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ORIGINAL PAPER

Residual Effects of Nickel and Its Interaction with Applied Zinc and NPK Improve the Growth, Yield, and Nutritional Quality of Cowpea and Urease Activity of Soil Grown in Vertisols

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Abstract
Soil application of nickel (Ni) has low efficiency and expected to produce enough residual effect to cater the need of the next crop in the sequence. A pot experiment was conducted on the soil of previous season pot study, wherein Ni and zinc (Zn) were applied with recommended dose of fertilizers (RDF). This study with cowpea as test crop was conducted on residual level of Ni in soil along with the application of RDF and Zn. The result showed significant increase in plant height, greenness index, number of branches, number of pods plant^{-1}, number of seed pod^{-1}, stover yield, seed yield, and weight of 100 seed of cowpea. All these attributes were highest at 10 mg Ni kg^{-1} applied in the previous crop along with Zn at the rate of 10 mg kg^{-1} in the current experiment (T10). The concentration of iron (Fe), manganese (Mn), and Zn in grain and stover significantly increased up to 10 mg kg^{-1} residual Ni (T10), and beyond this, a reduction in concentration was observed. The behavior of these elements with respect to uptake in both grain and stover was similar as that of their concentration. The urease activity and available N content in post-harvest soil increased as the residual Ni content in the soil increased.

Keywords Growth attributes · Nickel · Urease activity · Yield attributes · Zinc

1 Introduction

Nickel (Ni) and zinc (Zn) have been considered as an essential nutrient for plant growth and development. Experimental reports suggested that the optimum concentration (dry weight basis) of Ni and Zn for maintaining enzymes activity and physiological processes in crop plants was 0.01–5 and 8–100 µg g^{-1}, respectively (Yusuf et al. 2011; Patra et al. 2021). Nickel is the 5th most abundant element by weight after iron, oxygen, magnesium, and silicon, constituting about 3% of the earth composition (Patra et al. 2019). It is considered to be an essential element for plants and designated as an "ultra-micronutrient" (Brown and Bassil 2011; Kumar et al. 2018a). Nickel acts as a co-factor for several enzymes, such as urease, glyoxalase-I, hydrogenases, superoxide dismutases, carbon monoxide dehydrogenase, methyl-coenzyme M reductase, and nitrate reductase (NR) (Alibakhshi and Khoshgoftarmanesh 2015; Brown and Bassil 2011). The importance of Ni in plant nutrition first time reported by Dixon et al. (1975), and "mouse ear" was the first described Ni deficiency symptoms found in the young leaves of pecan trees (*Carya illinoensis* K.) (Wood et al. 2006). Ni toxicity symptoms are common above 0.1 ppm in crops, and the symptoms are imbalanced nutrition, reduction in seed yield, and malfunction in physiological processes, i.e., synthesis of plant pigments, hampering stomatal activity and untimely yield reduction (Fabiano et al. 2015; Saad et al. 2016). In soybean, Ni promoted urease activity which eventually improves nitrogen (N) nutrition and hastens the N translocation to different plant parts (Lavres et al. 2016; Kutman et al. 2014). It has been also proved that Ni nutrition especially in legumes improves Zn uptake which can be finally

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seen in increased crop productivity (de Queiroz Barcelos et al. 2017; Sikka and Singh 2021).

Zinc is most deficient micronutrient in the soil (Patel et al. 2022). It is now an integral part of fertilizer recommendation for most of the crops in several countries (Mohapatra et al. 2022). Zinc is a constituent of prosthetic group in a large number of proteins and is involved in the activation of all the six groups of enzymes, namely, oxidoreductases, transferases, hydrolases, lyase isomerases, and ligases (Prasad et al. 2016). It is also important for different biochemical and physiochemical processes in the plants like protein synthesis, metabolism of plant hormones and carbohydrate synthesis, and formation of pollen tube during reproductive phase of the plant. Therefore, maintaining optimum Zn nutrition is of great importance for field crops like rice, wheat, and maize achieving higher crop productivity and ensuring nutritional security (Manzeke et al. 2019; Mohapatra et al. 2021; Yaseen and Hussain 2021).

Grain legumes are store house of dietary proteins and important minerals and play pivotal role in food and nutritional security particularly for the vegetarians (Dutta et al. 2022). The total area under cowpea cultivation in India is about 136,000 ha with productions of about 1,373,000 million tonnes (Singh et al. 2012). The productivity of cowpea is yardstick due to unavailability of high yielding varieties and crop husbandry practices (nutrient, water, and pest management), and strategies should come out to boost the productivity and income in the marginal lands. In the Ni-deficient soils, applied Ni in the previous crop can enhance the N fixation in cowpea due to the residual effect (Boer et al. 2014; Macedo et al. 2020). As the range of toxicity and sufficiency is very close in Ni, maintaining optimum level of Ni is prerequisite to for hydrolyzing urea vis-à-vis carry on N assimilation (Zhran et al. 2021).

Generally, optimum Ni application has synergistic impact on Zn content. Experimental evidences showed that in different soil types particularly under deficient Zn conditions, the application of Ni had more promising impact on crop growth, yield attributes, and available Zn content in the soil. De Queiroz Barcelos et al. (2017) revealed that foliar Zn concentration showed a parabolic response in response to Ni application, and the highest Zn concentration was obtained at 40 g ha^{-1} of Ni. At higher Ni concentrations, wheat cultivars took up significantly more Ni at lower Zn level (400 nM $ZnSO_4$) than at higher Zn level (2 mM $ZnSO_4$) (Dalir et al. 2017). Similarly, Tang et al. (2019) found that Ni uptake could be severely suppressed by the presence of Zn while, greatly stimulated under Zn deficiency, almost 2.1 times higher Ni uptake over control. Besides, Zn translocation factor from root to shoot decreased continuously as Ni concentration in solutions increased. Because both elements are cationic in nature and compete for the same adsorption site, an appropriate application rate is critical to get a favorable response from both nutrients. Therefore, from the above scientific works, it can be well apprehended that the Zn × N is highly synergistic on crop growth and physiology which is further modified by Ni. Being a nutrient of minimal dose, the quantity of Ni should be carefully managed to avoid any kind of crop damage. Hence, the presence of optimal or sub-optimal amount of Ni in the residual soils may be effective to boost the cowpea growth and positively regulate other nutrient uptakes. Thus, the present study hypothesized that optimal Ni in the previous crop may be sufficient to succeeding crop under Ni-deficient conditions. As commercially Ni application is rare and used in substantially lower amount (0.1–1 mg kg^{-1}), the significance of residual or limited Ni is of cardinal importance by serving dual purpose of satisfying crop need without extra monetary input. It was hypothesized that Ni application in Ni-deficient soil may leave sufficient residual value which could be sufficient to succeeding crop. The importance of residual Ni and its interaction with Zn by the crops grown in low Ni soils is one of the lesser known facts and needs specific research on this aspect. Therefore, to test this hypothesis, this experiment was set up with cowpea in the same pots in which soybean was grown in the previous season with the application of Ni and Zn. Keeping these points in mind, our objective was to evaluate the response on growth, yield, and uptake of micronutrient by cowpea to the residual Ni present in soil and its interaction with Zn.

2 Materials and Methods

2.1 Experimental Site

A pot experiment was conducted in summer season of 2019 (February to May) in the Department of Soil Science and Agricultural Chemistry, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, India. Varanasi is located at an altitude of 80.2 m above mean sea level between 25°14′ and 25°23′N latitude and 82°56′ and 83°03′E longitude. This area falls in a semi-arid to sub-humid climate with a moisture deficit index in between 20 and 40. The maximum and the minimum temperature varied from 19.8 to 42.2 °C and 4.7 to 24.0 °C during cowpea cultivation (February to May). The maximum and the minimum relative humidity varied between 37–92% and 19–69%, respectively, with an annual mean rainfall of 1100 mm.

2.2 Experimental Setup

Nickel deficient ($<$0.13 mg Ni kg^{-1}) bulk soil samples were collected from Sikhar Block of Mirzapur District, Uttar Pradesh (25°80′ N latitude and 82°47′ E longitude). Kumar et al. (2018b) reported the critical limit of deficiency for DTPA-extractable Ni content in soil was 0.22 mg kg^{-1}, whereas Barman et al. (2020) documented 0.17 mg Ni kg^{-1}. The initial soil had clay loam texture (36.1% sand, 28.6% silt, and 35.3% clay), slightly alkaline in reaction (pH 7.55), normal in salt content (EC 0.48 dS m^{-1}), low in organic carbon (OC) content (4.2 g kg^{-1}), low in available N (182 kg ha^{-1}), high in available P (21.9 kg ha^{-1}), medium in available K (245 kg ha^{-1}), and high in available S content (25.6 mg kg^{-1}). The DTPA-extractable zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), and nickel (Ni) contents in the soil were 0.41, 1.27, 3.78, 4.01, and 0.13 mg kg^{-1}, respectively. The critical limit of deficiency for DTPA-extractable Ni content in soil was 0.6 mg kg^{-1} (Shukla and Behera 2019). Therefore, the soil was deficient both in Zn and Ni. In the rainy season of 2018 (July to November), a pot experiment was conducted taking soybean (variety Kashi Nidhi) as test crop, and the treatments details are given in Table 1. After completion of this experiment, the same pots were used to assess the left over residual effect of Ni and its interaction with Zn by taking cowpea as test crop.

For conducting the present study, the previous year's pots soil was air dried, grounded to pass through 2-mm sieve, and filled in polythene lined pots. The experiment was conducted by taking thirteen treatments (Table 1) with three replications in a completely randomized design (CRD). The treatments comprise four levels of residual Ni (2.5, 5.0, 10, and 20 mg Ni kg^{-1}) and three levels of Zn (2.5, 5.0, and 10 mg Zn kg^{-1}) in combination with recommended dose of fertilizers (RDF). The recommended dose of N, P_2O_5, and K_2O for cowpea was applied at the rate of 26.8, 13.4, and 13.4 mg kg^{-1} using urea, single super phosphate (SSP), and muriate of potash (MOP), respectively, as source of N, P, and K. Full dose of these fertilizers were applied in solution form before sowing of cowpea. The amount of $ZnSO_4.7H_2O$ (21% Zn) for 10 kg soil was calculated for applying 2.5, 5.0, and 10 mg Zn kg^{-1} in solution form before sowing. Six seeds of cowpea were sown in each pot however; for proper maintenance, only four plants are kept till last, and the pots are maintained in field capacity throughout the experimental period.

2.3 Growth and Yield Attributes

Growth attributing characters of cowpea mainly plant height and greenness index (SPAD value) were recorded at 30 and 60 days after sowing (DAS). At maturity, number of branch $plant^{-1}$, number of pod $plant^{-1}$, and number of seed pod^{-1} were recorded. The plants (seed and stover) were then washed sequentially in 0.2% detergent solution, 0.1 N HCl, and finally with doubled distilled water, dried in hot air oven at 60 °C till constant weight. The grain yield, straw yield, and 1000 grain weight were recorded, and harvest index (HI) was calculated:

$$\text{Harvest index (\%)} = \frac{\text{Economic yield}}{\text{Total biological yield}} \times 100$$

2.4 Soil and Plant Analyses

For laboratory analysis, all the three replicates of soil and plant samples were taken, and the mean of the three is given as final value. From every pot, post-harvest soil (PHS) was

Table 1 Treatments detail

Treatments	Previous crop (rainy season, 2018) treatments detail (crop, soybean)	Present experimental (summer season, 2019) treatments[#] (crop, cowpea)
T1	RDF[*]	RDF
T2	RDF + 2.5 mg Ni kg^{-1} + 2.5 mg Zn kg^{-1}	RDF + 2.5 mg Zn kg^{-1}
T3	RDF + 2.5 mg Ni kg^{-1} + 5.0 mg Zn kg^{-1}	RDF + 5.0 mg Zn kg^{-1}
T4	RDF + 2.5 mg Ni kg^{-1} + 10 mg Zn kg^{-1}	RDF + 10 mg Zn kg^{-1}
T5	RDF + 5.0 mg Ni kg^{-1} + 2.5 mg Zn kg^{-1}	RDF + 2.5 mg Zn kg^{-1}
T6	RDF + 5.0 mg Ni kg^{-1} + 5.0 mg Zn kg^{-1}	RDF + 5.0 mg Zn kg^{-1}
T7	RDF + 5.0 mg Ni kg^{-1} + 10 mg Zn kg^{-1}	RDF + 10 mg Zn kg^{-1}
T8	RDF + 10 mg Ni kg^{-1} + 2.5 mg Zn kg^{-1}	RDF + 2.5 mg Zn kg^{-1}
T9	RDF + 10 mg Ni kg^{-1} + 5.0 mg Zn kg^{-1}	RDF + 5.0 mg Zn kg^{-1}
T10	RDF + 10 mg Ni kg^{-1} + 10 mg Zn kg^{-1}	RDF + 10 mg Zn kg^{-1}
T11	RDF + 20 mg Ni kg^{-1} + 2.5 mg Zn kg^{-1}	RDF + 2.5 mg Zn kg^{-1}
T12	RDF + 20 mg Ni kg^{-1} + 5.0 mg Zn kg^{-1}	RDF + 5.0 mg Zn kg^{-1}
T13	RDF + 20 mg Ni kg^{-1} + 10 mg Zn kg^{-1}	RDF + 10 mg Zn kg^{-1}

[#] Residual effect of Ni was observed, applied in previous crop

[*] *RDF*, recommended dose of fertilizer

Recommended dose of fertilizer (RDF) for cowpea crop, i.e., N, P_2O_5, and K_2O:: 26.8, 13.4, and 13.4 mg kg^{-1}, respectively collected and divided into two halves. One half of sample was processed by passing it through 2-mm and subsequently with 0.5-mm sieves and kept for chemical analysis. The other portion of sieved (2 mm), homogenized sample was kept in 4 °C for biochemical analysis. The moisture content was determined immediately by the gravimetric method.

The soil samples were analyzed for pH by following the procedure as outlined in Sparks et al. (1996), and the same solution was used for measurement of EC. Potassium dichromate (1 N $K_2Cr_2O_7$) oxidizable organic carbon was determined by the method of Walkley and Black (1934), available N by alkaline potassium permanganate ($KMnO_4$) method (Subbiah and Asija 1956), available P by extracting the soil with sodium bicarbonate ($NaHCO_3$) (Olsen et al. 1954), and available K using neutral normal ammonium acetate extraction method (Jackson 1973). The micronutrient content in PHS was determined by DTPA extraction in 1:2 soil:extractant ratio (Lindsay and Norvell 1978) and analyzed by atomic absorption spectrophotometer (AAS), model Agilent 240FS-AA (Agilent Technologies, Santa Clara, USA). Urease activity was determined in the refrigerated soil samples following incubation method by Tabatabai and Bremner (1972). Finely grounded seed and stover samples were digested with di-acid mixture (HNO_3:$HClO_4$:: 3:1, v/v) and analyzed for Zn, Cu, Fe, Mn, and Ni using AAS (Tandon 2001).

2.5 Statistical Analysis

The research data were analyzed using statistical software SPSS 16.0 for ANOVA (complete randomized design). Duncan multiple range test (DMRT) at $p \leq 0.05$ levels of significance was used to evaluate the significant differences among mean values (Gomez and Gomez 1984).

3 Results

3.1 Growth Attributes of Cowpea

The plant height at 30 DAS and 60 DAS (Table 2) varied from 19.5 to 23.3 and 39.5 to 53.1 cm, respectively. The highest plant height 23.3 cm was recorded at 30 DAS in T12, while at 60 DAS, 53.1 cm was observed in T9. These treatments recorded a significant respective increase of 8.88 and 30.1% in plant height over RDF (T1) at 30 and 60 DAS. Moreover, T10 (19.5 cm) and T5 (39.5 cm) documented the lowest plant height at 30 and 60 DAS, respectively.

At 30 DAS, all treatments showed significantly higher greenness index over RDF except T2 which was statistically at par with RDF (Table 2). The maximum greenness index was recorded in T10 followed by T9 showing a significant increase of 41.0 and 35.9%, respectively over RDF. At 60 DAS, the maximum greenness index was in treatment T9 which increased by 30.1% over RDF. The minimum greenness index was in T5 that decreased by 3.18% over RDF.

The total number of branch plant^{-1} is influenced by the application of different levels of Zn fertilizer along with residual effects of Ni (Table 2). The maximum number of branches was in T10 (11.3 plant^{-1}) followed by T8 (9.6 plant^{-1}) and T9 (9.3 plant^{-1}) with corresponding significant increase of 88.3, 60, and 55% over RDF, and the minimum (6 plant^{-1}) was in T1 and T2.

3.2 Yield Attributes and Yields of Cowpea

Data pertaining to the number of pod plant^{-1} and the number of seed per pod were presented in Table 2. The number of pods per plant varied from 8.0 to 18.3, with T10 having the highest value, increasing by 90.6% over RDF. The number of seed pod^{-1} varied between 6.3 and 10. The highest number of seed pod^{-1} was in T10 followed by T8 and T7, which increased by 25, 16.3, and 12.5% over RDF, respectively. The lowest was in T11 which decreased by 21% from the RDF.

The stover yield varied significantly from 9.9 to 13.6 g pot^{-1} (Table 2). The maximum stover yield (13.6 g pot^{-1}) was found in T10 followed by T8 (12.7 g pot^{-1}) and T9 (12.7 g pot^{-1}) with respective increase of 15.3, 7.60, and 7.60% than RDF. The minimum stover yield (9.9 g pot^{-1}) was recorded in T11 that showed a decline of 16.1% over RDF. Seed yield of cowpea significantly varied from 5.4–6.8 g pot^{-1} (Table 2). The maximum seed yield was obtained from T10 (6.8 g pot^{-1}) followed by T9 and T8 that corresponds a significant increase of 25.9, 22.2, and 20.4% over RDF; however, the lowest seed yield (5.4 g pot^{-1}) was registered in RDF.

Data pertaining to 100 seed weight (Table 2) showed a variation from 5.2 to 7.4 g. The maximum weight was found in T10 (7.4 g) which increased by 7.24% over RDF. The minimum 100 seed weight was recorded with T11 (5.2 g) which was significantly lower by 24.6% than RDF.

Harvest index significantly varied with different residual levels of Ni in soil (Table 2), and it ranged from 31.7 to 38%. The highest percent harvest index of 38 was observed with T12 followed by 36.8 in T11 and 36.4 in T13 which resulted significant respective increase of 19.9, 16.1, and 14.8% over RDF. The lowest per cent harvest index (31.7) was in RDF.

3.3 Nutrient Concentration in Seed and Stover

The data pertaining to the residual effect of different levels of Ni and soil application of recommended dose of fertilizers along with different levels of Zn on micronutrient (Fe, Cu, Mn, and Zn) concentration in stover and seed of cowpea has been presented in Figs. 1 and 2.

Table 2 Residual effect of nickel application on plant height, greenness index (SPAD value), yield attributes, and yields of cowpea (mean of 3 replication ± standard error)

Treatments	Plant height (cm)		Greenness index (SPAD)		No. of branches plant^{-1}	No. of pods plant^{-1}	No. of seeds pod^{-1}
	30 DAS[#]	60 DAS	30 DAS	60 DAS			
T1	21.4 ± 0.34 cd	40.8 ± 0.85 efg	33.9 ± 0.41 i	40.8 ± 0.52 hi	6.0 ± 0.7 g	9.60 ± 1.1 efg	8.0 ± 0.7 abcd
T2	22.7 ± 0.36 ab	40.3 ± 0.82 fg	35.0 ± 0.46 hi	40.3 ± 0.51 gh	6.0 ± 0.3 g	8.60 ± 0.7 f	7.3 ± 0.6 bcd
T3	20.0 ± 0.28 f	42.8 ± 0.89 cdef	36.5 ± 0.47 gh	42.8 ± 0.52 cf	6.6 ± 0.5 fg	9.30 ± 0.9 ef	8.3 ± 0.7 abcd
T4	21.4 ± 0.36 cde	44.0 ± 0.92 cd	38.1 ± 0.48 f	44.0 ± 0.56 fg	7.0 ± 0.4 efg	10.0 ± 0.7 efg	8.6 ± 0.8 abc
T5	21.9 ± 0.36 bcd	39.5 ± 0.75 g	39.8 ± 0.48 e	39.5 ± 0.47 c	7.6 ± 0.7 cdef	8.00 ± 0.8 f	7.3 ± 0.7 bcd
T6	21.2 ± 0.36 de	39.8 ± 0.77 g	42.7 ± 0.59 d	39.8 ± 0.45 d	8.3 ± 0.8 bcde	12.0 ± 1.1 def	8.6 ± 0.8 abc
T7	20.3 ± 0.27 cf	42.8 ± 0.87 cdef	43.4 ± 0.58 cd	42.8 ± 0.50 cf	8.6 ± 0.5 bcd	12.3 ± 0.8 cde	9.0 ± 0.7 ab
T8	21.3 ± 0.36 cde	44.8 ± 0.93 c	44.7 ± 0.61 bc	44.8 ± 0.60 bc	9.6 ± 0.7 ab	15.0 ± 0.9 bc	9.3 ± 0.5 ab
T9	22.3 ± 0.38 abc	53.1 ± 0.11 a	46.1 ± 0.64 b	53.1 ± 0.69 ab	9.3 ± 0.6 bc	15.3 ± 1.2 b	8.3 ± 0.8 abcd
T10	19.5 ± 0.25 f	43.5 ± 0.88 cde	47.8 ± 0.68 a	43.5 ± 0.56 a	11.3 ± 0.7 a	18.3 ± 0.8 a	10.0 ± 0.6 a
T11	21.7 ± 0.36 bcd	44.4 ± 0.86 c	38.7 ± 0.52 ef	44.4 ± 0.57 j	6.3 ± 0.6 g	9.60 ± 0.9 efg	6.3 ± 0.7 d
T12	23.3 ± 0.38 a	47.6 ± 0.88 b	36.0 ± 0.41 gb	47.6 ± 0.59 ij	7.3 ± 0.8 efg	13.3 ± 1.1 bcd	7.3 ± 0.6 bcd
T13	21.6 ± 0.33 cd	41.2 ± 0.81 defg	37.3 ± 0.40 fg	41.2 ± 0.56 j	9.3 ± 0.6 bc	13.3 ± 0.7 bcd	6.6 ± 0.5 cd
CD[*] ($p \le 0.05$)	0.98	2.54	1.51	1.59	1.76	2.63	1.93
	Stover yield (g pot^{-1})	Seed yield (g pot^{-1})		Weight of 100 seeds		Harvest index (%)	
T1	11.8 ± 0.4 cd	5.4 ± 0.08 i		6.9 ± 0.13 bcd		31.7 ± 0.51 d	
T2	11.0 ± 0.1 ef	5.6 ± 0.07 hi		6.8 ± 0.11 bcd		33.7 ± 0.69 c	
T3	10.6 ± 0.2 fg	5.9 ± 0.06 fg		6.7 ± 0.06 cd		36.0 ± 0.72 b	
T4	10.8 ± 0.3 ef	6.1 ± 0.05 ef		6.4 ± 0.09 ef		36.2 ± 0.42 ab	
T5	11.0 ± 0.5 def	6.2 ± 0.07 de		6.6 ± 0.1 de		36.1 ± 0.43 ab	
T6	11.5 ± 0.1 cde	6.3 ± 0.06 cde		6.7 ± 0.12 cd		35.4 ± 0.75 bc	
T7	12.0 ± 0.3 c	6.4 ± 0.07 bcd		6.8 ± 0.05 bcd		34.7 ± 0.76 bc	
T8	12.7 ± 0.2 b	6.5 ± 0.08 bc		7.1 ± 0.08 b		33.8 ± 0.81 c	
T9	12.7 ± 0.1 b	6.6 ± 0.03 b		6.9 ± 0.12 bc		34.7 ± 0.53 bc	
T10	13.6 ± 0.2 a	6.8 ± 0.09 a		7.4 ± 0.13 a		33.4 ± 0.57 cd	
T11	9.90 ± 0.3 g	5.8 ± 0.06 gh		5.2 ± 0.05 h		36.8 ± 0.82 ab	
T12	10.0 ± 0.1 g	6.1 ± 0.12 ef		5.9 ± 0.11 g		38.0 ± 0.71 a	
T13	11.2 ± 0.2 cde	6.4 ± 0.07 bcd		6.2 ± 0.07 f		36.4 ± 0.51 ab	
CD ($p \le 0.05$)	0.67	0.20		0.28		1.82	

[#] *DAS*, days after sowing. [*] *CD*, coefficient of dispersion. Please see Table 1 for treatment details

Means with similar lowercase letters within a column are not significantly different at $p \le 0.05$ according to the Duncan's multiple range test

The Fe, Cu, Mn, Zn, and Ni concentration in seed ranged from 34.6–50.3, 12.1–22.0, 29.6–42.3, 17.5–23.4 to 1.0–3.6 mg kg^{-1}. Similarly, in stover, the micronutrient concentration (Fe, Cu, Mn, Zn, and Ni) varied from 85–117, 8.2–17.9, 19.9–28.4, 26.9–45.6 to 0.66–0.93 mg kg^{-1}. The maximum Fe (50.3, 117 mg kg^{-1}), Mn (42.3, 28.4 mg kg^{-1}), Cu (22.0, 17.9 mg kg^{-1}), and Zn (23.4, 45.6 mg kg^{-1}) concentration in seed and stover, respectively, were recorded in T10, which showed a respective significant increase of by 45.4 and 37.6%, 42.7 and 42.9%, 27.9 and 46.7%, and 33.7 and 69.5% over RDF. The maximum Ni concentration in both seed and stover was recorded in T13, which had corresponding increase of 260 and 40.9% over RDF. Except Cu, the minimum Fe, Mn, Zn, and Ni concentration both in seed and stover were recorded in RDF.

3.4 Post-harvest Soil Properties

The data regarding physicochemical properties of post-harvest soil, such as pH, EC, and OC, varied from 7.95–8.39, 0.14–0.21 dS m^{-1} to 0.40–0.58 g kg^{-1}, respectively (Table 3). The maximum pH (8.39) was recorded in T10 which was at par with T2, T3, T12, and T13. However, the minimum pH was observed in RDF (7.95). The maximum EC (0.21 dS m^{-1}) was in T10 which was 31.3% higher than RDF (0.16 dS m^{-1}), whereas the minimum EC (0.14 dS m^{-1}) was recorded

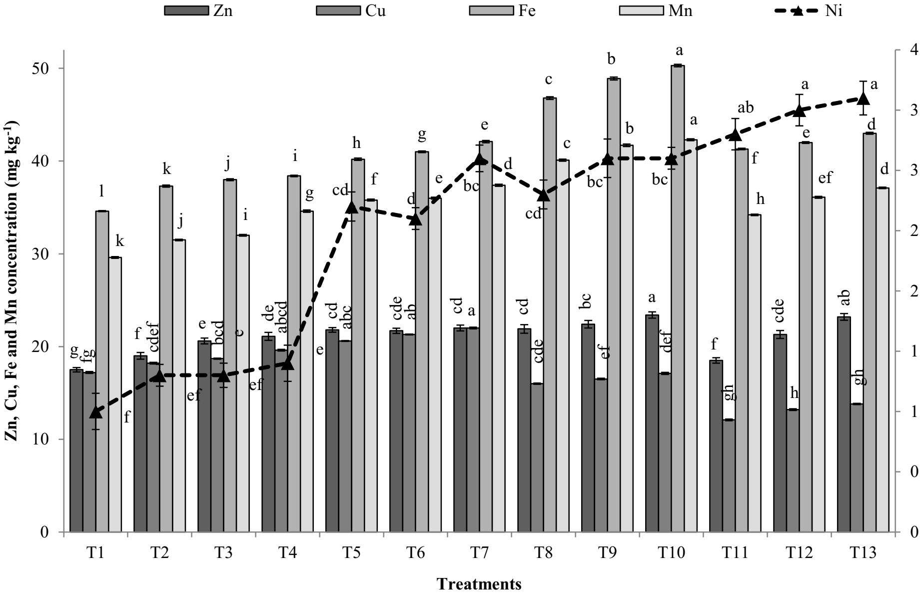

Fig. 1 Residual effect of nickel application on micronutrients (mg kg^{-1}) concentration in seed of cowpea. Please see Table 1 for treatment details. Different letters for each parameter show significant difference at $p \le 0.05$ by Duncan's multiple range test. Error bars identify standard errors of different treatments

in T7 which was 14.2% lower than RDF. The maximum OC was observed in T5 (0.58 g kg^{-1}) which was significantly higher by 23.4%, and the minimum OC (0.40 g kg^{-1}) was in T12 which were significantly lower by 14.8% than RDF.

Data on available N content in post-harvest soil has been presented in Table 3. It ranged from 155 to 270 kg ha^{-1}. The maximum N content (270 kg ha^{-1}) was obtained with T10 followed by 254 kg ha^{-1} with T9 and 252 kg ha^{-1} with T8 which resulted a significant increase of 74, 63.8, and 62.5% over RDF (155 kg ha^{-1}), respectively. The lowest N content was recorded in RDF (155 kg ha^{-1}).

The data pertaining to DTPA-extractable Fe, Mn, Cu, Zn, and Ni content significant variation range from 1.83–2.22, 2.05–2.14, 0.66–0.81, 1.19–1.29 to 0.68–2.92 mg kg^{-1} (Table 3). The maximum DTPA Fe content (2.22 mg kg^{-1}) was observed in RDF. The minimum Fe content (1.83 mg kg^{-1}) was observed in T10, which was significantly lowered by 17.5% than RDF. The highest DTPA Mn content (2.14 mg kg^{-1}) was observed in T3 which significantly increased by 0.46% than RDF. The minimum Mn content (2.05 mg kg^{-1}) was observed in T13 which was significantly lower by 3.75% than RDF (2.13 mg kg^{-1}). The maximum DTPA Cu content (0.81 mg kg^{-1}) was in RDF and the minimum (0.66 mg kg^{-1}) in T10. The maximum DTPA Zn

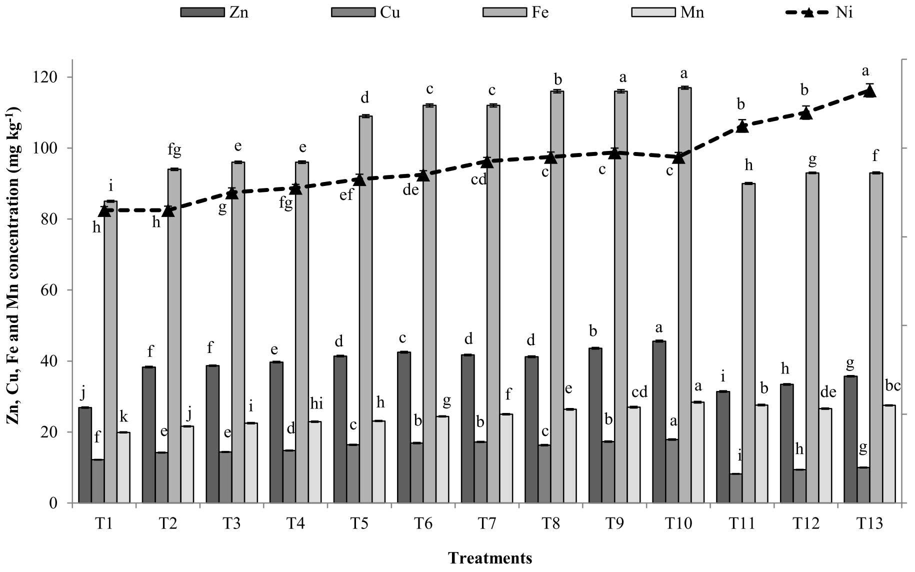

Fig. 2 Residual effect of nickel application on micronutrients (mg kg^{-1}) concentration in stover of cowpea. Please see Table 1 for treatment details. Different letters for each parameter show significant difference at $p \le 0.05$ by Duncan's multiple range test. Error bars identify standard errors of different treatments

Table 3 Residual effect of nickel application on physicochemical properties of post-harvest soil (mean of 3 replication ± standard error)

Treatments	pH	EC[#] (dS m^{-1})	OC[$] (g kg^{-1})	Available N (kg ha^{-1})	DTPA-extractable micronutrients (mg kg^{-1})				
					Zn	Cu	Fe	Mn	Ni
T1	7.95 ± 0.01 d	0.16 ± 0.001 e	0.47 ± 0.01 de	155 ± 1.53 h	1.25 ± 0.01 bcd	0.81 ± 0.02 a	2.22 ± 0.03 a	2.13 ± 0.02 abc	0.16 ± 0.01 i
T2	8.38 ± 0.03 a	0.19 ± 0.002 c	0.46 ± 0.01 e	175 ± 1.67 g	1.23 ± 0.01 de	0.80 ± 0.02 ab	2.11 ± 0.02 b	2.13 ± 0.02 abc	0.68 ± 0.01 i
T3	8.36 ± 0.02 a	0.20 ± 0.003 b	0.51 ± 0.02 cd	182 ± 1.82 g	1.23 ± 0.01 de	0.78 ± 0.02 bc	2.01 ± 0.02 c	2.14 ± 0.02 a	0.69 ± 0.02 h
T4	8.26 ± 0.02 bc	0.16 ± 0.001 e	0.53 ± 0.02 bc	197 ± 1.87 f	1.24 ± 0.01 cde	0.78 ± 0.02 bc	1.98 ± 0.02 cd	2.12 ± 0.02 abc	0.78 ± 0.02 g
T5	8.34 ± 0.02 a	0.18 ± 0.002 cd	0.58 ± 0.02 a	216 ± 2.31 e	1.23 ± 0.01 de	0.78 ± 0.01 bc	1.96 ± 0.02 cde	2.13 ± 0.02 ab	1.04 ± 0.02 f
T6	8.26 ± 0.03 bc	0.20 ± 0.004 b	0.56 ± 0.02 ab	228 ± 2.42 d	1.25 ± 0.01 bcd	0.77 ± 0.01 c	1.92 ± 0.02 defg	2.11 ± 0.01 abc	1.07 ± 0.02 f
T7	8.31 ± 0.04 ab	0.14 ± 0.001 f	0.55 ± 0.02 abc	233 ± 2.59 d	1.28 ± 0.02 ab	0.76 ± 0.01 cd	1.92 ± 0.02 defg	2.11 ± 0.01 bcd	1.08 ± 0.02 f
T8	8.24 ± 0.02 bc	0.20 ± 0.003 ab	0.44 ± 0.01 ef	252 ± 3.02 b	1.27 ± 0.02 abc	0.72 ± 0.01 e	1.87 ± 0.01 fgh	2.08 ± 0.01 d	1.35 ± 0.03 e
T9	8.32 ± 0.02 ab	0.17 ± 0.002 d	0.40 ± 0.01 f	254 ± 3.14 b	1.28 ± 0.02 ab	0.69 ± 0.01 f	1.86 ± 0.01 gh	2.10 ± 0.01 cd	1.45 ± 0.04 d
T10	8.39 ± 0.01 a	0.21 ± 0.004 a	0.40 ± 0.01 f	270 ± 3.32 a	1.29 ± 0.02 a	0.66 ± 0.01 g	1.83 ± 0.01 h	2.08 ± 0.01 d	1.60 ± 0.04 c
T11	8.21 ± 0.01 c	0.16 ± 0.001 e	0.41 ± 0.01 f	244 ± 2.51 c	1.22 ± 0.01 ef	0.80 ± 0.02 ab	1.99 ± 0.02 cd	2.11 ± 0.01 abcd	2.78 ± 0.05 b
T12	8.34 ± 0.02 a	0.16 ± 0.001 e	0.40 ± 0.01 f	248 ± 2.86 bc	1.19 ± 0.01 f	0.77 ± 0.01 c	1.94 ± 0.02 cdef	2.08 ± 0.01 d	2.92 ± 0.05 a
T13	8.36 ± 0.01 a	0.18 ± 0.002 c	0.43 ± 0.01 ef	254 ± 3.16b	1.22 ± 0.01 de	0.74 ± 0.01 de	1.90 ± 0.02 efgh	2.05 ± 0.01 e	2.87 ± 0.05 a
CD[*] ($p \leq 0.05$)	0.07	0.01	0.04	7.22	0.03	0.02	0.07	0.02	0.08

[#] *EC*, electrical conductivity. [$] *OC*, organic carbon. [*] *CD*, coefficient of dispersion. Please see Table 1 for treatment details

Means with similar lowercase letters within a column are not significantly different at $p \leq 0.05$ according to the Duncan's multiple range test

content (1.29 mg kg^{-1}) was in T10 followed by T9 (1.28 mg kg^{-1}) and T8 (1.27 mg kg^{-1}) with respective increase of 3.2, 2.4, and 1.6% over RDF. The minimum Zn content (1.19 mg kg^{-1}) was in T12 with significantly lower value of 4.8% over RDF (1.25 mg kg^{-1}). The maximum DTPA Ni content (2.92 mg kg^{-1}) was in T12 followed by T13 (2.87 mg kg^{-1}) and T11 (2.78 mg kg^{-1}), while the minimum was in RDF (0.16 mg kg^{-1}).

3.5 Urease Activity

Urease is a constitutive intracellular enzyme which consists of two Ni ions. Urease catalyzes the hydrolysis of urea to carbon dioxide and ammonia. The data on urease activity of the post-harvest soil were presented in Fig. 3. The urease activity in soils increased significantly with different grades of available residual Ni in soil as a result of its application

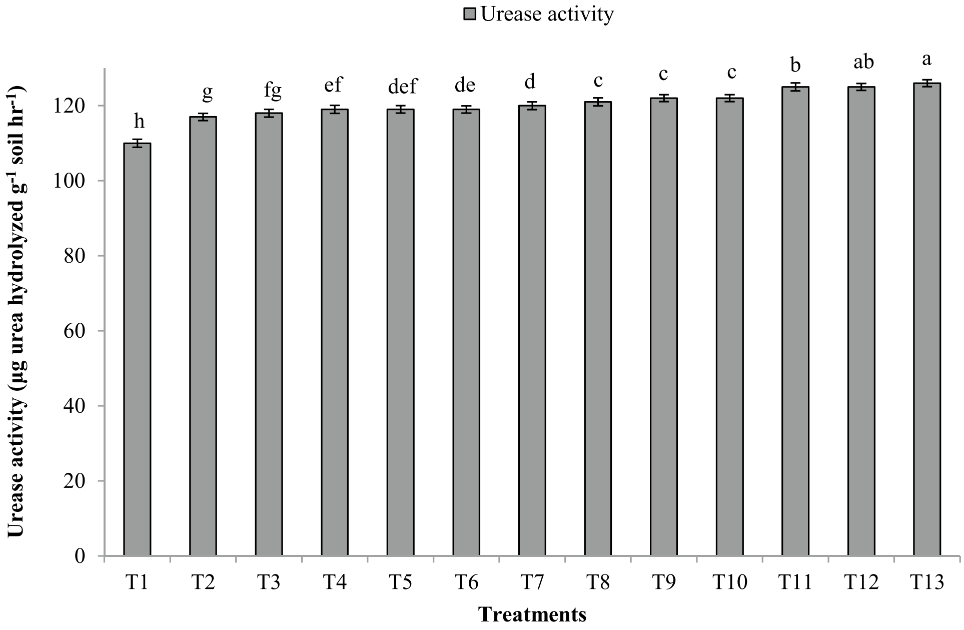

Fig. 3 Residual effect of nickel application on urease activity in post-harvest soil. Please see Table 1 for treatment details. Different letters for each parameter show significant difference at $p \leq 0.05$ by Duncan's multiple range test. Error bars identify standard errors of different treatments

in the previous crop. Its activity in soil ranged from 109.8 to 126 µg urea hydrolyzed g^{-1} soil h^{-1}. The maximum urease activity was in T13 (126 µg urea hydrolyzed g^{-1} soil h^{-1}) followed by T12 and T11 which showed a significant increase of 14.75, 14, and 13.4% over RDF, respectively. The minimum urease activity (117.2 µg urea hydrolyzed g^{-1} soil h^{-1}) was noted in RDF.

3.6 Correlation Analysis

Simple Pearson's correlation coefficient values (*r*) of N content, Ni content, and urease activity in post-harvest soil with growth and yield attributes of cowpea are given in Table 4. Correlation analysis revealed that plant height at 60 DAS in cowpea had a positive and significant relation with N (0.44**) and residual Ni content (0.32*). Greenness index, number of branch $plant^{-1}$ and number of pod $plant^{-1}$ had positive correlation with N and Zn content in soil. It has been observed that cowpea grain yield was correlated positively with available N, DTPA-extractable Zn, and urease activity. However, weight of 100 seeds was negatively correlated with DTPA-extractable Ni content and urease activity and positively contributes towards DTPA-extractable Zn content in soil. Correlation analysis of harvest index with DTPA-extractable Ni content and urease activity in soil indicated both are positively correlated where as it was negatively correlated with DTPA-extractable Zn content.

4 Discussion

The results supported the hypothesis that the application of Zn and residual Ni in soil improved the growth, yield, and nutritional quality of cowpea. Previous results strongly suggested the potential benefit of foliar Ni application on crop performances, but none of them showed the importance of residual Ni on present crop; hence, this study is of utmost importance. As indicated in the results, T10 had higher plant height, number of branch $plant^{-1}$, number of pod $plant^{-1}$, number of seed pod^{-1}, stover yield, seed yield, and weight of 100 seeds which is in agreement with the study conducted by Pande et al. (2012) and Ain et al. (2016). It has been reported that Ni deficiency adversely affected amino acid metabolism in cowpea (Walker et al. 1985) and hampered the urease activity, induced metabolic N deficiency, and affected the biomass production by the plant. Therefore, the presence of residual Ni in the soil might be helpful in enhancing the availability of N and their proper hydrolysis in NH_3 and CO_2 in leaves, thus increasing plant height and overall biomass of cowpea. In addition, the application of Zn to cowpea is expected to enhance tryptophan concentration, photosynthetic activity, protein synthesis, and metabolism of carbohydrate, thus contributing to the increase in growth and development of cowpea (Mathpal et al. 2015; Lavres et al. 2016). Experimental findings revealed that residual level obtained up to 10 mg kg^{-1} of Ni applied in previous crop was beneficial for cowpea, but over this, it becomes harmful for crop growth. This confirmed that there was a significant increase in yield of crops like wheat, barley, oat, and maize due to lower rate Ni application. Similarly, higher yield due to Zn application may increase the activity of many metallic enzyme systems, auxin production, and enhanced synthesis of

Table 4 Pearson's correlation coefficients (*r*) of nitrogen, nickel, and zinc content and urease activity in post-harvest soil with growth and yield attributes of cowpea

Plant attributes	Post-harvest soil			
	Available N	DTPA-extractable micronutrients		Urease activity
		Ni	Zn	
Plant height at 30 DAS[#]	-0.05	0.28	-0.48^{**}	0.14
Plant height at 60 DAS	0.44^{**}	0.32^{*}	0.17	0.38^{*}
Greenness index at 30 DAS	0.71^{***}	0.06	0.69^{***}	0.32^{*}
Greenness index at 60 DAS	0.41^{**}	-0.28	0.76^{***}	0.01
No of branches $plant^{-1}$	0.70^{***}	0.23	0.50^{***}	0.43^{**}
No of pods $plant^{-1}$	0.71^{***}	0.33^{*}	0.47^{**}	0.44^{**}
No of seeds pod^{-1}	0.11	-0.36^{*}	0.49^{**}	-0.15
Grain yield	0.79^{***}	0.28	0.41^{**}	0.54^{***}
Stover yield	0.33^{*}	-0.27	0.76^{***}	-0.11
Weight of 100 seeds	-0.09	-0.63^{***}	0.66^{***}	-0.42^{**}
Harvest Index	0.29	0.59^{***}	-0.54^{***}	0.61^{***}

*Significance at $p < 0.05$ level, **significance at $p < 0.01$ level, and ***significance at $p < 0.001$ level

[#] *DAS*, days after sowing

carbohydrates and their transport to the site of grain production (Das et al. 2019; de Moraes et al. 2021). On that account it can be apprehended that Ni content up to a certain limit (10 mg kg^{-1}) in association with Zn augmented crop performance in grain legumes especially cowpea.

Like yield and yield attributing characters, the pragmatic impact of residual Ni can be witnessed in partitioning of various cationic micronutrients inside cowpea which is further influenced by extraneous Zn supplementation. Zinc fertilization along with residual available Ni in soil significantly increased the essential micronutrient (Zn, Fe, Mn, Cu, and Ni) concentrations in cowpea. Khalid and Tinsley (1980) reported that Fe content in shoots of wheat had a positive correlation with low Ni and vice versa, and similar response can be witnessed by other researchers (de Queiroz Barcelos et al. 2017; Zhao et al. 2019). Analogous to Fe, the good amount of Mn content in the plant can be seen up to a critical content. Gerendas and Sattelmacher (1997) observed the maximum and minimum of Mn content of straw of berseem at Ni80 × Zn0 and Ni0 × Zn10 level of interaction, respectively. Thus, they concluded that with the increase in Ni application, the Mn content in plant dry matter increases. Similar kind of trend was found out by Kumar et al. (2018c) and Fatma et al. (2021) where they found a positive interaction between elevated dosage of Ni and the Mn concentration in straw and grain of barley and rice, respectively, up to soil application of Ni at 17.5 mg kg^{-1}. Lastly, Cu which is a very important micronutrient for grain legumes which behave similarly like other cationic micronutrients. Kumar et al. (2018c) also found that Cu concentration gradually increased trend up to soil application of Ni at 2.5 mg kg^{-1} in both straw and grain of barley, and beyond that, Ni doses were lethal for the crop curtailing the productivity substantially. The critical limit of deficiency of the Ni concentration in barley plant was established as 2.40 mg kg^{-1} (Kumar et al. 2018b) and 2.27 mg Ni kg^{-1} in spinach (Kumar et al. 2021a). Nickel application at ≥ 5.0 mg kg^{-1} (T5 to T13) was able to alleviate Ni insufficiency in cowpea seed; however, the maximum Ni concentration in stover was only 0.93 mg kg^{-1}, which was considerably lower than Ni sufficiency in crop. Hussain et al. (2018) observed the increase in Zn concentration in rice grain over RDF due to gradual increase in Zn levels. Experimental findings in cereal crops like wheat and maize with Ni application authenticate current experimental findings showing Zn buildup in the shoots (Sabir et al. 2011; Kumar et al. 2018a). However, findings of Deng et al. (2018) showed that in *Alyssum murale*, Zn and Ni concentration in solution is inversely related when solution Ni concentration is > 2 μM and reason being competition for the same uptake site by both the divalent ions. In nutshell, it can be said that the optimistic impact of Ni can only be passable up to a threshold level which depend upon crop species, soil and crop management factors, and interaction with other cationic micronutrients.

Phytoavailability of Ni and other metals generally decreased with increasing pH due to the formation of insoluble complexes in soils. Moreover, it may increase with a decrease in soil pH due to competition between hydrogen (H^+) and metal ions for soil sorption sites (Soleimani et al. 2009). Recent studies focused on the effects of Zn fertilization and residual Ni on the quality of soils. Kumar et al. (2021b) and Rodak et al. (2021) reported that the increasing pH impose negative effect on extractability of Ni in soils due to the decrease in solubility of Ni at higher pH. At high pH, bonds of Ni and other metals with OM might disrupt and thus could increase the solubility of Ni and other metals in soils. Nickel supplement was reported to have an advantage for BNF in respect of pulses in tropical conditions (Lavres et al. 2016). As such, fixed N is incorporated in root nodules into soil which may increase the availability of N to plant. DTPA extractability of micronutrients (Fe, Mn, Cu, and Zn) in the soil significantly increased in Zn- and Ni-fortified treatment compared to RDF (Morawska-Płoskonka and Niklińska (2013), Fatma et al. (2021), and Sikka and Singh (2021)). Goyal et al. (2016) observed that the application of Ni significantly increased DTPA Ni in both sandy loam and loamy sand soil which supports the results found in the current experiment. It resulted that as the dose of Ni increases, the urease enzyme activity enhances proportionally (Seregin and Kozhevnikova 2006; Kumar et al. 2018a; de Queiroz Barcelos et al. 2017). Dalton et al. (1985) reported that urease activity increased up to 150% with the addition of Ni in low Ni soil (total Ni 13 mg kg^{-1}), and even in contaminated soils, the favorable effect of Ni on urease can be seen (Wyszkowska et al. 2008). Overall, the effective implication of residual Ni on availability of macro- and micronutrients and urease was apparent although care must be taken while recommending the dose as minor variations can lead to significant changes.

5 Conclusions

It can be concluded that the residual effect of 10 mg Ni kg^{-1} applied in the previous crop along with Zn at 10 mg kg^{-1} was most effective for achieving higher growth and yield attributing characters of cowpea. The concentration and uptake of Fe, Mn, Cu, and Zn (except Ni) increased at lower level of residual Ni, whereas a significant decline was noticed when its supply exceeds by the application of 10 mg Ni kg^{-1} soil in the previous crop. Uptake of Ni increased with increasing levels of residual Ni in soil. The urease activity and available N content in soil significantly increased with the increase in residual Ni content. The utilization of residual Ni in soil applied in previous crop could be an effective strategy for sustainable management of Ni application in Ni-deficient soil. This may lead to better N fixation and provided higher yield of cowpea.

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Declarations

Conflict of Interest The authors declare no competing interests.

References

Ain Q, Akhtar J, Amjad M, Haq MA, Saqib ZA (2016) Effect of enhanced nickel levels on wheat plant growth and physiology under salt stress. Commun Soil Sci Plant Anal 47:2538–2546. https://doi.org/10.1080/00103624.2016.1254796

Alibakhshi M, Khoshgoftarmanesh AH (2015) Effects of nickel nutrition in the mineral form and complexed with histidine in the nitrogen metabolism of onion bulb. Plant Growth Regul 75:733–740. https://doi.org/10.1007/s10725-014-9975-z

Barman M, Datta SP, Rattan RK, Meena MC (2020) Critical limits of deficiency of nickel in intensively cultivated alluvial soils. J Plant Nutr Soil Sci 20:284–292. https://doi.org/10.1007/s42729-019-00141-9

Boer JL, Mulrooney SB, Hausinger RP (2014) Nickel-dependent metalloenzymes. Arch Biochem Biophys 544:142–152. https://doi.org/10.1016/j.abb.2013.09.002

Brown PH, Bassil E (2011) Overview of the acquisition and utilization of boron, chlorine, copper, manganese, molybdenum, and nickel by plants and prospects for improvement of micronutrient use efficiency The molecular and physiological basis of nutrient use efficiency in crops. John Wiley Sons USA 19:377–428

Dalir N, Tandy S, Gramlich A, Khoshgoftarmanesh A, Schulin R (2017) Effects of nickel on zinc uptake and translocation in two wheat cultivars differing in zinc efficiency. Environ Exp Bot 134:96–101. https://doi.org/10.1016/j.envexpbot.2016.11.009

Dalton DA, Evans JH, Hanus FJ (1985) Stimulation by nickel of soil microbial urease activity and urease and hydrogenase activities in soybeans grown in a low-nickel. Plant Soil 88:245–258. https://doi.org/10.1007/BF02182451

Das KK, Reddy RC, Bagoji IB, Das S, Bagali S, Mullur L, Biradar MS (2019) Primary concept of nickel toxicity–an overview. J Basic Clin Physiol Pharmacol 30:141–152. https://doi.org/10.1515/jbcpp-2017-0171

de QueirozBarcelos JP, de Souza Osorio CRW, Leal AJF, Alves CZ, Santos EF, Reis HPG, dos Reis AR (2017) Effects of foliar nickel (Ni) application on mineral nutrition status, urease activity and physiological quality of soybean seeds. Aust J Crop Sci 11:184–192. https://doi.org/10.21475/ajcs.17.11.02.p240

Deng TH, van der Ent A, Tang YT, Sterckeman T, Echevarria G, Morel JL, Qiu RL (2018) Nickel hyperaccumulation mechanisms: a review on the current state of knowledge. Plant Soil 423:1–11. https://doi.org/10.1007/s11104-017-3539-8

Dixon NE, Gazzola C, Blakeley RL, Zerner B (1975) Jack bean urease (EC 3.5. 1.5). Metalloenzyme. Simple biological role for nickel. J Am Chem Soc 97:4131–4133

Dutta A, Trivedi A, Nath CP, Gupta DS, Hazra KK (2022) A comprehensive review on grain legumes as climate-smart crops: challenges and prospects. Environ Chall 7:100479. https://doi.org/10.1016/j.envc.2022.100479

Fabiano CC, Tezotto T, Favarin JL, Polacco JC, Mazzafera P (2015) Essentiality of nickel in plants: a role in plant stresses. Front Plant Sci 6:754. https://doi.org/10.3389/fpls.2015.00754

Fatma S, Sabir M, Aziz T, Ahmad HR, Yaseen M, Zia-ur-Rehman M, Hakeem KR (2021) Comparison of fine and coarse rice varieties for nickel accumulation and growth response at different levels of nickel. Clean - Soil Air Water 49:2000336. https://doi.org/10.1002/clen.202000336

Gerendas J, Sattelmacher B (1997) Significance of Ni supply for growth, urease activity and concentrations of urea, amino acids and mineral nutrients of urea grown plants. Plant Soil 190:153–162. https://doi.org/10.1023/A:1004260730027

Gomez KA, Gomez AA (1984) Statistical procedures for agricultural research. John Wiley and Sons, New York

Goyal A, Kapoor S, Samuel P, Singhal S (2016) Magnetically retrievable modified nickel ferrite nanoparticles: efficient catalytic reduction of nitroarenes and photo-oxidation of hazardous dyes. Anal Chem Lett 6:98–123. https://doi.org/10.1080/22297928.2016.1188724

Hussain ST, Hussain A, Dar SA (2018) Biofortification benefits of zinc application to rice genotypes. J Pharmacogn Phytochem 7:1555–1558

Jackson ML (1973) Soil chemical analysis, Pentice hall of India Pvt. Ltd. New Delhi, India 498:151–154

Khalid BY, Tinsley J (1980) Some effect of Ni toxicity on rye grasses. Plant Soil 55:139–144. https://doi.org/10.1007/BF02149717

Kumar O, Singh SK, Latare AM, Yadav SN (2018a) Foliar fertilization of nickel affects growth, yield component and micronutrient status of barley (*Hordeum vulgare* L.) grown on low nickel soil. Arch Agron Soil Sci 64:1407–1418. https://doi.org/10.1080/03650340.2018.1438600

Kumar O, Singh SK, Singh AP, Yadav SN, Latare AM (2018b) Effect of soil application of nickel on growth, micronutrient concentration and uptake in barley *Hordeum vulgare* L. grown in Inceptisols of Varanasi. J Plant Nutr 41:50–66. https://doi.org/10.1080/01904167.2017.1381724

Kumar O, Singh SK, Singh AP, Yadav SN, Latare AM, Kumar M (2018c) Assessing a suitable extractant and critical limits of nickel in soil and plant for predicting the response of barley (*Hordeum vulgare* L.) to nickel grown in Inceptisols. Commun Soil Sci Plant Anal 49:2602–2613. https://doi.org/10.1080/00103624.2018.1526948

Kumar D, Ramani VP, Patel KC, Shukla AK (2021a) Establishing critical limits for nickel in soil and plant for predicting the response of spinach (*Spinaciaoleracea*). J Indian Soc Soil Sci 69:105–110. https://doi.org/10.5958/0974-0228.2021.00026.8

Kumar O, Singh SK, Patra A, Latare A, Yadav SN (2021b) A comparative study of soil and foliar nickel application on growth, yield and nutritional quality of barley (*Hordeum Vulgare* L.) grown in Inceptisol. Commun Soil Sci Plant Anal 52:1207–1223. https://doi.org/10.1080/00103624.2021.1879119

Kutman BY, Kutman UB, Cakmak I (2014) Effects of seed nickel reserves or externally supplied nickel on the growth, nitrogen metabolites and nitrogen use efficiency of urea-or nitrate-fed soybean. Plant Soil 376:261–276. https://doi.org/10.1007/s11104-013-1983-7

Lavres J, Castro Franco G, de Sousa Câmara GM (2016) Soybean seed treatment with nickel improves biological nitrogen fixation and urease activity. Front Environ Sci 4:37. https://doi.org/10.3389/fenvs.2016.00037

Lindsay WL, Norvell WA (1978) Development of DTPA soil test for Zn, iron, manganese and copper. Soil Sci Soc Am J 42:421–428. https://doi.org/10.2136/sssaj1978.03615995004200030009x

Macedo FG, Santos EF, Lavres J (2020) Agricultural crop influences availability of nickel in the rhizosphere; a study on base cation saturations Ni Dosages and Crop Succession. Rhizosphere 13:100182. https://doi.org/10.1016/j.rhisph.2019.100182

Manzeke MG, Mtambanengwe F, Watts MJ, Hamilton EM, Lark RM, Broadley MR, Mapfumo P (2019) Fertilizer management and soil type influence grain zinc and iron concentration under contrasting smallholder cropping systems in Zimbabwe. Sci Rep 9:1–13. https://doi.org/10.1038/s41598-019-42828-0

Mathpal B, Srivastava PC, Shankhdhar D, Shankhdhar SC (2015) Zinc enrichment in wheat genotypes under various methods of zinc application. Plant Soil Environ 61:171–175. https://doi.org/10.17221/41/2015-PSE

Mohapatra KK, Singh SK, Patra A (2021) Influence of varying levels of zinc on yield and zinc biofortification in hybrid rice (*Oryza sativa* L.) grown in moderate zinc soil. J Indian Soc Soil Sci 9:220–223. https://doi.org/10.5958/0974-0228.2021.00034.7

Mohapatra KK, Singh SK, Patra A, Jatav SS, Rajput VD, Popova V, Puzikova O, Nazarenko O, Sushkova S (2022) Biogeoaccumulation of zinc in hybrid rice (Oryza sativa L.) in an Inceptisol amended with soil zinc application and its bioavailability to human being. Eurasian J Soil Sci 11:184–197. https://doi.org/10.18393/ejss.1057928

Morawska-Płoskonka J, Niklińska M (2013) Effects of soil moisture and nickel contamination on microbial respiration rates in heavy metal-polluted soils. Pol J Environ Stud 22:1411–1418

Olsen SR, Cole CV, Watanable FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate USDA circular no. 939

Pande J, Srivastava PC, Singh SK (2012) Plant availability of nickel as influenced by farmyard manure and its critical toxic limits in French bean. J Plant Nutr 35:384–395. https://doi.org/10.1080/01904167.2012.639919

Patel PS, Singh SK, Patra A, Jatav SS (2022) Root dipping, foliar and soil application of zinc increase growth, yields, and grain zinc in rice (*Oryza sativa* L.) grown in moderate zinc soil of Inceptisol order. Commun Soil Sci Plant Anal 53:1917–1929. https://doi.org/10.1080/00103624.2022.2069800

Patra A, Dutta A, Jatav SS, Choudhary S, Chattopadhyay A (2019) Horizon of nickel as essential to toxic element. Int J Chem Stud 7:1185–1191

Patra A, Singh SK, Chattopadhyay A, Sharma VK, Rekwar RK (2021) Chemical fractionations and mobility of heavy metals in soils of eastern Uttar Pradesh. Indian J Agric Sci 91:761–766

Prasad R, Shivay YS, Kumar D (2016) Interactions of zinc with other nutrients in soils and plants-a review. Indian J Ferti 12:16–26

Rodak BW, Freitas DS, Bernardes LF, Lima GJEO, Reis AR, Lavres Junior J, Guimarães Guilherme LR (2021) Short-term nickel residual effect in field-grown soybeans: nickel-enriched soil acidity amendments promote plant growth and safe soil nickel levels. Arch Agron Soil Sci 1–16. https://doi.org/10.1080/03650340.2021.1912325

Saad R, Kobaissi A, Robin C, Echevarria G, Benizri E (2016) Nitrogen fixation and growth of Lens culinaris as affected by nickel availability: a pre-requisite for optimization of agromining. Environ Exp Bot 131:9. https://doi.org/10.1016/j.envexpbot.2016.06.010

Sabir MA, Ghafoor RM, Saifullah ZU, Ahmad H, Aziz T (2011) Growth and metal ionic composition of *Zea mays* as affected by nickel supplementation in the nutrient solution. Int J Agric Biol 13:186–190

Seregin IV, Kozhevnikova AD (2006) Physiological role of nickel and its toxic effects on higher plants. Russ J Plant Physiol 53:257–277. https://doi.org/10.1134/S1021443706020178

Shukla AK, Behera SK (2019) All India coordinated research project on micro- and secondary nutrients and pollutant element in soil and plant. Indian J Fertil 15:522–543

Sikka R, Singh D (2021) Influence of soil moisture regimes, amendments and ageing on nickel availability in soils. J Indian Soc Soil Sci 69:210–215. https://doi.org/10.5958/0974-0228.2021.00041.4

Singh AK, Bhatt BP, Sundaram PK, Kumar S, Bahrati RC, Chandra N, Rai M (2012) Study of site specific nutrients management of cowpea seed production and their effect on soil nutrient status. J Agric Sci 4:191–198. https://doi.org/10.5539/jas.v4n10p191

Soleimani M, Hajabbasi MA, Charkhabi AH, Shariatmadari H (2009) Bioaccumulation of nickel and lead by bermuda grass (Cynodon dactylon) and tall fescue (Festuca arundinacea) from two contaminated soils. Casp J Environ Sci 7:59–70

Sparks DL, Page AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabatabai MA, Johnston CT, Sumner ME (1996) Methods of soil analysis, part 3: chemical methods. John Wiley and Sons

Subbiah B, Asija GL (1956) Alkaline permanganate method of available nitrogen determination. Curr Sci 25:259

Tabatabai MA, Bremner JM (1972) Assay of urease activity in soils. Soil Bio Biochem 4:479–487. https://doi.org/10.1016/0038-0717(72)90064-8

Tandon HLS (2001) Methods of analysis of soils, plants, waters, and fertilizers. Fertilizer Development and Consultation Organization, New Delhi, India

Tang YT, Sterckeman T, Echevarria G, Morel JL, Qiu RL (2019) Effects of the interactions between nickel and other trace metals on their accumulation in the hyperaccumulator *Noccaeacaerulescens*. Environ Exp Bot 158:73–79. https://doi.org/10.1016/j.envexpbot.2018.11.015

Walker CD, Graham RD, Madison JT, Cary EE, Welch RM (1985) Effect of Ni deficiency on some nitrogen metabolites in cowpeas (*Vignaunguiculata* L. Walp). Plant Physiol 79:474–479. https://doi.org/10.1104/pp.79.2.474

Walkley A, Black CA (1934) Estimation of organic carbon by chromic acid and titration method. Soil Sci 37:28–29

Wood BW, Reilly CC, Nyczepir AP (2006) Field deficiency of nickel in trees: symptoms and causes. Acta Hortic 721:83–98. https://doi.org/10.17660/ActaHortic.2006.721.10

Wyszkowska J, Boros E, Kucharski J (2008) Enzymatic activity of nickel contaminated soil. J Elementol 13:139–151

Yaseen MK, Hussain S (2021) Zinc-biofortified wheat required only a medium rate of soil zinc application to attain the targets of zinc biofortification. Arch Agron Soil Sci 67:551–562. https://doi.org/10.1080/03650340.2020.1739659

Yusuf M, Fariduddin Q, Hayat S, Ahmad A (2011) Nickel: an overview of uptake, essentiality and toxicity in plants. Bull Environ Contam Toxicol 86:1–17. https://doi.org/10.1007/s00128-010-0171-1

Zhao J, Lu C, Tariq M, Xiao Q, Zhang W, Huang K, Lu Q, Lin K, Liu Z (2019) The response and tolerance mechanisms of lettuce (*Lactuca sativa* L.) exposed to nickel in a spiked soil system. Chemosphere 222:399–406. https://doi.org/10.1016/j.chemosphere.2019.01.119

Zhran M, Moursy A, Lynn TM, Fahmy A (2021) Effect of urea fertilization on growth of broad bean (*Viciafaba* L.) under various nickel (Ni) levels with or without acetic acid addition, using 15N-labeled fertilizer. Environ Geochem Health 43:2423–2431. https://doi.org/10.1007/s10653-020-00707-y