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RESIDUAL INFLUENCE OF NANO UREA AND BORON NUTRITION ON POST-HARVEST SOIL PHYSICAL AND CHEMICAL PROPERTIES UNDER INDIAN MUSTARD

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ABSTRACT:
Keeping soil healthy while still pushing crop productivity upward is one of the quiet, ongoing challenges of Indian mustard (Brassica juncea L.) cultivation, especially in tracts such as the Kymore Plateau of Madhya Pradesh where nitrogen-use efficiency is often poor and boron deficiency is common. To examine this issue from the soil's point of view rather than only the crop's, a two-factor factorial field experiment in a randomized block design was carried out over two Rabi seasons (2022–23 and 2023–24) at the Rajaula Research Farm, Chitrakoot–Satna. The trial combined three levels of foliar nano urea (N0: two water sprays; N1: one nano urea spray at 20 DAS followed by a water spray at 40 DAS; N2: nano urea sprays at both 20 and 40 DAS) with five levels of soil-applied boron (0, 0.5, 1.0, 1.5 and 2.0 kg ha^{-1}), replicated three times, and the post-harvest soil in every plot was analysed each season for pH, electrical conductivity (EC), organic carbon (OC), and the available status of nitrogen, phosphorus, potassium, sulphur and boron. Across both years and on a pooled basis, neither nano urea nor boron altered soil pH, EC or organic carbon to a statistically detectable degree, so the soil's basic chemical character stayed essentially where it started. Available nitrogen, phosphorus, potassium, sulphur and boron, however, rose significantly ($p \leq 0.05$) as the level of either input increased, with the strongest residual enrichment recorded under the twin nano urea spray (N2) and the highest boron dose (B4, 2.0 kg ha^{-1}); their interaction remained statistically non-significant for every soil parameter studied, indicating that the two nutrients act largely independently rather than reinforcing or dampening one another's effect on the soil. On a pooled basis, available N, P, K, S and B increased from 218.06, 15.20, 155.04, 18.24 kg ha^{-1} and 0.52 mg kg^{-1} under N0 to 231.66, 16.77, 171.42, 19.52 kg ha^{-1} and 0.56 mg kg^{-1} under N2, and from 212.56, 14.69, 149.74, 17.71 kg ha^{-1} and 0.39 mg kg^{-1} under B0 to 233.44, 17.03, 174.10, 19.76 kg ha^{-1} and 0.68 mg kg^{-1} under B4. Read together, these numbers describe a fertilization strategy that quietly builds up the soil's available-nutrient reserve without disturbing its pH, salinity or organic matter balance — a combination that appears well suited to the sustainable nutrient management of mustard-based cropping systems on sandy loam soils of central India.

KEYWORDS: Nano urea, Boron nutrition, Indian mustard, Post-harvest soil, Available nutrients, Soil physio-chemical properties, Residual soil fertility, Sustainable nutrient management

INTRODUCTION

Indian mustard (Brassica juncea L. Czern & Coss.) is, in every practical sense, the backbone of India's edible-oil economy among the rapeseed–mustard group of crops, the second most important oilseed group in the world after soybean. It is grown across a broad swathe of the country, but Madhya Pradesh — and within it the Gird and Kymore Plateau agro-climatic zones — accounts for a disproportionately large share of national output. Even so, average mustard yields in the state, and in India as a whole, remain well below the crop's demonstrated genetic potential, a gap that farmers and researchers alike have long attributed to two closely linked constraints: inefficient nitrogen management and the widespread, often silent, deficiency of boron in Indian soils.

Nitrogen is supplied overwhelmingly through conventional urea, yet under open-field conditions its recovery by the crop rarely exceeds 30–35%, the remainder being lost through ammonia volatilisation, nitrate leaching and denitrification. These losses are not merely an agronomic inconvenience; they translate into real environmental costs, from nitrate contamination of shallow groundwater to the greenhouse-gas footprint associated with urea manufacture and use. It is against this backdrop that nanotechnology-enabled fertilizers, and liquid nano urea in particular, have attracted growing research and policy interest as a more efficient nitrogen-delivery route. Because nano urea particles are formulated in the nanometre size range, they present a markedly higher surface-area-to-volume ratio than conventional granular urea, and are designed to release nitrogen gradually, in step with the plant's own demand, rather than in one large, leachable pulse [16, 6]. A growing body of field evidence supports the idea that this controlled-release behaviour can improve nitrogen-use efficiency and reduce environmental losses relative to conventional urea, while also cutting the sheer bulk of fertilizer that needs to be transported, stored and applied [25, 46].

Boron occupies an equally important, if quite different, place in mustard nutrition. Unlike nitrogen, which is required in bulk, boron is needed only in trace amounts, yet its absence is disproportionately damaging: it disrupts cell-wall synthesis, pollen viability, sugar translocation and the general reproductive physiology of the plant, all of which bear directly on seed set and oil yield in Brassica species [43, 33]. Boron deficiency is not a rare or localised problem in India — historical surveys placed it at around 2% of cultivated soils as far back as 1980, but more recent assessments suggest that over half of Indian soils now test deficient, with roughly a third of the country's farmable land affected to varying degrees [27, 20]. Correcting this deficiency, whether through soil or foliar application, has repeatedly been shown to raise mustard seed yield, oil content and boron uptake, and is now a well-established recommendation in boron-poor tracts [29, 1].

Most of the published work on nano urea and boron in mustard and allied crops, understandably, has focused on what these inputs do for the plant — growth, dry-matter accumulation, yield attributes and nutrient uptake. Far less attention has been paid to what happens to the soil itself once the crop has been harvested and removed from the field. This is not a minor omission. The post-harvest status of soil pH, electrical conductivity and organic carbon reflects whether a fertilization programme is chemically benign or is quietly nudging the soil toward acidification, salinisation or organic-matter decline, while the residual pool of available nitrogen, phosphorus, potassium, sulphur and boron left behind after crop removal indicates how much of the applied nutrient was genuinely used, how much remains available for the next crop in rotation, and how efficiently the whole system is cycling nutrients. In a cropping sequence where mustard is typically followed by another cereal or pulse crop, this residual fertility carries direct practical consequences for input planning in the succeeding season.

A handful of studies have examined the soil-level effects of nano urea in other crops — rice, maize, wheat and okra among them — generally reporting either a neutral or a mildly favourable influence on soil reaction and nutrient availability [38, 52, 31]. Boron's effects on soil chemical properties have also been documented, though mostly in the context of soils and crops other than mustard, and mostly without reference to its interaction with a nitrogen source as specific as nano urea [47, 17, 21]. To our knowledge, no study has yet brought nano urea and boron together in a single factorial framework to examine their combined and independent residual influence on post-harvest soil physical and chemical properties specifically under Indian mustard grown on the sandy loam soils of the Kymore Plateau — a genuine gap given how frequently the two inputs are now recommended together in practice.

It was to address this gap that the present study was designed. Working from data generated in a two-year field experiment, we set out to answer three closely related questions. First, do nano urea and boron, applied at graded levels, alter the basic chemical character of the soil — its pH, electrical conductivity and organic carbon — after mustard is harvested? Second, how do they influence the residual availability of the major and secondary macronutrients (nitrogen, phosphorus, potassium and sulphur) and of boron itself in the post-harvest soil? And third, do the two inputs interact with one another in shaping these outcomes, or does each act more or less independently? The answers, we believe, have a direct bearing on how confidently nano urea and boron can be recommended as a routine, soil-friendly component of nutrient management for mustard-based cropping systems in central India.

2.MATERIALS AND METHODS

2.1.Experimental Site And Agro-Climatic Setting

The field trial was conducted over two consecutive Rabi seasons, 2022–23 and 2023–24, at the Rajaula Research Farm, Faculty of Agricultural Sciences, Mahatma Gandhi Chitrakoot Gramodaya Vishwavidyalaya, Chitrakoot–Satna, Madhya Pradesh, located at 25° 10′ N latitude and 80° 52′ E longitude at an elevation of about 210 m above mean sea level. This part of north-eastern Madhya Pradesh experiences a semi-arid, sub-tropical climate: winters can dip close to 2°C while summer temperatures regularly climb past 47°C, and the region is periodically swept by hot, desiccating winds locally referred to as the Loo. Average annual rainfall lies between 90 and 100 cm, most of it delivered during the July–September monsoon, with occasional light showers extending into winter. Both crop seasons of the present study were characterised by generally favourable weather, moderated by the tail of the monsoon and by pre-winter showers, allowing normal crop establishment and growth in both years.

2.2.Soil of the experimental field before sowing

A homogeneous block of the research farm, uniform in texture and fertility, was selected for the trial. Before the first season began, composite surface soil samples (0–15 cm depth) were drawn with a tube auger from across the site, air-dried in shade, passed through a 2 mm sieve, and analysed for mechanical composition and initial physico-chemical status. The soil was sandy loam in texture (52.8% sand, 22.6% silt and 24.6% clay by the Bouyoucos hydrometer method [10]), close to neutral in reaction, low in organic carbon, low in available nitrogen and phosphorus, medium in available potassium and sulphur, and only marginally supplied with boron — a profile broadly typical of the sandy loam tracts of the Kymore Plateau (Table 1).

Table 1. Physico-chemical characterisation of the experimental soil before sowing (mean of the two pre-sowing samplings, 2022–23 and 2023–24)

Soil parameter	Mean value	Fertility rating	Analytical method
Soil reaction, pH (1:2 soil–water)	7.62	Neutral to slightly alkaline	Glass electrode pH meter [23]
Electrical conductivity (dS m^{-1})	0.355	Normal, non-saline	Solubridge method [39]
Organic carbon (%)	0.39	Low	Walkley–Black wet-oxidation method [53]
Available nitrogen (kg ha^{-1})	216.78	Low	Alkaline permanganate distillation [44]
Available phosphorus (kg ha^{-1})	11.19	Low	Olsen's sodium bicarbonate method [36]
Available potassium (kg ha^{-1})	146.18	Medium	Neutral ammonium acetate, flame photometry [23]
Available sulphur (kg ha^{-1})	18.24	Medium	Turbidimetric method, 0.15% $CaCl_2$ [11]
Available boron (mg kg^{-1})	0.37	Marginal / deficient	Hot-water extractable, Azomethine-H [8]
Sand : Silt : Clay (%)	52.8 : 22.6 : 24.6	Sandy loam textural class	Bouyoucos hydrometer method [10]

2.3.Treatments and experimental design

The trial followed a two-factor factorial randomized block design, with three replications and fifteen treatment combinations arising from three levels of foliar nano urea (Factor 1) crossed with five levels of soil-applied boron (Factor 2) (Table 2). Mustard variety Pusa Mahak was sown at 5 kg seed ha^{-1} with 45 cm between rows and 15 cm between plants, on a gross plot of 1136.41 m^2 and net plot of 701.66 m^2 per treatment. A uniform basal fertilizer dose of $N:P_2O_5:K_2O$ :: 80:40:40 kg ha^{-1} was applied to every plot, ensuring that any differences observed between treatments could be attributed specifically to the nano urea and boron regimes rather than to differences in overall NPK nutrition. Sowing was carried out on 18 October 2022 and 12 October 2023 in the two seasons, with harvest on 11 February 2023 and 5 February 2024, respectively.

Table 2. Treatment structure of the experiment

Factor	Level	Description
Nano urea (N)	N0	Two foliar water sprays (control)
	N1	One nano urea spray at 20 DAS + one water spray at 40 DAS
	N2	Nano urea sprays at 20 DAS and 40 DAS
Boron (B), as borax	B0	0.0 kg B ha^{-1} (control)
	B1	0.5 kg B ha^{-1}
	B2	1.0 kg B ha^{-1}
	B3	1.5 kg B ha^{-1}
	B4	2.0 kg B ha^{-1}

Boron was applied to the soil at sowing as borax, while nano urea was sprayed on the crop canopy at the specified growth stages; the 3 × 5 factorial arrangement gave fifteen treatment combinations (T1–T15), each replicated three times across forty-five plots per season.

2.4.Post-harvest soil sampling and analytical procedures

After the crop was harvested in each season, composite soil samples (0–15 cm) were again collected from every individual plot, shade-dried, sieved through a 2 mm mesh, and subjected to the same analytical procedures used for the pre-sowing characterisation, so that pre- and post-harvest values would be directly comparable. Soil pH was measured potentiometrically in a 1:2 soil–water suspension using a glass electrode pH meter, and electrical conductivity was recorded from the same suspension with a conductivity meter [39]. Organic carbon was estimated by the Walkley–Black wet-oxidation procedure, in which soil organic matter is oxidised by a measured excess of potassium dichromate in the presence of concentrated sulphuric acid, and the unreacted dichromate is back-titrated with ferrous ammonium sulphate [53]. Available nitrogen was determined by alkaline potassium permanganate distillation [44]; available phosphorus by Olsen's sodium bicarbonate extraction followed by colorimetric determination of the phosphomolybdenum-blue complex at 660 nm [36]; available potassium by neutral normal ammonium acetate extraction and flame photometry [23]; available sulphur by the turbidimetric method following extraction with 0.15% calcium chloride [11]; and available boron by hot-water extraction followed by colorimetric estimation of the boron–Azomethine-H complex at 420 nm [8].

2.5.Statistical analysis

Data recorded in each season, together with the pooled two-year mean, were analysed by analysis of variance appropriate to a two-factor factorial randomized block design. Treatment means were compared using the critical difference (CD) at the 5% level of probability; where the calculated F-value did not exceed the tabulated value, the corresponding effect was recorded as non-significant (NS). This approach allowed the main effect of nano urea, the main effect of boron, and their interaction to be evaluated separately for every soil parameter measured.

3.Results And Discussion

The results are presented and discussed parameter by parameter, beginning with the three indicators of basic soil chemical character — pH, electrical conductivity and organic carbon — and moving on to the five available-nutrient parameters, before drawing the threads together in a concluding synthesis.

3.1.Soil reaction (pH)

Post-harvest soil pH is summarised, season by season and pooled, in Table 3 and Figure 1. In both years, and in the two-year pooled analysis, neither nano urea nor boron — alone or together — produced a statistically significant shift in soil pH. Pooled pH ranged only from 7.31 to 7.35 across the three nano urea levels and from 7.32 to 7.35 across the five boron levels, a spread of little more than two-hundredths of a pH unit, well within the noise one would expect between replicated field plots. Both sets of values sit modestly below the pre-sowing figure of 7.62, but this small downward drift was common to every treatment, including the untreated control, and is better explained by the normal course of a cropping season — root respiration, organic-acid exudation and nutrient uptake all tend to nudge field soils very slightly toward neutrality — than by any specific action of nano urea or boron.

Table 3. Effect of nano urea and boron levels on post-harvest soil pH (2022–23, 2023–24 and pooled data)

Treatment	pH 2022–23	pH 2023–24	pH Pooled
Initial value	7.63	7.60	7.62
N0	7.37	7.34	7.35
N1	7.34	7.30	7.32
N2	7.33	7.30	7.31
F-test (N)	NS	NS	NS
B0	7.36	7.33	7.35
B1	7.35	7.32	7.33
B2	7.34	7.31	7.33
B3	7.34	7.31	7.32
B4	7.33	7.30	7.32
F-test (B)	NS	NS	NS
N × B interaction	NS	NS	NS

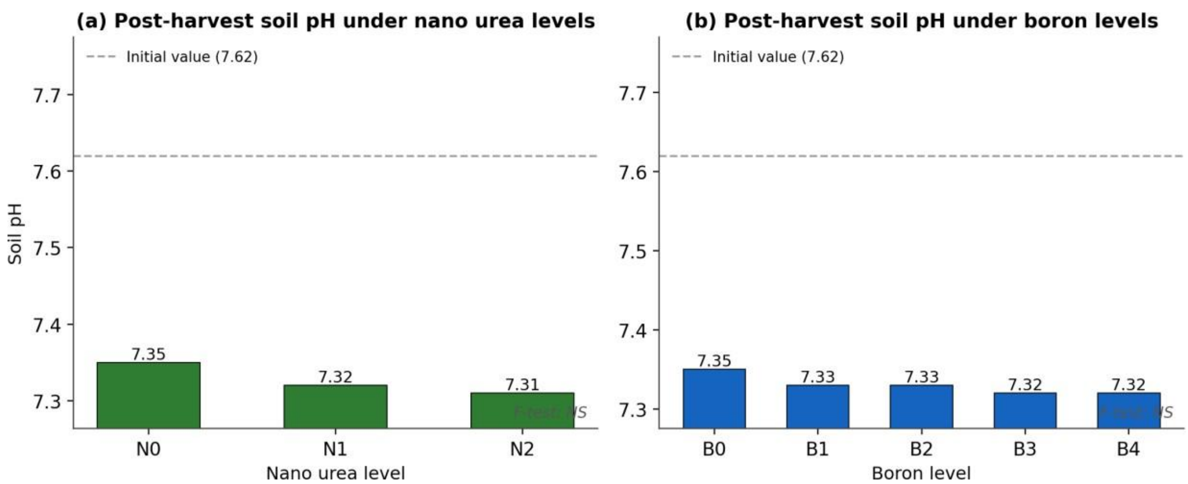

Figure 1. Post-harvest soil pH as influenced by (a) nano urea levels and (b) boron levels (pooled data, dashed line = pre-sowing value).

The stability of pH under nano urea is consistent with its design as a controlled-release nitrogen source. Conventional urea, once hydrolysed by soil urease, first raises pH transiently through ammonium and ammonia formation and then depresses it as nitrification converts that ammonium to nitrate, releasing hydrogen ions in the process; nano urea, by releasing nitrogen more gradually and in smaller increments, avoids the sharp pulse of this reaction sequence and therefore leaves soil pH comparatively undisturbed [41, 34]. Field evidence from other crops points the same way — Rathore et al. [38] and Gogoi et al. [18] both reported negligible change in soil pH under nano urea relative to conventional fertilizer sources, and Velmurugan et al. [52] similarly found no significant effect of foliar nano urea on pH, EC or organic carbon in rice, a pattern that mirrors the present findings closely.

Boron's lack of influence on pH is, if anything, even more predictable on chemical grounds. Applied in gram-to-kilogram quantities per hectare rather than the tens of kilograms typical of major fertilizers, and not itself a strong acid- or base-forming species, boron does not meaningfully participate in the soil's acid–base buffering reactions [19, 35]. This is consistent with earlier reports of statistically stable pH under a range of boron doses in mustard and other crops [4], and reinforces the view that boron fertilization, at agronomically relevant rates, is essentially neutral with respect to soil reaction.

3.2.Electrical conductivity (EC)

Electrical conductivity, an index of the soluble-salt load of the soil, likewise showed no significant response to either nano urea or boron in either season or in the pooled data (Table 4, Figure 2). Pooled EC ranged from 0.381 to 0.387 dS m^{-1} across nano urea levels and from 0.377 to 0.389 dS m^{-1} across boron levels — all comfortably within the normal, non-saline range and close to the pre-sowing value of 0.355 dS m^{-1}.

Table 4. Effect of nano urea and boron levels on post-harvest soil electrical conductivity, EC (2022–23, 2023–24 and pooled data)

Treatment	EC 2022–23	EC 2023–24	EC Pooled
Initial value	0.350	0.360	0.355
N0	0.389	0.374	0.381
N1	0.390	0.380	0.385
N2	0.391	0.384	0.387
F-test (N)	NS	NS	NS
B0	0.382	0.371	0.377
B1	0.389	0.378	0.383
B2	0.392	0.382	0.387
B3	0.392	0.382	0.387
B4	0.395	0.384	0.389
F-test (B)	NS	NS	NS
N × B interaction	NS	NS	NS

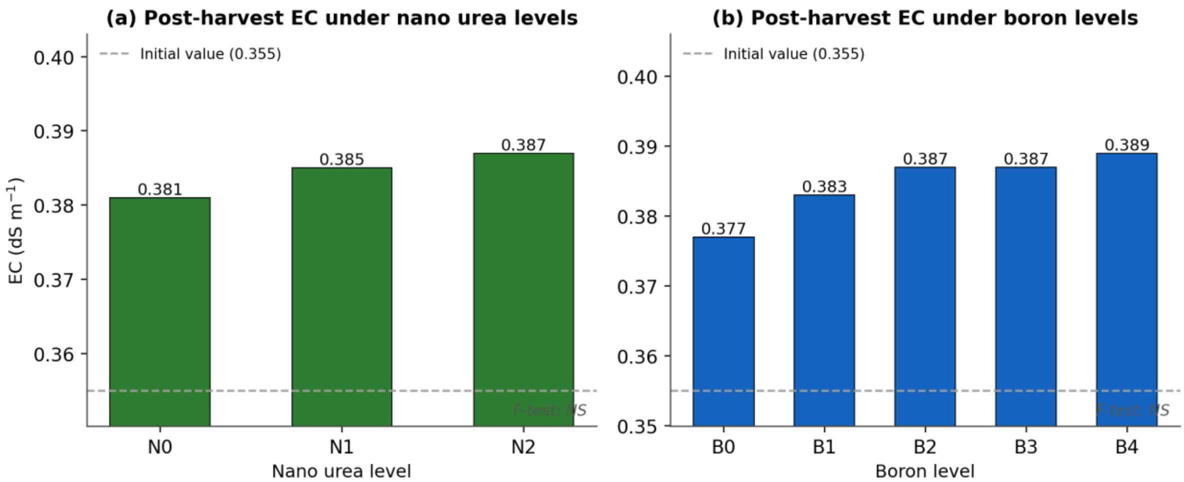

Figure 2. Post-harvest soil electrical conductivity (EC) as influenced by (a) nano urea levels and (b) boron levels (pooled data).

Because nano urea delivers nitrogen in a slow, plant-synchronised manner, it limits the transient build-up of soluble ammonium and nitrate ions that can otherwise raise the electrolyte concentration of the soil solution, particularly after conventional urea's rapid hydrolysis and the accompanying leaching of nitrate [50]. Conventional urea, by contrast, is more often associated with short-lived spikes in EC immediately after application, a pattern not observed here because nano urea was the nitrogen source under study [45]. Boron, applied in small amounts relative to the ionic strength of the bulk soil solution, contributed no detectable change in EC either, in agreement with earlier reports that boron fertilization at conventional agronomic rates leaves soil salinity indices essentially unaffected [17].

3.3.Organic carbon (OC)

Post-harvest soil organic carbon showed a similarly flat response to both factors (Table 5, Figure 3). Pooled OC varied only between 0.39% and 0.40% across nano urea levels, and between 0.38% and 0.40% across boron levels— differences too small to register as statistically significant, and close to the pre-sowing value of 0.39%.

Table 5. Effect of nano urea and boron levels on post-harvest soil organic carbon, OC (2022–23, 2023–24 and pooled data)

Treatment	OC (%) 2022–23	OC (%) 2023–24	OC (%) Pooled
Initial value	0.39	0.39	0.39
N0	0.38	0.39	0.39
N1	0.39	0.40	0.39
N2	0.39	0.40	0.40
F-test (N)	NS	NS	NS
B0	0.37	0.38	0.38
B1	0.38	0.39	0.38
B2	0.39	0.40	0.40
B3	0.40	0.40	0.40
B4	0.40	0.41	0.40
F-test (B)	NS	NS	NS
N × B interaction	NS	NS	NS

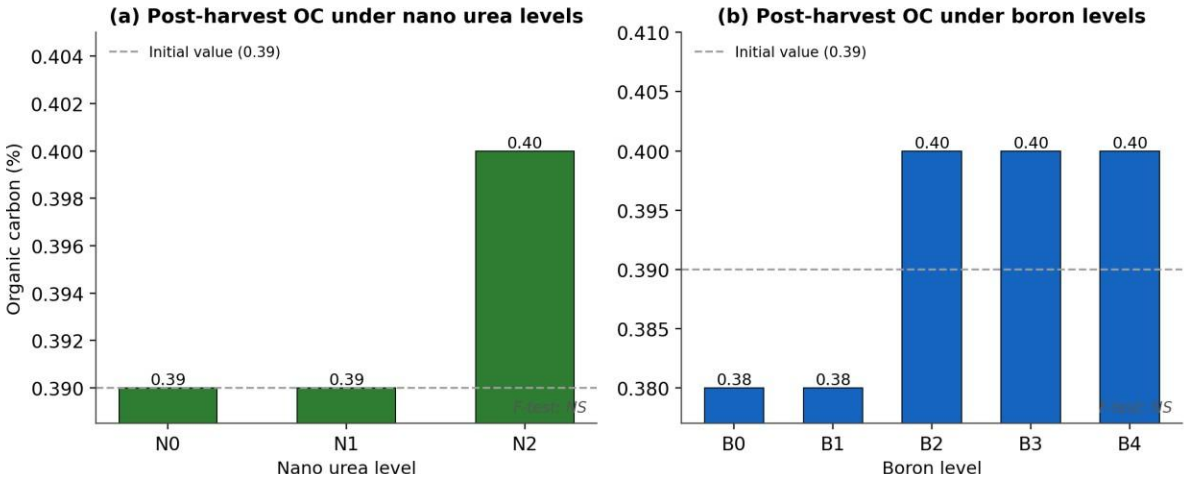

Figure 3. Post-harvest soil organic carbon (OC) as influenced by (a) nano urea levels and (b) boron levels (pooled data).

Soil organic carbon is governed chiefly by the balance between organic-matter inputs — crop residues, root turnover, farmyard manure — and their microbial decomposition, rather than by the addition of an inorganic nitrogen source or a micronutrient in isolation [54]. Nano urea, being a purely mineral nitrogen carrier with no organic-matter content of its own, would not be expected to alter OC directly, and its role here appears limited to marginally supporting root and residue biomass through improved nitrogen nutrition — an indirect pathway too slow to register within a single two-year trial [42]. Boron, for its part, is required by the plant only in trace quantities and does not itself constitute an organic-carbon input; its very slight numerical association with higher OC at the higher doses is more plausibly linked to marginally greater root and stubble biomass return than to any direct chemical action on soil carbon [13].

3.4.Available nitrogen

In sharp contrast to the three parameters discussed above, post-harvest available nitrogen responded strongly and significantly to both nano urea and boron, in both seasons and in the pooled analysis (Table 6, Figure 4). Pooled available nitrogen rose from 218.06 kg ha^{-1} under the control (N0) to 224.55 kg ha^{-1} under N1 and a significant maximum of 231.66 kg ha^{-1} under N2 — an increase of roughly 6% over the control. The response to boron was, if anything, more pronounced: pooled available nitrogen climbed steadily from 212.56 kg ha^{-1} at B0 to 233.44 kgha^{-1} at B4, with the top three boron levels (B2, B3 and B4) statistically at par with one another. The nano urea × boron interaction, however, remained non-significant throughout, meaning the two factors added to, rather than multiplied, one another's effect.

Table 6. Effect of nano urea and boron levels on post-harvest available nitrogen in soil (2022–23, 2023–24 and pooled data)

Treatment	N (kg ha^{-1}) 2022–23	N (kg ha^{-1}) 2023–24	N (kg ha^{-1}) Pooled
Initial value	215.11	218.44	216.78
N0	215.42	220.71	218.06
N1	221.62	227.48	224.55

N2	228.64	234.68	231.66
F-test (N)	S	S	S
CD at 5% (N)	7.32	9.52	5.87
B0	210.12	215.00	212.56
B1	216.70	222.42	219.56
B2	224.10	230.03	227.07
B3	228.15	234.18	231.16
B4	230.40	236.49	233.44
F-test (B)	S	S	S
CD at 5% (B)	9.45	12.29	7.58
N × B interaction	NS	NS	NS

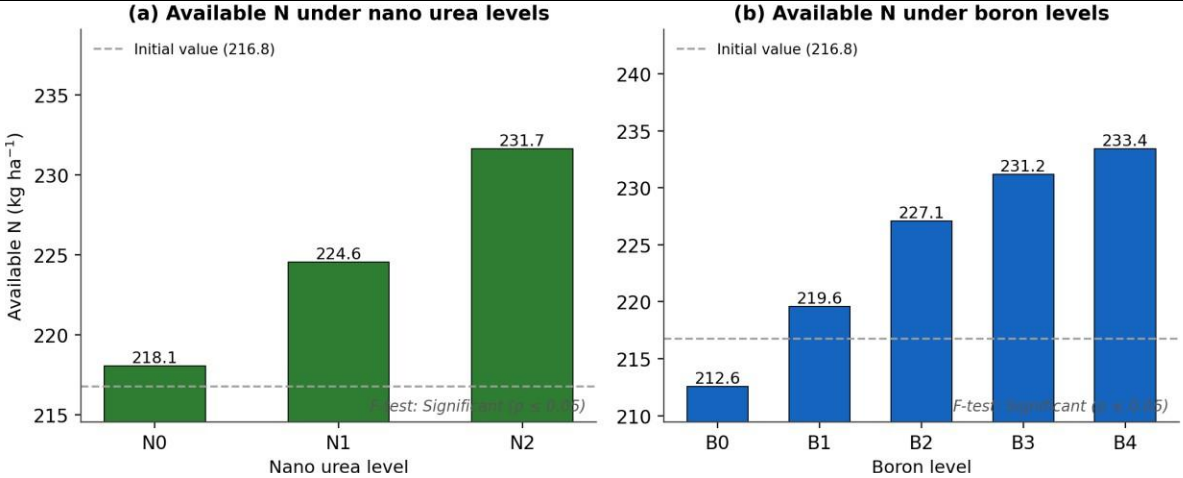

Figure 4. Post-harvest available soil nitrogen as influenced by (a) nano urea levels and (b) boron levels (pooled data).

The larger residual nitrogen pool left behind under nano urea is exactly what its slow-release design would predict: by limiting the volatilisation, leaching and denitrification losses that erode the efficiency of conventional urea, a greater fraction of the applied nitrogen either remains unused by the crop or is returned through root and residue turnover, both of which show up as available nitrogen in the post-harvest soil [34, 50]. The very high surface-area-to-volume ratio of nano-sized urea particles is also thought to promote closer, more efficient contact with soil colloids and root surfaces during the growing season, a mechanism proposed to explain the improved apparent nitrogen-use efficiency reported for nano urea across several field crops [2, 12]. Similar improvement in post-harvest soil nitrogen under nano urea, relative to conventional urea, has been reported directly in rice, maize and vegetable crops [22, 37, 51].

Boron's positive association with residual soil nitrogen, though perhaps less intuitive at first glance, is well grounded physiologically. Adequate boron nutrition promotes root elongation and branching, effectively enlarging the volume of soil explored by the root system and increasing the surface area available for nitrogen capture during the growing season [49]; a well-boron-nourished crop also tends to support a more active rhizosphere microbial community, which in turn accelerates the mineralisation-immobilisation turnover that keeps nitrogen cycling through the plant-available pool [43]. Comparable boron-linked increases in post-harvest soil nitrogen status have been reported in Brassica and other field crops receiving graded boron doses [14, 29].

3.5.Available phosphorus

Available phosphorus followed a similar upward trajectory with increasing levels of both inputs (Table 7, Figure 5). The pooled value rose from 15.20 kg ha^{-1} under N0 to a significant maximum of 16.77 kg ha^{-1} under N2, and from 14.69 kg ha^{-1} at B0 to 17.03 kg ha^{-1} at B4 — the latter statistically on par with B3. As with nitrogen, the interaction between nano urea and boron was not significant.

Table 7. Effect of nano urea and boron levels on post-harvest available phosphorus in soil (2022–23, 2023–24 and pooled data)

Treatment	P (kg ha^{-1}) 2022–23	P (kg ha^{-1}) 2023–24	P (kg ha^{-1}) Pooled
Initial value	11.11	11.26	11.19
N0	15.10	15.29	15.20
N1	15.87	16.07	15.97
N2	16.66	16.88	16.77
F-test (N)	S	S	S

CD at 5% (N)	0.70	0.76	0.50
B0	14.61	14.78	14.69
B1	15.25	15.45	15.35
B2	16.08	16.29	16.19
B3	16.53	16.75	16.64
B4	16.92	17.14	17.03
F-test (B)	S	S	S
CD at 5% (B)	0.90	0.98	0.65
N × B interaction	NS	NS	NS

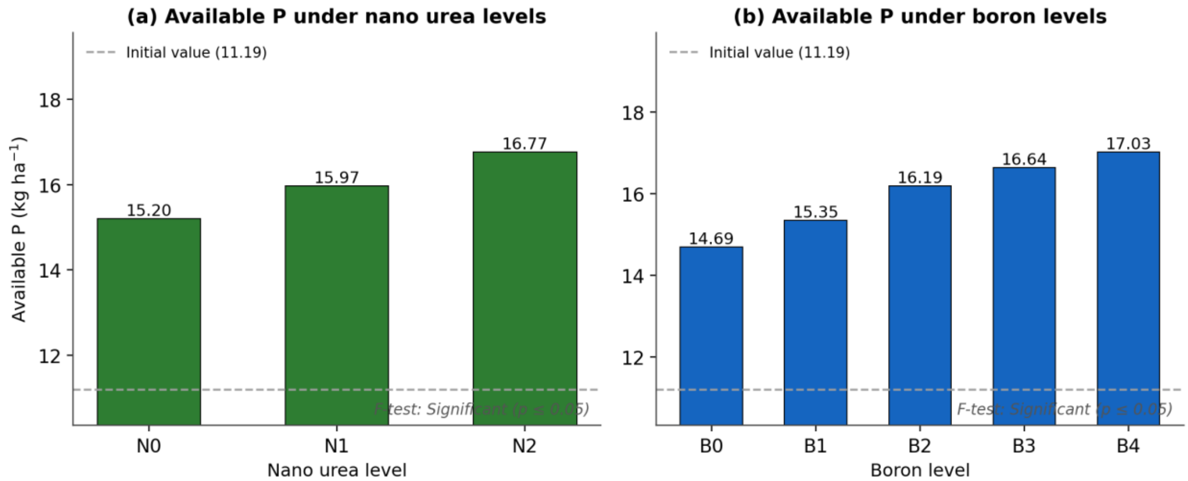

Figure 5. Post-harvest available soil phosphorus as influenced by (a) nano urea levels and (b) boron levels (pooled data).

Because nano urea is fundamentally a nitrogen carrier, its influence on phosphorus availability is necessarily indirect. The most plausible pathway runs through the crop's root system and its associated microflora: an assured nitrogen supply encourages more vigorous root proliferation and greater exudation of organic acids and phosphatase enzymes, both of which help solubilise phosphorus fractions that would otherwise remain fixed in the soil, particularly on sandy loam soils with only moderate phosphorus-fixing capacity [49, 31]. Boron's contribution appears to work along a related but distinct route — its well-documented role in promoting root extension increases the soil volume from which phosphorus can be drawn, while a direct physiological interaction between boron and phosphorus metabolism, operating at the level of energy transfer and nucleic-acid synthesis, has been proposed to reduce phosphorus fixation and support its mobility within the soil–plant system [43]. Field-level corroboration for boron-linked improvement in residual soil phosphorus comes from a range of crops and soil types [17, 7].

3.6.Available potassium

Post-harvest available potassium mirrored the pattern already seen for nitrogen and phosphorus (Table 8, Figure 6). The pooled maximum of 171.42 kg ha^{-1} was recorded under N2, significantly above the 155.04 kg ha^{-1} recorded under N0, while boron increased pooled available potassium steadily from 149.74 kg ha^{-1} at B0 to a significant maximum of 174.10 kg ha^{-1} at B4, statistically at par with B2. The interaction effect remained non-significant.

Table 8. Effect of nano urea and boron levels on post-harvest available potassium in soil (2022–23, 2023–24 and pooled data)

Treatment	K (kg ha^{-1}) 2022–23	K (kg ha^{-1}) 2023–24	K (kg ha^{-1}) Pooled
Initial value	145.45	146.91	146.18
N0	153.82	156.25	155.04
N1	161.77	164.54	163.15
N2	169.97	172.88	171.42
F-test (N)	S	S	S
CD at 5% (N)	7.15	8.04	5.26
B0	148.64	150.85	149.74
B1	155.42	158.08	156.75
B2	164.02	166.83	165.43
B3	168.55	171.44	170.00

B4	172.63	175.58	174.10
F-test (B)	S	S	S
CD at 5% (B)	9.24	10.38	6.79
N × B interaction	NS	NS	NS

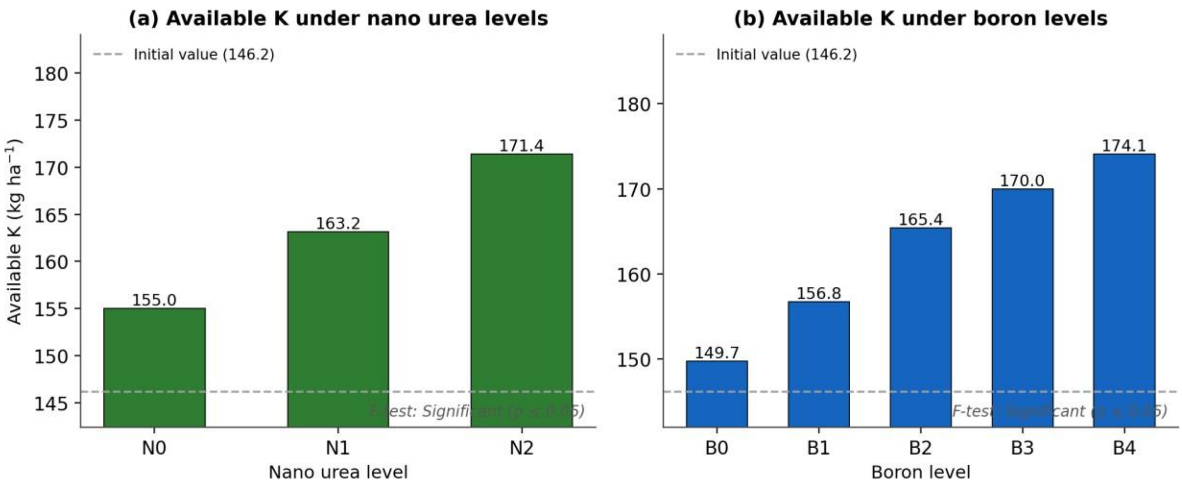

Figure 6. Post-harvest available soil potassium as influenced by (a) nano urea levels and (b) boron levels (pooled data).

The pathway proposed for potassium runs close to that already described for phosphorus: better nitrogen nutrition from nano urea supports more extensive rooting and a more active rhizosphere, both of which improve the crop's — and, by extension, the soil profile's — access to and cycling of potassium reserves [31, 16]. Boron's role in maintaining membrane integrity and regulating ion-transport processes across cell membranes is well established in plant physiology, and there is also evidence that boron can modestly improve the cation exchange capacity of soil, thereby helping the soil matrix retain and later release potassium ions more effectively [13]. Similar boron-associated gains in post-harvest soil potassium status have been reported in oilseed and legume crops receiving comparable boron doses [26].

3.7.Available sulphur

Available sulphur in the post-harvest soil rose significantly with both nano urea and boron (Table 9, Figure 7). The pooled value increased from 18.24 kg ha^{-1} under N0 to a significant maximum of 19.52 kg ha^{-1} under N2, and from 17.71 kg ha^{-1} at B0 to 19.76 kg ha^{-1} at B4, the latter statistically comparable with B3 and B2. As with the other nutrients, the interaction term was not significant.

Table 9. Effect of nano urea and boron levels on post-harvest available sulphur in soil (2022–23, 2023–24 and pooled data)

Treatment	S (kg ha^{-1}) 2022–23	S (kg ha^{-1}) 2023–24	S (kg ha^{-1}) Pooled
Initial value	17.90	18.38	18.14
N0	18.00	18.48	18.24
N1	18.76	19.27	19.01
N2	19.26	19.78	19.52
F-test (N)	S	S	S
CD at 5% (N)	0.62	0.86	0.52
B0	17.49	17.94	17.71
B1	18.12	18.62	18.37
B2	18.92	19.43	19.18
B3	19.34	19.87	19.61
B4	19.49	20.02	19.76
F-test (B)	S	S	S
CD at 5% (B)	0.80	1.11	0.67
N × B interaction	NS	NS	NS

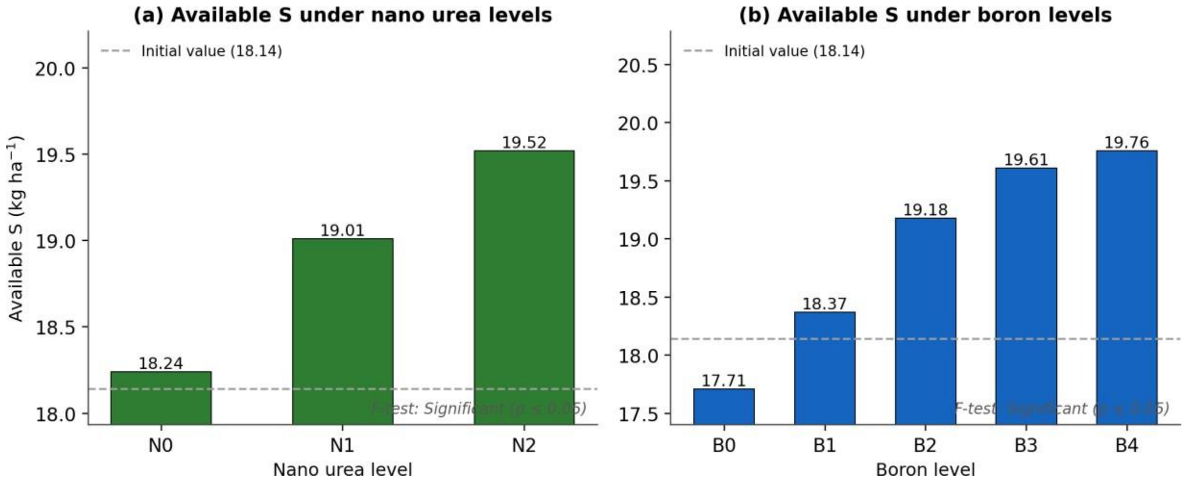

Figure 7. Post-harvest available soil sulphur as influenced by (a) nano urea levels and (b) boron levels (pooled data).

The nitrogen-driven boost in microbial activity that has already been invoked for phosphorus and potassium appears to extend to sulphur as well: an assured, steady nitrogen supply from nano urea favours a more active soil microbial community capable of mineralising organic sulphur reserves into plant-available sulphate at a faster rate [49]. Boron's contribution here is more direct, since several of the key enzymes involved in sulphur assimilation — glutathione synthase among them — depend on an adequately boron-nourished plant for their activity, and boron-enhanced root development further reinforces the plant's, and indirectly the soil's, capacity to draw down and later return sulphate-sulphur through residue decomposition [24, 43].

3.8.Available boron

Post-harvest available boron responded significantly to both factors, though the magnitude of the boron response dwarfed that of nano urea (Table 10, Figure 8). Pooled available boron rose modestly from 0.52 mg kg^{-1} under N0 to a significant 0.56 mg kg^{-1} under N2. Direct boron application produced a far larger and more consistent gradient, with pooled available soil boron climbing from 0.39 mg kg^{-1} at B0 to 0.68 mg kg^{-1} at B4 — very nearly a doubling relative to the control. Once again, the nano urea × boron interaction was statistically non-significant.

Table 10. Effect of nano urea and boron levels on post-harvest available boron in soil (2022–23, 2023–24 and pooled data)

Treatment	B (mg kg^{-1}) 2022–23	B (mg kg^{-1}) 2023–24	B (mg kg^{-1}) Pooled
Initial value	0.36	0.38	0.37
N0	0.51	0.53	0.52
N1	0.52	0.55	0.54
N2	0.55	0.57	0.56
F-test (N)	S	S	S
CD at 5% (N)	0.02	0.02	0.01
B0	0.38	0.40	0.39
B1	0.47	0.49	0.48
B2	0.51	0.54	0.53
B3	0.59	0.62	0.61
B4	0.67	0.70	0.68
F-test (B)	S	S	S
CD at 5% (B)	0.03	0.03	0.02
N × B interaction	NS	NS	NS

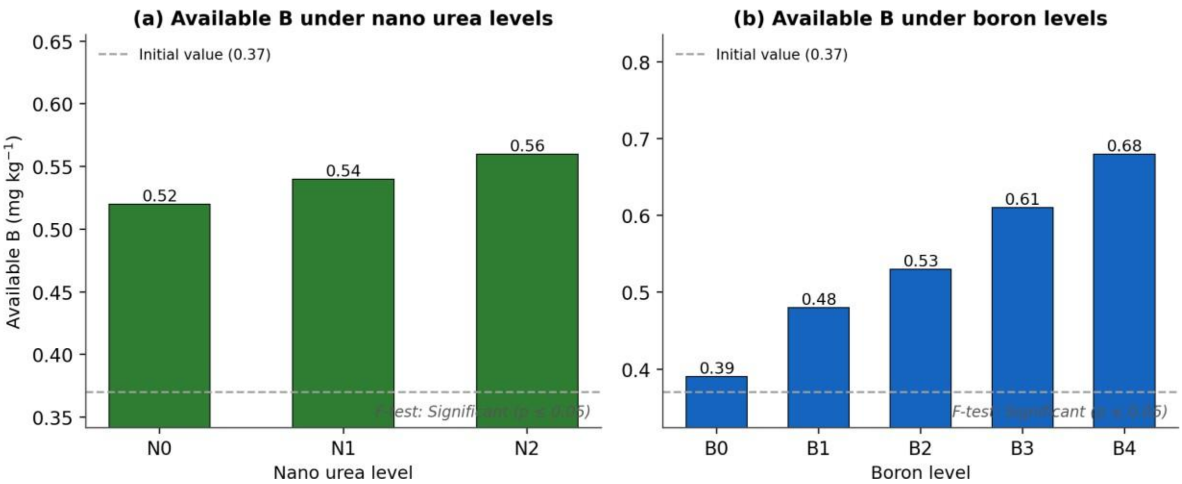

Figure 8. Post-harvest available soil boron as influenced by (a) nano urea levels and (b) boron levels (pooled data).

That nano urea produced any increase at all in residual soil boron, given that it supplies no boron itself, is best explained through its effect — or rather its lack of effect — on soil pH. Boron solubility and plant availability are strongly pH-dependent, dropping sharply as soils become more alkaline; because nano urea leaves soil pH essentially unchanged (Section 3.1), it also helps preserve the pH range within which boron remains most soluble, while the accompanying stimulation of root growth and microbial activity assists in mobilising boron from soil minerals and organic matter [30, 5]. The much larger response to direct boron application is, unsurprisingly, a straightforward reflection of the added dose: hot-water-soluble boron in soil has repeatedly been shown to rise in close proportion to the rate of borax applied, an effect that is typically most pronounced, as it was here, in soils where the initial boron status is already low [32, 29]. Given that the experimental soil began the trial only marginally supplied with boron (0.37 mg kg^{-1}), the near-doubling of available boron under B4 represents a genuinely meaningful improvement in the soil's boron-supplying capacity for the crop that follows mustard in the rotation.

3.9.Interaction effect of nano urea and boron

Across every one of the eight soil parameters examined — pH, EC, organic carbon, and available nitrogen, phosphorus, potassium, sulphur and boron — the statistical interaction between nano urea and boron levels was non-significant, in both years and in the pooled analysis. In practical terms, this means that while each input independently and significantly enriched the post-harvest available-nutrient pool, combining them did not produce an effect disproportionately larger (or smaller) than the sum of their separate contributions — there was no evidence of either synergism or antagonism between the two factors at the soil-chemistry level. That said, when the fifteen treatment combinations are compared numerically rather than statistically, the combination receiving both the twin nano urea spray and the highest boron dose (N2 × B4) consistently recorded the highest, or among the highest, available-nutrient values, simply because it combines the strongest level of each independently beneficial factor.

Overall trends and synthesis

Bringing the eight parameters together highlights a consistent and, we think, agronomically reassuring pattern. Figure 9 expresses this pattern as the percentage increase in each available nutrient recorded under the best nano urea treatment (N2, relative to N0) and the best boron treatment (B4, relative to B0). Nano urea's twin spray raised available N, P, K, S and B by 6.2%, 10.3%, 10.6%, 7.0% and 7.7% respectively over the control, while the highest boron dose raised the same five parameters by 9.8%, 15.9%, 16.3%, 11.6% and 74.4% over its own control — the very large percentage gain in available boron being an expected consequence of starting from a genuinely low baseline (0.37 mg kg^{-1}) rather than any unusual mechanism.

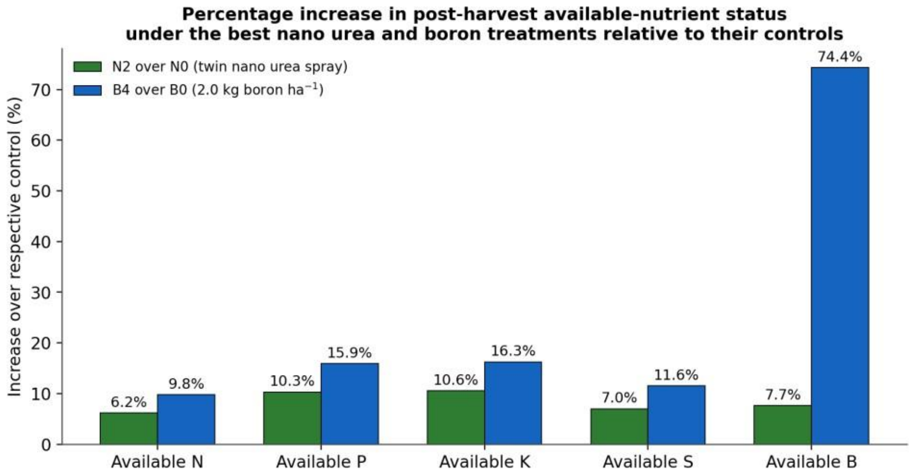

Figure 9. Percentage increase in post-harvest available nitrogen, phosphorus, potassium, sulphur and boron under the highest nano urea (N2, relative to N0) and highest boron (B4, relative to B0) treatments.

What stands out from this comparison is not simply that both inputs raise soil nutrient status, but that they do so while leaving the soil's more fundamental chemical properties — its pH, its salt load, its organic carbon reserve — essentially untouched. That combination is not something that can be taken for granted with every fertilization strategy; many conventional nutrient sources trade short-term nutrient supply for a longer-term drift in soil reaction or salinity. The pattern observed here, of nutrient enrichment without chemical disturbance, is precisely what one would hope to see from inputs marketed as components of sustainable, soil-friendly nutrient management, and the present data lend that description reasonably direct empirical support.

4.Practical And Agronomic Implications

The residual soil-fertility gains documented here carry consequences that extend beyond the mustard crop itself. In the double- or triple-cropped systems typical of the Kymore Plateau, where mustard is commonly followed by a cereal, pulse or fodder crop in rotation, a larger residual pool of available nitrogen, phosphorus, potassium, sulphur and boron effectively lowers the fertilizer requirement of the succeeding crop, or at minimum improves the odds that it will establish and grow on a more favourable nutrient base. This is particularly relevant for boron, where the post-harvest soil status under B4 (0.68 mg kg^{-1}) had moved from a marginally deficient starting point to a level much closer to sufficiency, a shift that could meaningfully reduce the risk of boron-deficiency symptoms in a subsequent boron-sensitive crop such as cauliflower, groundnut or another Brassica.

It is also worth situating these soil-level findings alongside the crop-performance and economic outcomes recorded in the parent study from which this soil dataset is drawn. There, the same N2 and B4 treatments that produced the strongest residual soil-fertility gains also delivered the highest seed yield, gross income, net income and benefit–cost ratio, with the N2 × B4 combination returning the best benefit–cost ratio (2.06) among all fifteen treatment combinations. Taken together, the soil-chemistry evidence presented here and the yield-and-economics evidence reported alongside it point in the same direction: nano urea and boron, used jointly at these levels, appear to be agronomically effective, economically attractive and chemically conservative — a combination not often achieved simultaneously by a single nutrient-management intervention.

5.Limitations And Future Research Directions

A few limitations of the present study are worth noting, both to properly qualify its conclusions and to point toward useful next steps. First, the trial was conducted over two Rabi seasons at a single location; while two years of data lend reasonable confidence to the trends reported, soil chemical properties — particularly organic carbon — often change slowly and may require a longer run of seasons, or a multi-location trial, before firmer conclusions can be drawn about their long-term trajectory under repeated nano urea and boron application. Second, the present analysis was restricted to the 0–15 cm surface layer; boron and other nutrients can move, however slowly, through the soil profile, and a depth-wise assessment down to at least 30 or 45 cm would give a fuller picture of nutrient distribution and any risk of subsoil accumulation, particularly for boron given its potential for phytotoxicity at high concentrations in some soil types. Third, the present study did not directly measure soil microbial biomass, enzyme activity or the specific chemical fractions of soil phosphorus and sulphur; the mechanistic explanations offered here for the observed nutrient-availability trends, while consistent with the wider literature, would benefit from more direct microbiological and fractionation-based confirmation in future work. Finally, because nano urea formulations available in the market are not chemically identical, and their nitrogen-release kinetics may vary by manufacturer and batch, the specific residual-fertility response documented here should be treated as characteristic of the particular formulation used in this trial rather than as a universal property of all nano urea products.

6.CONCLUSION

Over two years of field experimentation on the sandy loam soils of the Kymore Plateau, foliar nano urea and soil-applied boron proved to be chemically conservative yet nutritionally productive inputs. Neither altered post-harvest soil pH, electrical conductivity or organic carbon to a statistically detectable extent, but both significantly enriched the residual pool of available nitrogen, phosphorus, potassium, sulphur and boron, with the twin nano urea spray (N2) and the highest boron dose (B4, 2.0 kg ha^{-1}) consistently producing the strongest gains, and with no significant interaction between the two factors at the soil-chemistry level. On a practical level, these findings support recommending the joint use of nano urea and boron — specifically, two nano urea sprays at 20 and 40 days after sowing together with 2.0 kg boron ha^{-1} — as a nutrient-management option for Indian mustard grown under the rainfed conditions of Chitrakoot–Satna and agro-climatically similar tracts of Madhya Pradesh, on the grounds that it builds up soil fertility for the succeeding crop without compromising the soil's basic chemical equilibrium. Multi-season, multi-location trials that extend the depth of soil sampling and incorporate direct measures of microbial and enzymatic activity would help confirm and refine these conclusions, and are recommended as the logical next step in this line of research.

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