at par with 100% RDF indicate that partial substitution of inorganic fertilizers with FYM can sustain productivity while improve overall system efficiency. The economic analysis of data revealed that application of 75% RDF + 25% FYM recorded the highest net return and B: C ratio which was comparable with 100% RDF and significantly superior to 50% RDF + 50% FYM and absolute control.

The combined application of 75% RDF and 25% FYM ensured both immediate nutrient supply from inorganic fertilizers and gradual nutrient release from organic source leading to optimal nutrition throughout the crop's growth period. FYM enhance soil structure, moisture retention, microbial health and root proliferation, all of which support greater biomass production and yield (Behera and Pany, 2021) [1].

The higher grain yield obtained with the application of 75% RDF + 25% FYM may be integrated application of chemical fertilizers and FYM markedly improved dry matter accumulation per unit area by enhanced morphological traits and photosynthetic efficiency, leading to greater nutrient uptake and metabolite availability for vegetative and reproductive growth of the crop. Grain yield is a complex trait governed by the

collective interaction of effective tillers, ear length, grains per ear and test weight. The yield advantage under integrated nutrient management can be attributed to simultaneous improvement in these yield-determining components. Similar responses under integrated nutrient management have been reported by Fazily *et al.* (2021) [4] and Kumar *et al.* (2024) [9].

The significant increase in straw yield observed under the application of 75% RDF + 50% FYM may be attributed to enhanced dry matter production at successive growth stages resulting from improved photosynthetic efficiency. Additionally, higher nutrient uptakes under adequate fertilization promote the development of productive tillers, longer spikes and higher grains per ear resulting in increased straw yield. The marked increase in biological yield under integrated application of RDF and FYM can be ascribed to its combined effect on both vegetative growth and reproductive development. These findings are in close agreement with the results reported by Prasad *et al.* (2019) [11] and Kumari *et al.* (2024) [10].

A higher net return and B: C ratio was recorded under the application of 75% RDF + 25% FYM indicate the economic viability of integrating organic and inorganic nutrient sources. Use of 75% RDF reduced the cost of chemical fertilizers. FYM lowered input costs compare to use of 100% chemical fertilizers. FYM improved nutrient uptake efficiency, leading to high productivity per unit input cost and long-term use of FYM contribute to soil carbon and microbial health which supported sustainable yield and economic return. This combination maintain yield equivalent to 100% RDF due to balanced and sustained nutrient supply. The treatment 75% RDF + 25% FYM resulted similar yield to 100% RDF but with lower input cost, improved nutrient efficiency and better soil health. This leads to higher economic return making it a cost-effective and sustainable nutrient management strategy. These finding are align with Jat *et al.* (2021) [7], shivani *et al.* (2024) [16] and Singh *et al.* (2025) [18].

Zinc biofortification

Zinc biofortification significantly influenced grain, straw and biological yield as well as economic return of barley during both seasons: On pooled analysis, application of 2.5 kg Zn/ha + *Zinc Solubilising Bacteria* at 5.0 ml/kg seed recorded the highest grain yield which statistically at par with 5 kg Zn/ha and *ZnSB* applied alone and significantly superior to the control. A similar trend was observed for straw yield, the maximum pooled straw yield obtained under 2.5 kg Zn/ha + *ZnSB* comparable with 5 kg Zn/ha but significantly higher than *ZnSB* alone and the control. Likewise, the highest pooled biological yield was recorded under 2.5 kg Zn/ha + *ZnSB* followed by 5 kg Zn/ha both outperformed the control. The economic analysis further revealed that 2.5 kg Zn/ha + *ZnSB* produced the maximum pooled net return and benefit: cost ratio which was comparable with 5 kg Zn/ha and significantly higher than *ZnSB* alone and control.

The application of 2.5 kg Zn/ha + *Zinc Solubilising Bacteria* at 5.0 ml/kg seed resulted significantly higher yield attributing characters such as the number of effective tillers, grains per ear and yield (grain, straw and biological yield). These results were statistically at par with 5 kg/ha Zn. Zinc is a vital micronutrient involved in enzyme activation, protein synthesis, auxin metabolism and reproductive development which directly affect flowering, grain setting and seed filling. Adequate zinc availability enhances tillering, spike development and grain formation. Effective tiller count is a key determinant of grain

yield making this parameter important for evaluating treatment efficacy. The synergistic interaction between *ZnSB* and applied zinc improves zinc use efficiency leading to improved physiological functions and greater partitioning of photosynthates into grain and straw biomass (Ramesh *et al.*, 2014) [12]. These yield improvements were attributed to the efficient nutrient mobilizing ability and strong plant growth promoting traits of these microbial strains even under stress conditions. In the present study, co-inoculation of *ZnSB* with Zn led to an increase in straw yield. The resulting crop performance of both yield components and total productivity becomes comparable to that of the higher zinc dose (5 kg Zn/ha) when used with *ZnSB* alone. Several studies have further confirmed the positive effects of zinc-solubilizing bacteria on grain yield enhancement. Similar findings were observed by Shakeel *et al.* (2015) [15] and Hussain *et al.* (2018) [6].

Significantly higher net return and benefit: cost ratio of barley was gained by applying 2.5 kg Zn/ha + *Zinc Solubilising Bacteria* at 5.0 ml/kg seed. The synergistic effect of zinc and *ZnSB* at a reduced zinc rate (2.5 kg Zn/ha) thus matches or surpasses the performance of higher zinc rates without microbes, optimizing growth while reducing input costs. The input cost of 2.5 kg Zn/ha + *ZnSB* is lower than that of applying 5 kg Zn/ha alone. However, because *ZnSB* boosts the availability of even small amounts of Zn, the yield remains comparable, resulting in a higher net return. Economically, this leads to a better benefit: cost ratio, as the same output is achieved with less expenditure reported by Rangaswamy *et al.* (2024) [13].

Interaction effect of fertility levels and zinc biofortification

Pooled analysis revealed a significant interaction between fertility levels and zinc biofortification treatments on grain yield and benefit: cost ratio (Table 3 and 4). The highest grain yield (77063 ₹/ha) was recorded with the combined application of 75% RDF + 25% FYM along with *Zinc Solubilising Bacteria* at 5.0 ml/kg seed which remained statistically at par with treatment combinations involving 75% RDF + 25% FYM with 5 kg/ha Zn, 100% RDF with 2.5 kg Zn/ha + *Zinc Solubilising Bacteria* and 50% RDF + 50% FYM combined with either 2.5 kg Zn/ha + *Zinc Solubilising Bacteria* or 5 kg Zn/ha. In contrast, the interaction of absolute control along with control treatment gave significantly lower grain yield. Similarly, the maximum B: C ratio (2.49) was obtained under the interaction of 75% RDF + 25% FYM with 2.5 kg/ha Zn + *Zinc Solubilising Bacteria*, which was statistically comparable with combinations of 75% RDF + 25% FYM with 5 kg Zn/ha, 75% RDF + 25% FYM with *Zinc Solubilising Bacteria* alone and control combined with either 2.5 kg Zn/ha + *Zinc Solubilising Bacteria* or 5 kg Zn/ha, indicating the economic advantage of integrated nutrient and zinc management.

75% RDF + 25% FYM with *Zinc Solubilising Bacteria* at 5.0 ml/kg seed recorded higher grain yield. This might be due to the integrated nutrient management strategy optimally supports the physiological and morphological needs of barley during its critical tillering stage resulting in maximum effective tillers and ultimately contributing to higher yield. Benefit: cost ratio was higher with the treatment combination of 75% RDF + 25% FYM along with 2.5 kg Zn/ha + *Zinc Solubilising Bacteria* at 5.0 ml/kg seed. This result might be due to lower fertilizer input, reduces costs and the extra yield and quality gain from Zn + *ZnSB* outweighs added cost, boosting net profit and producing a superior B: C ratio compared to other treatments.

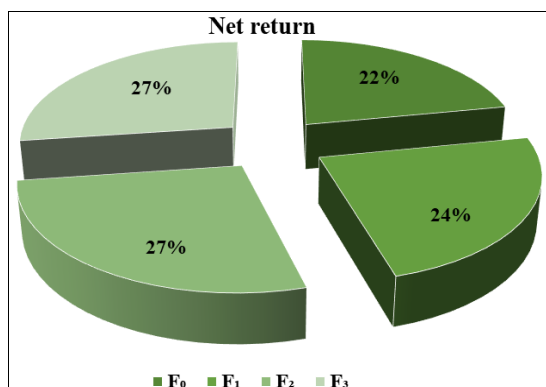


Fig 1: Effect of fertility levels on net return of barley

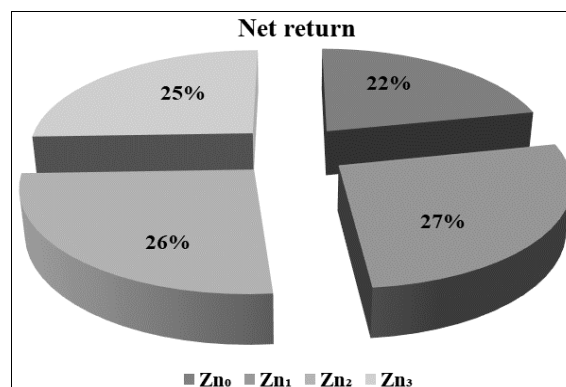


Fig 2: Effect of zinc biofortification on net return of barley

Table 2: Effect of fertility levels and zinc biofortification on yield and economics of barley (pooled data of 2023-24 and 2024-25)

Treatments	Yield (kg/ha)			Net return (₹/ha)	B: C ratio
	Grain	Straw	Biological		
Fertility Levels					
Absolute control	4338	8217	12679	63147	2.03
50% RDF + 50% FYM	5137	9251	14768	68065	2.20
75% RDF + 25% FYM	5403	9791	15588	78165	2.39
100% RDF	5183	9561	15166	78027	2.29
S.Em.±	87	153	320	-	-
C.D.(P=0.05)	268	473	1109	-	-
Zinc Biofortification					
Control	4547	8502	13239	62275	1.95
2.5 kg/ha Zn + Zinc Solubilising Bacteria (5.0 ml/kg seed)	5257	9700	15278	77063	2.38
5 kg/ha Zn	5163	9396	14975	74627	2.29
Zinc Solubilising Bacteria (5.0 ml/kg seed)	5095	9223	14707	73439	2.28
S.Em.±	58	126	206	-	-
C.D.(P=0.05)	164	359	601	-	-

RDF=recommended dose of fertilizer; FYM= farm yard manure

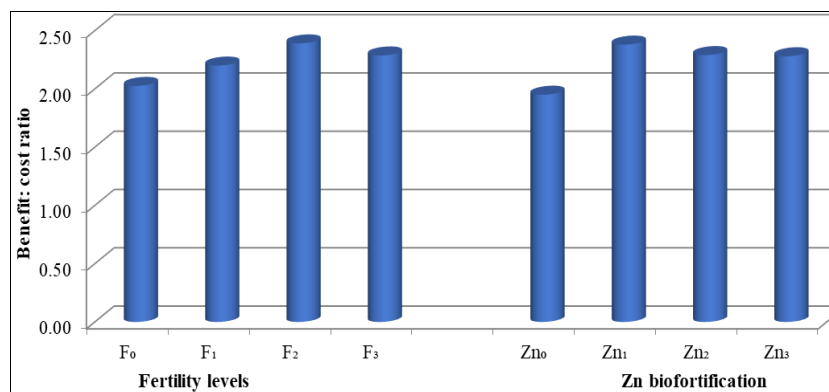


Fig 3: Effect of fertility levels and zinc biofortification on B: C ratio of barley

Table 3: Interaction effects of fertility levels and zinc biofortification on grain yield of barley (Pooled)

Zinc Biofortification	Fertility Levels			
	F ₀	F ₁	F ₂	F ₃
Zn ₀	3672	4692	5042	4781
Zn ₁	4770	5325	5608	5342
Zn ₂	4713	5298	5404	5235
Zn ₃	4197	5233	5556	5375
			S.E.m.(±)	C.D. (P=0.05)
Zinc Biofortification at the same level of Fertility			115	327
Fertility at the same level of Zinc Biofortification			132	389

Treatment details with symbols are given table 1

Table 4: Interaction effects of fertility levels and zinc biofortification on B: C ratio (Pooled)

Zinc Biofortification	Fertility Levels			
	F ₀	F ₁	F ₂	F ₃
Zn ₀	1.62	1.96	2.17	2.05
Zn ₁	2.30	2.30	2.49	2.41
Zn ₂	2.24	2.26	2.38	2.29
Zn ₃	1.94	2.26	2.42	2.39
			S.Em.(±)	C.D. (P=0.05)
Zinc biofortification at the same level of fertility			0.07	0.20
Fertility at the same level of zinc biofortification			0.08	0.24

Treatment details with symbols are given table 1

Table 5: Treatment wise costs of cultivation, yield and economic return (pooled of 2023-24 and 2024-25)

S. No.	Treatment combination	Seed yield (kg/ha)	Straw yield (kg/ha)	Gross return (₹/ha)	Cost of cultivation (₹/ha)	Net return (₹/ha)	Benefit: cost ratio
1.	F ₀ Zn ₀	3672	7491	80899	30915	49984	1.62
2.	F ₀ Zn ₁	4770	8817	103237	31243	71994	2.30
3.	F ₀ Zn ₂	4713	8566	101714	31390	70324	2.24
4.	F ₀ Zn ₃	4197	7992	91291	31005	60286	1.94
5.	F ₁ Zn ₀	4692	8750	101711	34395	67316	1.96
6.	F ₁ Zn ₁	5325	9517	114579	34723	79856	2.30
7.	F ₁ Zn ₂	5298	9401	113875	34870	79005	2.26
8.	F ₁ Zn ₃	5233	9338	112568	34485	78082	2.26
9.	F ₂ Zn ₀	5042	8933	108352	34136	74216	2.17
10.	F ₂ Zn ₁	5556	10350	120392	34463	85929	2.49
11.	F ₂ Zn ₂	5404	9999	116966	34611	82356	2.38
12.	F ₂ Zn ₃	5608	9882	120383	34226	86158	2.52
13.	F ₃ Zn ₀	4781	8833	103461	33876	69586	2.05
14.	F ₃ Zn ₁	5375	10117	116673	34203	82470	2.41
15.	F ₃ Zn ₂	5235	9618	113174	34351	78823	2.29
16.	F ₃ Zn ₃	5342	9678	115195	33966	81229	2.39

Conclusion

The pooled result of two consecutive *rabi* seasons (2023–24 and 2024–25) revealed that fertility levels and zinc biofortification significantly influenced the productivity and economic returns of barley under the agro-climatic conditions of southern Rajasthan. Application of 75% RDF + 25% FYM produced grain yield comparable to 100% RDF while recorded higher net returns and benefit: cost ratio due to reduced fertilizer input cost and improved nutrient use efficiency. Among zinc biofortification treatments, soil application of 2.5 kg Zn/ha in combination with *Zinc Solubilising Bacteria* at 5.0 ml/kg seed proved most effective and economical, performing on par with 5 kg Zn/ha. The interaction effect further confirmed that the combined application of 75% RDF + 25% FYM along with 2.5 kg Zn/ha + *ZnSB* resulted in the highest grain yield and benefit: cost ratio. Therefore, this integrated use of RDF, FYM coupled with zinc biofortification through Zn and *ZnSB* is recommended for sustainable barley production.

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