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Enhancing nutritional quality of vegetables through sustainable soil microbial approaches

Raju Lal Bhardwaj[1*], Aabha Parashar[2], Premlata Meena[2] and K. Choudhary[1]

[1]College of Agriculture, Sumerpur-Pali, Agriculture University, Jodhpur 306902, Rajasthan

ABSTRACT

The long-term use of nitrogen-based chemical fertilizers in vegetable production has led to a decline in essential minerals and organoleptic quality. The study examined the effects of varying proportions of chemical and organic nutrient sources, with or without plant growth-promoting microbes (PGPM) inoculation, on vegetable nutritional quality. Results indicate that replacing chemical fertilizers with organic manures and microbial consortia significantly enhances dietary value, with mean increase in crude fat (37.78%), crude fiber (10.82%), total carbohydrates (0.73%), total sugars (78.10%), calcium (10.83%), phosphorus (8.75%), iron (46.63%), zinc (53.92%), magnesium (6.80%), nitrogen (15.95%), and potassium (5.55%). Additionally, organoleptic scores improved by 15.69%, while *in-vitro* protein and starch digestibility increased by 11.04 and 11.54%, respectively, over four years. In conclusion, organic nutrition combined with PGPMs effectively restores nutritional density and organoleptic quality while mitigating nutrient dilution in vegetables, ensuring better human nutrition.

Key words: Chemical fertilizers, *in-vitro* digestibility, nutrient dilution, organic sources.

INTRODUCTION

India is the world's second-largest vegetable producer after China, with 212.55 million metric tons in 2022–23, contributing 15% to global production from 11.35 million hectares. It leads in okra and onion production, ranks second for potato, brinjal, and cabbage, and holds a strong position in tomato, pea, radish, cowpea, and cluster bean (FAO, 3). Vegetables are vital for nutritional security, offering essential minerals, fiber, and carbohydrates. However, declining plant nutritional quality and widespread micronutrient deficiencies pose serious health and economic concerns. Key vegetables like tomato, onion, potato, pea, cabbage, and okra have lost 25–50% of their original nutrient density over the past 80 years (Mayer *et al*., 11), with notable reductions in vitamins A and C, iron, calcium, and other essential nutrients (Gopalakrishnan, 6). Nutrient depletion is linked to unsustainable agricultural practices, soil degradation, microbial decline, and excessive chemical fertilizer use, which disrupts soil ecosystems and diminishes farm produce quality (Bhardwaj *et al*., 1; Han *et al*., 7; Huang *et al*., 8). Despite their role in enhancing productivity, chemical fertilizers contribute to soil health deterioration. In contrast, organically grown vegetables contain higher levels of protein, essential minerals, polyphenols, and phytochemicals, improving both nutritional and organoleptic qualities (Bhardwaj *et al*., 2; Popa *et al*., 15; Rahman *et al*., 19).

This study explores nutrient management strategies to counteract the adverse effects of excessive chemical fertilization. Approaches include restoring soil biodiversity (Pretty *et al*., 16), microbial inoculation (Gomiero, 5), earthworm enhancement (Bhardwaj *et al*., 1), green manuring, soil amendments, and farm waste recycling (Bhardwaj *et al*., 2). Plant growth-promoting microbes (PGPMs) improve nutrient availability and phytohormone modulation (Glick and Gamalaro, 4), enhancing soil organic matter, water retention, and carbon sequestration. Given the limited research on organic amendments and microbial consortia in improving vegetable nutrition, this experiment investigates optimal fertilization ratios and PGPM contributions to mitigating nutritional dilution in key vegetables.

MATERIALS AND METHODS

Long-term field research at the Agricultural Research Substation, Sumerpur-Pali (Rajasthan), India, assessed the impact of different nutrient supply sources on the nutritional and organoleptic quality of ten key vegetable crops potato, cabbage, tomato, brinjal, onion, pea, radish, cowpea, okra, and cluster beans under arid conditions. The initial (2019-20) soil nutrient status was: organic carbon (0.29%), N_2 (220 kg/ha), P_2O_5 (37.5 kg/ha), K_2O (225.4 kg/ha), S (7.55 ppm), Zn (0.35 ppm), Fe (1.85 ppm), Cu (0.60 ppm), and Mn (5.99 ppm), with a sandy loam texture. The experiment followed a Randomized Block Design with six nutrient treatments (NS_1-NS_6) and four replications: NS_1 [100% recommended dose

*Corresponding author: rajubhardwaj3@gmail.com

[2]Agricultural Research Sub Station, Sumerpur-Pali, Agriculture University, Jodhpur 306902, Rajasthan

of fertilizer (RDF) chemical], NS_2 (75% RDF chemical + 25% RDF organic), NS_3 (50% RDF chemical + 50% RDF organic), NS_4 (25% RDF chemical + 75% RDF organic), NS_5 (100% RDF organic), and NS_6 [100% RDF organic + plant growth promoting subtances (PGPMs)] (Fig. 1). Chemical fertilizers were sourced from IFFCO outlets, and PGPMs from the ICAR-IARI Microbiology Department. Standard agronomic practices were followed, with results presented for the last two years (2022-23 and 2023-24).

All parameter analyses were conducted in triplicate, with data expressed as g/100 g dry matter. Vegetable samples were randomly selected from each treatment and replication. Moisture content was determined by calculating the percentage weight loss of fresh samples. Protein content was analyzed using the AACC-approved Dumas combustion nitrogen method (N × 6.25). Crude fat estimation followed the standard method using an Automatic SOCS plus Solvent Extraction Apparatus. Fiber content was assessed using the total dietary fibre assay kit, while total carbohydrates (%) were calculated as: 100 - [moisture (%) + crude protein (%) + crude fat (%) + crude fiber (%) + total ash (%)]. Total nitrogen (N) was measured using the micro-Kjeldahl method, and phosphorus was analyzed with a vanadate-molybdate reagent, with absorbance recorded at 420 nm. Total sugars were estimated by anthrone method. Potassium levels were determined using a flame photometer, while Fe, Zn, Ca, and Mg in acid-digested samples were quantified *via* Atomic Absorption Spectrophotometry. Organoleptic evaluation was performed by a panel of seven semi-trained judges using a 9-point hedonic scale. *In-vitro* starch and protein digestibility were assessed using standard estimation methods. Statistical analysis included ANOVA, with means compared through per cent change calculations and separated by post hoc Tukey's test at α = 0.05 ($p < 0.05$). To characterize nutrient supply sources, principal component analysis (PCA) was performed based on correlations. Data analysis was conducted using JMP software (SAS Institute Inc., Cary, NC, USA, version 8).

RESULTS AND DISCUSSION

Moisture and crude protein content in potato tubers, onion bulbs, and radish roots slightly decreased with an increasing proportion of organic sources and PGPM inoculation. The NS_1 treatment yielded the highest crude protein content (1.50, 1.71, and 0.64% in potato, onion, and radish, respectively), significantly ($p < 0.001$) surpassing other treatments (Table 1). In contrast, crude fat and crude fiber content increased linearly with organic inputs, reaching significantly higher levels in NS_6-treated crops–by 24.14 and 18.52% in potatoes, 39.29 and 24.60% in onions, and 58.82 and 6.48% in radishes compared to NS_1. Similarly, total carbohydrates and

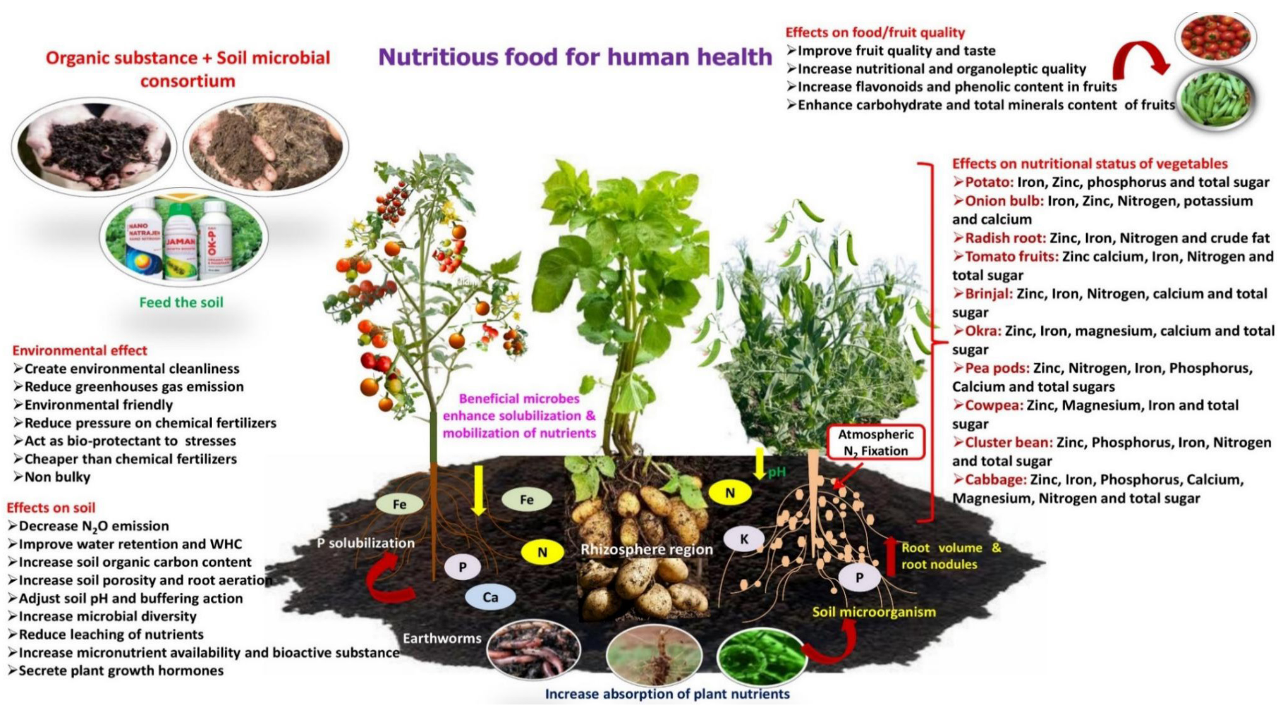

Fig. 1. Schematic representation of effects of organic fertilizers (biofertilizer; arbuscular mycorrhiza fungi; plant growth-promoting rhizobacteria) on nutrient status of vegetable crops and surrounding environment.

Table 1. Effect of nutrient supply sources on nutritional and organoleptic quality of underground vegetables (potatoes, onions and radish).

Quality parameter	NS_1	NS_2	NS_3	NS_4	NS_5	NS_6	S.Em ±	CD (p = 0.05)	Per cent change
Potato tuber (100 g of pulp)									
Moisture (%)	86.24	84.33	82.03	81.46	81.44	81.38	0.792	**	-5.64
Crude protein (%)	1.50	1.48	1.39	1.31	1.34	1.38	0.026	**	-8.00
Crude fat (%)	0.29	0.29	0.31	0.33	0.35	0.36	0.006	**	24.14
Crude fiber (%)	1.62	1.66	1.75	1.78	1.81	1.92	0.041	**	18.52
Total carbohydrates (g)	86.22	86.46	86.27	86.24	86.29	86.35	0.857	NS	0.15
Total sugars (%)	0.86	0.88	0.93	1.14	1.2	1.22	0.445	**	41.86
Calcium (mg)	22.15	22.38	22.53	22.76	22.92	23.78	0.455	NS	7.36
Phosphorus (mg)	37.87	37.86	38	38.18	40.5	41.12	0.577	**	8.58
Iron (mg)	0.9	1.02	1.34	1.42	1.65	1.72	0.047	**	91.11
Zinc (mg)	0.35	0.36	0.36	0.41	0.49	0.56	0.006	**	60.00
Magnesium (mg)	22.38	22.41	22.53	22.76	22.92	23.37	0.414	NS	4.42
Nitrogen (g)	0.24	0.23	0.22	0.21	0.20	0.26	0.006	**	8.33
Potassium (mg)	490.41	490.63	492.76	494.31	498.43	512.44	4.089	*	4.49
Organoleptic score**	6.60	6.69	6.81	6.94	7.26	7.68	0.087	**	16.36
Protein digestibility (%)*	69.27	70.26	73.99	74.37	76.59	77.89	0.904	**	12.44
Starch digestibility (%)*	83.11	85.90	86.26	87.88	89.50	92.11	0.906	**	10.83
Onion bulb (100 g of pulp)									
Moisture (%)	85.97	85.48	85.24	85.01	84.78	84.66	1.316	NS	-4.39
Crude protein (%)	1.71	1.68	1.6	1.56	1.57	1.63	0.009	**	-4.68
Crude fat (%)	0.26	0.29	0.29	0.34	0.36	0.41	0.008	**	39.29
Crude fiber (%)	2.48	2.5	2.54	2.9	3.03	3.09	0.082	**	24.60
Total carbohydrates (g)	89.84	88.53	86.09	86.20	86.15	90.45	0.898	*	0.68
Total sugars (%)	6.45	6.59	6.92	7.23	8.72	8.96	0.082	**	38.91
Calcium (mg)	20.27	20.57	20.70	21.55	21.94	22.07	0.490	NS	8.88
Phosphorus (mg)	36.32	36.45	36.8	37.25	37.81	38.12	0.531	**	8.70
Iron (mg)	1.66	2.04	2.45	2.51	2.73	2.77	0.041	**	66.87
Zinc (mg)	1.92	2.04	2.45	2.53	2.65	2.79	0.043	**	45.31
Magnesium (mg)	16.62	16.68	16.98	17.29	17.46	17.68	0.451	NS	6.38
Nitrogen (g)	0.27	0.27	0.26	0.25	0.24	0.32	0.004	**	18.52
Potassium (mg)	168.79	170.12	170.53	171.1	175.28	182.55	1.333	**	8.15
Organoleptic score**	7.30	7.48	7.75	8.01	8.23	8.41	0.129	**	15.21
Protein digestibility (%)*	83.86	87.23	89.09	86.74	87.03	89.67	0.925	**	6.93
Starch digestibility (%)*	69.37	72.25	72.57	72.8	73.39	74.58	1.147	NS	7.51
Radish root (100 g of pulp)									
Moisture (%)	90.05	89.68	89.25	88.94	88.58	88.49	1.555	NS	-1.73
Crude protein (%)	0.64	0.58	0.55	0.48	0.49	0.52	0.004	**	-18.75
Crude fat (%)	0.15	0.17	0.19	0.23	0.25	0.28	0.006	**	58.82
Crude fiber (%)	2.47	2.54	2.48	2.54	2.58	2.63	0.061	NS	6.48

Contd...

Table 1 contd...

Quality parameter	NS_1	NS_2	NS_3	NS_4	NS_5	NS_6	S.Em ±	CD (p = 0.05)	Per cent change
Total carbohydrates (g)	86.26	86.01	86.21	86.27	86.27	87.15	0.877	NS	1.03
Total sugars (%)	1.87	1.07	1.31	1.42	2.43	2.61	0.087	**	39.57
Calcium (mg)	30.31	30.56	30.75	31.68	32.33	32.41	0.445	**	6.93
Phosphorus (mg)	28.35	28.62	28.63	29.32	29.54	30.55	0.455	*	7.76
Iron (mg)	0.43	0.44	0.48	0.52	0.6	0.65	0.005	**	51.16
Zinc (mg)	0.29	0.31	0.35	0.40	0.45	0.63	0.013	**	67.74
Magnesium (mg)	14.87	14.9	15.07	15.28	15.63	15.69	0.216	NS	5.51
Nitrogen (g)	0.10	0.09	0.08	0.07	0.09	0.16	0.006	**	30.00
Potassium (mg)	283.29	283.39	283.66	284.09	284.61	298.12	3.062	*	5.23
Organoleptic score**	6.99	7.00	7.04	7.21	7.56	7.83	0.164	**	12.02
Protein digestibility (%)*	65.39	66.51	67.94	68.86	70.4	72.14	0.735	**	10.32
Starch digestibility (%)*	62.1	63.29	65.75	66.68	67.31	69.48	0.776	**	11.88

**In-vitro* digestibility; N.S. non-significant at (p=0.05); **Organoleptic score out of 10 marks; *Significant at (p = 0.001)

total sugars were highest in NS_6 (86.35 and 1.22% in potato, 90.45 and 8.96% in onion, and 87.15 and 2.61% in radish), reflecting increases of 0.15 and 41.86, 0.68 and 38.91%, and 1.03 and 39.57%, respectively, over NS_1.

NS_6 treatment significantly improved mineral nutrient levels: calcium increased by 7.36, 8.88, and 6.93%; phosphorus by 8.58, 8.70, and 7.76%; iron by 91.11, 66.87, and 51.16%; zinc by 60, 45.31, and 67.74%; nitrogen by 8.33, 18.52, and 30%; and potassium by 4.49, 8.15, and 5.23% in potato, onion, and radish, respectively. Magnesium content showed a non-significant increase (4.42, 6.38, and 5.51%). Organoleptic quality improved significantly with organic inputs, scoring 7.68 (potato), 8.41 (onion), and 7.83 (radish) in NS_6-16.36, 15.21, and 12.02% higher than NS_1. *In-vitro* protein and starch digestibility also followed an increasing trend, peaking in NS_6 at 77.89 and 92.11% (potato), 89.67 and 74.58% (onion), and 72.14 and 69.48% (radish), marking substantial improvements over chemical fertilizer treatments.

Specifically, in NS_6 treatment tomato fruits led to an increase in crude fat (46.34%), crude fiber (8.72%), total carbohydrates (0.71%), total sugars (70.73%), calcium (31.44%), phosphorus (4.21%), iron (29.81%), zinc (51.72%), magnesium (2.42%), nitrogen (17.78%), potassium (5.12%), organoleptic score (23.30%), *in-vitro* protein digestibility (5.48%), and *in-vitro* starch digestibility (10.38%) compared with the NS_1 treatment, whereas NS_5 treatment was at par with the NS_6 treatment on many components and total carbohydrates, phosphorus, magnesium contentment of vegetables was non-significantly increased. Brinjal fruits from the NS_6 treatment exhibited significantly higher nutritional and organoleptic quality compared to all other treatments, except for total carbohydrates, phosphorus, and potassium. The NS_5 treatment closely followed, while NS_1 produced the lowest values across all measured parameters.

NS_6-treated brinjal fruits had the highest levels of crude fat (0.48%), crude fiber (4.15%), total sugars (3.07 g), calcium (18.43 mg), iron (0.63 mg), zinc (0.37 mg), magnesium (24.33 mg), nitrogen (0.27 g), organoleptic score (8.23), *in-vitro* protein digestibility (82.45%), and *in-vitro* starch digestibility (73.56%) per 100 g. Compared to NS1, these values increased significantly by 30.56, 5.33, 83.19, 12.93, 47.62, 71.43, 9.45, 17.39, 17.91, 12.62, and 13.55%, respectively. The results showed that organic sources with PGPMs inoculated filed okra fruits contain significantly more nutrients with higher organoleptic scores like crude fat increasing from 0.27 to 0.38% (35.71%), crude fibre 4.01 to 4.65% (15.96%), total sugars 0.83 to 1.52% (83.13%), calcium 85.95 to 95.12 mg 100 g^{-1} (10.67%), iron 0.99 to 1.62 mg 100g^{-1} (63.64%), zinc 0.31 to 0.67 mg 100g^{-1} (67.74%), magnesium 65.19 to 72.55 mg 100g^{-1} (11.29%), nitrogen 0.32 to 0.33 g 100 g^{-1} (3.13%), potassium 262.17 to 281.47 mg 100g^{-1} (7.39%), *in-vitro* protein digestibility 65.32 to 72.11% (10.39%), and *in-vitro* starch digestibility 51.71 to 56.87% (9.98%) than those produce from only chemical sources supplying fields (Table 2).

The results exhibited a notable decrease in moisture content in pods produced in NS_6 treatment, ranging from 74.22 to 72.80% (-1.91%) in pea pods, 90.66 to 89.52% (-1.26%) in cowpea pods

Table 2. Effect of nutrient supply sources on nutritional and organoleptic quality of fruit- vegetables (Tomato, brinjal and okra).

Quality parameter	NS_1	NS_2	NS_3	NS_4	NS_5	NS_6	S. Em ±	CD (p = 0.05)	Per cent change
Tomato fruit (100 g of pulp)									
Moisture (%)	96.42	95.13	94.66	92.66	92.16	92.10	1.184	NS	-4.48
Crude protein (%)	2.85	2.84	2.82	2.63	2.69	2.72	0.036	**	-4.56
Crude fat (%)	0.41	0.41	0.45	0.51	0.56	0.60	0.004	**	46.34
Crude fiber (%)	1.72	1.52	1.57	1.81	1.80	1.87	0.041	**	8.72
Total carbohydrates (g)	85.94	86.32	86.09	86.17	86.15	86.31	0.858	NS	0.71
Total sugars (%)	2.05	2.1	2.53	2.73	3.04	3.5	0.045	**	70.73
Calcium (mg)	10.21	10.62	10.75	12.88	13.28	13.42	0.453	**	31.44
Phosphorus (mg)	18.75	18.85	18.99	19.24	19.5	19.54	0.289	NS	4.21
Iron (mg)	1.04	1.09	1.13	1.18	1.28	1.35	0.045	**	29.81
Zinc (mg)	0.29	0.31	0.34	0.38	0.43	0.51	0.005	**	51.72
Magnesium (mg)	13.64	13.62	13.69	13.7	13.87	13.94	0.413	NS	2.42
Nitrogen (g)	0.45	0.45	0.45	0.42	0.43	0.53	0.004	**	17.78
Potassium (mg)	201.22	203.45	204.57	206.95	207.72	211.52	2.045	*	5.12
Organoleptic score**	6.91	7.05	7.38	7.8	8.08	8.52	0.205	**	23.30
Protein digestibility (%)*	84.91	85.95	87.47	87.64	88.97	79.56	1.021	*	5.48
Starch digestibility (%)*	74.78	76.23	78.87	79.8	81.19	82.54	1.027	**	10.38
Brinjal fruit (100 g of pulp)									
Moisture (%)	90.22	90.16	90.1	90.02	89.91	89.84	1.435	NS	0.42
Crude protein (%)	1.43	1.38	1.29	1.22	1.25	1.31	0.021	**	-8.39
Crude fat (%)	0.34	0.36	0.37	0.41	0.43	0.48	0.002	**	30.56
Crude fiber (%)	3.94	3.93	3.95	4.02	4.09	4.15	0.021	**	5.33
Total carbohydrates (g)	85.53	85.54	86.10	85.57	85.54	85.74	0.837	NS	0.25
Total sugars (%)	0.87	1.16	1.47	1.52	2.85	3.07	0.021	**	83.19
Calcium (mg)	16.32	16.60	16.85	17.57	18.36	18.43	0.429	**	12.93
Phosphorus (mg)	32.66	32.73	32.70	33.94	34.27	34.65	0.619	NS	6.09
Iron (mg)	0.42	0.42	0.44	0.47	0.50	0.63	0.021	**	47.62
Zinc (mg)	0.21	0.23	0.24	0.27	0.32	0.37	0.012	**	71.43
Magnesium (mg)	22.23	22.58	22.66	23.13	24.07	24.33	0.410	**	9.45
Nitrogen (g)	0.23	0.22	0.20	0.19	0.21	0.27	0.002	**	17.39
Potassium (mg)	246.22	246.41	246.68	247.19	247.41	252.44	2.063	NS	2.53
Organoleptic score**	6.98	7.11	7.24	7.51	7.72	8.23	0.210	**	17.91
Protein digestibility (%)*	73.21	73.9	75.76	77.25	78.98	82.45	1.027	**	12.62
Starch digestibility (%)*	64.78	66.23	68.87	69.8	71.19	73.56	1.108	**	13.55
Okra fruit (100 g of pulp)									
Moisture (%)	89.49	88.82	88.48	88.22	87.8	87.52	1.516	**	-2.20
Crude protein (%)	2.03	2.01	1.93	1.88	1.79	1.86	0.029	**	-8.37
Crude fat (%)	0.27	0.29	0.32	0.34	0.35	0.38	0.003	**	35.71
Crude fiber (%)	4.01	4.06	4.12	4.31	4.38	4.65	0.037	**	15.96

Contd...

Table 2 contd...

Quality parameter	NS_1	NS_2	NS_3	NS_4	NS_5	NS_6	S. Em ±	CD (p = 0.05)	Per cent change
Total carbohydrates (g)	83.74	83.84	83.81	83.92	84.18	84.25	1.262	NS	0.61
Total sugars (%)	0.83	0.87	0.94	1.12	1.35	1.52	0.037	**	83.13
Calcium (mg)	85.95	86.27	86.76	87.03	87.34	95.12	1.269	**	10.67
Phosphorus (mg)	56.99	57.69	58.32	59.16	61.10	61.23	1.271	NS	7.44
Iron (mg)	0.99	1.12	1.22	1.37	1.45	1.62	0.046	**	63.64
Zinc (mg)	0.31	0.33	0.39	0.44	0.49	0.67	0.005	**	67.74
Magnesium (mg)	65.19	66.22	66.53	66.84	68.34	72.55	0.821	**	11.29
Nitrogen (g)	0.32	0.24	0.31	0.30	0.28	0.33	0.004	**	3.13
Potassium (mg)	262.17	262.32	262.78	266.64	269.1	281.47	2.454	**	7.36
Organoleptic score**	7.66	7.64	7.67	7.73	7.83	8.14	0.163	NS	6.27
Protein digestibility (%)*	65.32	66.18	68.12	69.39	70.66	72.11	0.980	**	10.39
Starch digestibility (%)*	51.71	55.5	55.68	53.96	54.92	56.87	0.642	**	9.98

**In-vitro* digestibility; N.S. = non-significant at (p = 0.05); **Organoleptic score out of 10 marks; *Significant at (p = 0.001)

and 84.53 to 83.64% (-1.05%) in cluster bean pods compared with the NS_1 treatment pods. However, in legume-vegetables, the many parameters such as pod moisture, crude protein percent, total carbohydrate, and magnesium content in green pea pods; moisture percent, crude protein, crude fiber, total carbohydrates, calcium, nitrogen, and potassium contained in cowpea green pods and moisture percent, crude fiber, total carbohydrates, calcium, and magnesium contain in cluster bean pods did not exhibit significant differences when comparing the different nutrient supply sources (Table 3). When peas crop was cultivated in NS_6 treatment resulted in a significant increase in crude fat (20%), crude fiber (9.67%), total sugars (122.54%), calcium (9.68%), phosphorus (12.06%), iron (16.25%), zinc (37.39%), nitrogen (25%), potassium (7.14%), organoleptic score (16.52%), *in-vitro* protein digestibility (14.19%), and *in-vitro* starch digestibility (10.17%) compared with the NS_1 treatment, whereas NS_5 treatment was at par with the NS_6 treatment on many components (Table 3). Similarly, the cowpea crop was also grown in analogous fields, which have significant effects on the nutritional and organoleptic quality of pods and increase in crude fat (6.84%), total sugars (69.89%), phosphorus (6.45%), iron (9.13%), zinc (19.22%), magnesium (6.99%), organoleptic score (18.26%), *in-vitro* protein digestibility (10.01%), and *in-vitro* starch digestibility (15.58%) than those produce from only chemical sources nutrient supplying field (Table 3).

The crude protein and crude fat content of cluster bean pods at different nutrient supply sources significantly increased by about 2.23 and 69.44% reached a level (3.51 and 0.61%) in the pods respectively, that were grown in NS_6 treatment whereas the minimum value (3.65 and 0.36%) was observed in NS_1 treatment cluster bean pods. Notably, the NS_6 treatment showed significant increases in total sugar content by 133.30% compared with the NS_1 treatment. However, a non-significant difference in total sugar content was observed across all treatments to each other. The mineral contains cluster bean pods such as phosphorus, iron and zinc showed a slight and significant increase up to NS_6 treatment of about 14.71, 14.40, and 30.36% but the pods produced from NS_2 treatment (45.40, 3.82, and 0.57 mg 100 g^{-1}, respectively) and NS_1 treatment (45.34, 3.82, and 0.56 mg 100g^{-1}, respectively) had a non-significant difference to each other. The nitrogen and potassium content of cluster bean pods also showed a similar increasing trend from NS_1 treatment (0.58 g and 303.33 mg 100g^{-1}) to NS_6 treatment (0.69 g and 318.49 mg 100g^{-1}) of about 18.97% and 5.0% higher, respectively. The highest organoleptic score (8.11) was reported in NS_6 treatment-produced cluster bean pods which, showed a significant increase incessantly from NS_2 (0.97%), NS_3 (3.61%), NS_4 (4.99%), NS_5 (7.63%) and NS_6 treatment (12.48%) as compared to NS_1 treatment. The *in-vitro* protein and starch digestibility of cluster bean green pods significantly increased by 9.16 and 9.82%, respectively, under the NS_6 treatment compared to NS_1. The highest values (92.47 and 65.44%) were observed in NS_6-treated pods, surpassing NS_1-treated pods (84.71 and 59.59%). For cabbage, NS_6-treated heads contained slightly less moisture (-2.13%) and crude protein (-1.34%) but showed a non-significant increase

Table 3. Effect of nutrient supply sources on nutritional and organoleptic quality of legume (pod) vegetables (Pea, cowpea and cluster bean).

Quality parameter	NS_1	NS_2	NS_3	NS_4	NS_5	NS_6	S. Em ±	CD (p = 0.05)	Per cent change
Green pea pod (100 g of pulp)									
Moisture (%)	74.22	73.76	73.64	73.23	72.88	72.80	1.188	NS	-1.91
Crude protein (%)	7.24	7.2	7.15	7.08	7.1	7.15	0.037	NS	-1.24
Crude fat (%)	0.15	0.16	0.16	0.17	0.18	0.18	0.003	**	20.00
Crude fiber (%)	6.31	6.36	6.43	6.51	6.88	6.92	0.037	**	9.67
Total carbohydrates (g)	79.54	79.6	79.58	79.76	79.19	82.84	1.262	NS	4.15
Total sugars (%)	0.71	0.75	1.16	1.25	1.43	1.58	0.021	**	122.54
Calcium (mg)	28.40	28.48	28.55	30.00	31.07	31.15	0.429	**	9.68
Phosphorus (mg)	54.63	54.64	54.68	54.81	54.96	61.22	0.837	**	12.06
Iron (mg)	1.60	1.65	1.66	1.72	1.79	1.86	0.021	**	16.25
Zinc (mg)	1.15	1.19	1.21	1.36	1.45	1.58	0.029	**	37.39
Magnesium (mg)	40.21	40.32	40.33	41.1	41.21	42.15	0.845	NS	4.82
Nitrogen (g)	1.16	1.15	1.14	1.13	1.14	1.45	0.033	**	25.00
Potassium (mg)	248.13	248.62	248.97	249.56	249.93	265.84	3.299	**	7.14
Organoleptic score**	7.02	7.18	7.37	7.60	7.89	8.18	0.074	**	16.52
Protein digestibility (%)*	76.20	78.93	81.88	84.32	85.92	87.01	1.706	**	14.19
Starch digestibility (%)*	58.23	59.65	60.50	62.13	63.06	64.15	0.890	**	10.17
Cowpea green pod (100 g of pulp)									
Moisture (%)	90.66	90.27	90.18	89.92	89.65	89.52	2.115	NS	-1.26
Crude protein (%)	20.34	20.30	20.29	20.26	21.21	21.32	0.482	NS	4.82
Crude fat (%)	1.17	1.18	1.20	1.22	1.23	1.25	0.007	**	6.84
Crude fiber (%)	11.57	11.55	11.58	11.63	11.88	12.15	0.204	NS	5.01
Total carbohydrates (g)	54.64	54.71	54.73	54.75	54.8	54.92	1.021	NS	0.51
Total sugars (%)	3.52	3.68	3.84	3.97	5.74	5.98	0.205	**	69.89
Calcium (mg)	80.68	80.84	81.36	81.54	85.61	85.73	1.429	NS	6.26
Phosphorus (mg)	371.18	372.36	373.94	376.34	378.54	395.12	3.062	**	6.45
Iron (mg)	5.15	5.19	5.19	5.27	5.42	5.62	0.085	**	9.13
Zinc (mg)	3.33	3.36	3.45	3.52	3.86	3.97	0.090	**	19.22
Magnesium (mg)	212.15	212.7	217.11	220.78	223.69	226.97	1.712	**	6.99
Nitrogen (g)	3.27	3.25	3.24	3.23	3.24	3.31	0.034	NS	1.22
Potassium (mg)	1220.09	1239.05	1240.57	1249.33	1257.33	1268.44	10.240	NS	3.96
Organoleptic score**	7.23	7.34	7.47	7.76	7.91	8.55	0.044	**	18.26
Protein digestibility (%)*	78.56	81.12	82.65	83.87	85.12	86.42	1.269	**	10.01
Starch digestibility (%)*	59.69	59.72	63.69	64.80	66.18	68.99	1.272	**	15.58
Cluster bean green pod (100 g of pulp)									
Moisture (%)	84.53	84.35	84.4	83.97	83.8	83.64	1.681	NS	-1.05
Crude protein (%)	3.65	3.58	3.51	3.45	3.47	3.51	0.041	*	2.23
Crude fat (%)	0.36	0.36	0.47	0.51	0.56	0.61	0.004	**	69.44
Crude fiber (%)	4.71	4.80	4.83	4.83	4.86	4.92	0.126	NS	4.46

Contd...

Table 3 contd...

Quality parameter	NS_1	NS_2	NS_3	NS_4	NS_5	NS_6	S. Em ±	CD (p = 0.05)	Per cent change
Total carbohydrates (g)	82.97	83.15	83	83.07	83.2	83.63	1.156	NS	3.21
Total sugars (%)	0.48	0.51	0.83	0.94	1.03	1.12	0.013	**	133.30
Calcium (mg)	120.46	120.54	121.1	121.6	122.23	122.49	2.053	NS	5.01
Phosphorus (mg)	45.34	45.4	45.66	46.03	46.62	52.01	0.828	**	14.71
Iron (mg)	3.82	3.82	3.92	4.11	4.23	4.37	0.083	**	14.40
Zinc (mg)	0.56	0.57	0.59	0.61	0.67	0.73	0.008	**	30.36
Magnesium (mg)	81.74	81.83	81.86	82.1	82.36	86.55	1.233	NS	5.88
Nitrogen (g)	0.58	0.57	0.56	0.55	0.54	0.69	0.004	**	18.97
Potassium (mg)	303.33	303.41	303.65	304.16	304.75	318.49	3.270	*	5.00
Organoleptic score**	7.21	7.28	7.47	7.57	7.76	8.11	0.122	**	12.48
Protein digestibility (%)*	84.71	86.42	87.69	89.07	90.38	92.47	1.347	**	9.16
Starch digestibility (%)*	59.59	60.59	61.93	62.71	63.83	65.44	0.939	**	9.82

**In-vitro* digestibility; N.S. non-significant at (p=0.05); **Organoleptic score out of 10 marks; *Significant at (p=0.001)

in total carbohydrates (0.40%) and a significant increase in potassium (6.54%) compared to NS_1. The highest crude fat (0.44%), crude fiber (3.24%), and total sugars (3.78%) were recorded in NS_6-treated cabbage, showing significant increases of 46.67, 9.46, and 97.91%, respectively, over NS_1. NS_6 treatment also enhanced mineral content, with calcium increasing from 51.51 to 56.22 mg (9.16%), phosphorus from 30.10 to 33.56 mg (11.50%), iron from 0.38 to 0.67 mg (76.32%), zinc from 0.17 to 0.32 mg (88.24%), magnesium from 17.89 to 19.56 mg (9.33%), and nitrogen from 0.47 to 0.56 mg (19.15%) per 100 g, compared to NS_1. Additionally, NS_6 significantly improved the organoleptic quality of cabbage, raising the score from 7.04 to 8.35. *In-vitro* protein and starch digestibility also increased by 18.89 and 15.68%, respectively, under NS_6 compared to chemical fertilizer-only treatments (Table 4). The possible cause behind enhanced nutritional qualities and an organoleptic score of the vegetables under the organic production system in the active presence of PGPMs, in which the unique microbial community can activate bio-stimulants in the field soil, improve the physico-chemical properties of crop-growing soil, increase soil bioavailability of many nutrients, and enhance soil enzyme activity (Bhardwaj *et al*., 2; Qi *et al*., 17). These factors effectively extend the plant root system through mycelium, facilitating nutrient release from the soil and enhancing the absorption of diverse nutrients and stimulants. This improved nutrient uptake contributes to higher nutrient content in vegetables and a distinct organoleptic quality. Similar findings have been reported previously, indicating that organically nourished vegetables contain significantly higher nutrient levels and elevated organoleptic scores across various fruits and vegetables (Mukherjee *et al*., 14; Sousa *et al*., 21). Organically nurtured vegetables contain more phosphorus, potassium, calcium, iron, and magnesium (Popa *et al*., 15); phenolic compounds (+20%) and polyphenols, carotenoids, and antioxidants (Mie *et al*., 12; Rembialkowska *et al*., 20), which are directly responsible for the nutritional status, and development of definite taste of the vegetables. Applying plant growth-promoting rhizobacteria increased nutrients such as potassium, magnesium, sodium, phosphorus, iron, zinc, and nitrogen (Lal *et al*., 9; Radhakrishnan and Lee, 18; Sousa *et al*., 21), resulting in improved nutritional superiority of the vegetables. Similar results were also reported by Muhammad *et al*. (13) increasing concentrations of mineral nutrients such as potassium, calcium, magnesium, zinc, and iron up to 27.9% with vegetable crops nourished by organic sources in the presence of soil microbial consortium. Replacing 25, 50, and 75% of the inorganic NPK fertilizers with organic sources could improve the nutritional quality of vegetable crops, respectively, and benefit soil eco-functionality (Ling *et al*., 10).

Biplot analysis of six treatments (NS_1-NS_6) based on nutritional and sensory parameters reveals distinct groupings. NS_1, NS_2, and NS_3 are positively associated with total carbohydrates, moisture, and phosphorus, indicating a composition with higher carbohydrate and moisture content (Fig. 2a). In contrast, NS_4, NS_5, and NS_6 align with protein and starch digestibility and excel in organoleptic qualities and protein-related traits. While crude protein, crude

Table 4. Effect of nutrient supply sources on nutritional and organoleptic quality of cabbage heads.

Quality parameter	NS_1	NS_2	NS_3	NS_4	NS_5	NS_6	S. Em ±	CD (p = 0.05)	Per cent change
Cabbage head (100 g of cabbage heads pulp)									
Moisture (%)	87.88	87.81	87.33	86.44	86.12	86.01	1.347	NS	-2.13
Crude protein (%)	2.98	2.96	2.97	2.94	2.92	2.94	0.082	NS	-1.34
Crude fat (%)	0.30	0.31	0.34	0.40	0.42	0.44	0.008	**	46.67
Crude fiber (%)	2.96	2.89	2.92	3.11	3.03	3.24	0.041	**	9.46
Total carbohydrates (g)	85.17	85.29	85.16	85.15	85.31	85.51	1.265	NS	0.40
Total sugars (%)	1.91	1.97	2.08	2.27	3.61	3.78	0.041	**	97.91
Calcium (mg)	51.51	51.50	51.87	52.12	52.45	56.22	0.857	**	9.16
Phosphorus (mg)	30.10	30.30	30.48	31.33	31.72	33.56	0.449	**	11.50
Iron (mg)	0.38	0.42	0.45	0.52	0.58	0.67	0.004	**	76.32
Zinc (mg)	0.17	0.19	0.19	0.23	0.28	0.32	0.003	**	88.24
Magnesium (mg)	17.89	17.96	18.00	18.22	19.20	19.56	0.411	*	9.33
Nitrogen (g)	0.47	0.45	0.42	0.44	0.47	0.56	0.003	**	19.15
Potassium (mg)	230.11	232.37	232.72	233.87	234.1	245.16	3.677	NS	6.54
Organoleptic score**	7.04	7.17	7.39	7.68	8.05	8.35	0.204	**	18.61
Protein digestibility (%)*	51.77	53.46	54.78	57.84	59.21	61.55	1.020	**	18.89
Starch digestibility (%)*	49.43	50.23	51.56	53.07	54.13	57.18	1.143	**	15.68

**In-vitro* digestibility; N.S. non-significant at (p=0.05); **Organoleptic score out of 10 marks; *Significant at (p=0.001)

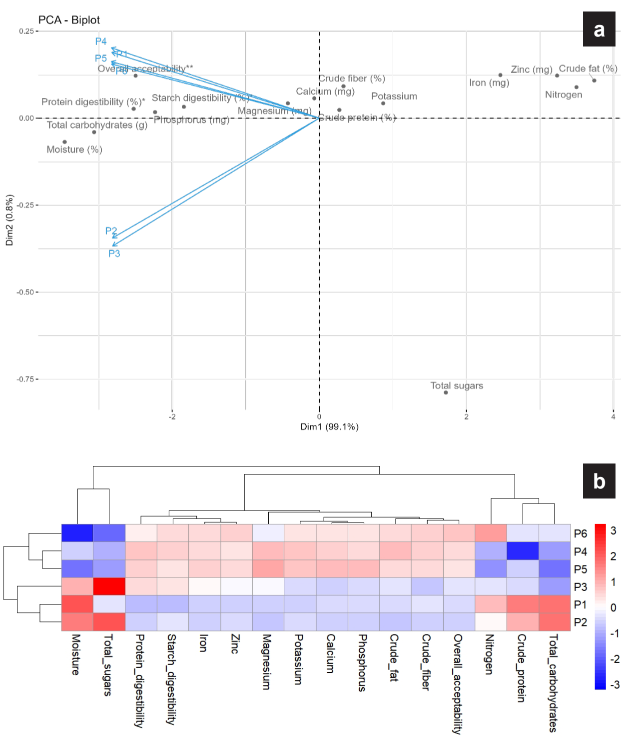

Fig. 2. (a) PCA biplot analysis of nutrient supply sources with soil fertility, physicochemical quality and soil biological activities of experimental fields, (b) Cluster heatmap relationship between nutritional and functional parameters across different treatments (NS_1 to NS_6).

fat, iron, and total sugars contribute moderately to treatment differentiation, zinc and magnesium show minimal variance. NS_6 stands out for its strong association with key sensory and nutritional traits, particularly protein digestibility, starch digestibility, and organoleptic quality, making it a promising choice for nutrient-dense food production. Its balanced nutritional profile, combining high protein content with easily digestible starch, enhances the overall nutritional value of the harvest, making it particularly beneficial for health-conscious consumers and high-quality food applications.

The cluster diagram (Fig. 2b) visually represents the relationships between nutritional and functional parameters across six treatments (NS_1-NS_6) using a heatmap. Red indicates higher values, while blue represents lower values. Hierarchical clustering groups treatments and parameters based on similarity. NS_2, NS_3, and NS_5 form a close cluster, with NS_1 being somewhat related but distinct. NS_4 and NS_6 cluster separately, particularly due to their higher crude protein and total carbohydrate content. Crude protein, total carbohydrates, nitrogen, and organoleptic quality show similar trends, while moisture, total sugars, and protein digestibility form another distinct cluster. NS2 has the highest total sugar content, while NS_1 and NS_3 show lower values. Protein digestibility is highest in NS_2, and moisture is more abundant in NS_6, NS_4, and NS_5. NS_6 and

NS_5 yield crops with higher crude protein, whereas NS_1 and NS_2 produce carbohydrate-dense crops. These findings suggest NS_6 and NS_4 are suitable for protein-rich formulations, while NS_1 and NS_2 favour carbohydrate-based products.

Earlier fertilizer programs prioritized yield over nutritional and organoleptic quality. This study confirms that organic sources with PGPMs significantly enhance calcium, phosphorus, iron, zinc, magnesium, potassium, organoleptic quality, and *in-vitro* protein and starch digestibility. A shift in fertilizer policies is needed to consider soil health impacts rather than simply contrasting organic and chemical fertilizers. These insights support optimized fertilization strategies to mitigate nutrient dilution and promote the balanced use of chemical fertilizers, organic manure, and microbial consortia.

AUTHORS' CONTRIBUTION

Investigation and conceptualization of the research (RLB; PM; SK); Designing of the experiment (KC); Scientific observations during experimentation (RLB, SK, PM, AS, JM); drafted the paper (RLB); Writing and editing (RLB, KC, PM). All authors have read and agreed to the published version of the manuscript.

DECLARATION

The authors declare no conflict of interest.

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