Journal of Environmental Biology
p-ISSN: 0254-8704 • e-ISSN: 2394-0379 • CODEN: JEBIDP

JEB®

Original Research Paper
Volume 45 Issue 6 November 2024 pp. 666-675
DOI: http://doi.org/10.22438/jeb/45/6/MRN-5374

J. Environ. Biol., 2024
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Journal website : www.jeb.co.in ★ E-mail : editor@jeb.co.in

Enriched Linz-Donawitz (LD) slag application for improving grain yield and quality of wheat grown under nutritionally poor degraded soil

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Received: 11 May 2024 **Revised:** 01 July 2024 **Accepted:** 30 August 2024

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Abstract

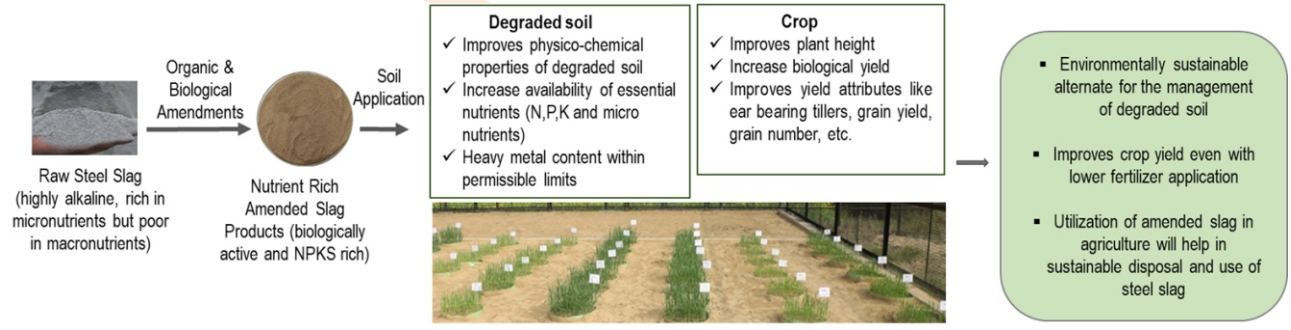
Aim: To evaluate the impact of enriched steel slag on the physico-chemical characteristics of soil and yield attributes of wheat under poor quality degraded soil.

Methodology: Steel slag was biologically and organically amended with natural sources of phosphorus (P), sulfur (S), potassium (K) and nitrogen (N) and characterized for its nutrient content along with biological activity. The impact of resultant products was assessed on soil quality and yield component traits of wheat for two consecutive years(2021-2022 and 2022-23).

Results: Application of slag based products significantly ($p<0.05$) improved the plant height, biological yield, grain yield and ear bearing tillers (EBT) of wheat even with 80% of recommended fertilizer dose (NPK). Further, in comparison to control, a moderation of soil pH (8.6 to 8.8), EC (0.18 to 0.20 dS m^{-1}), OC (0.22 to 0.24 %) and essential mineral macronutrients *viz.,* N (126 to 130 kg N ha^{-1}), P (8.0 to 13.0 kg ha^{-1}), K (100 to 125 kg ha^{-1}) were observed with the application of amended steel slag products. No significant change with respect to existing heavy metal concentration *viz.,* Co, Ni, Cd and Pb in soil was observed when supplemented with amended slag products.

Interpretation: Steel slag can be transformed favorably for on-farm application to improve wheat yield besides serving as an environmentally sustainable alternate of soil conditioner for the management of degraded soil.

Key words: Degraded soil, Heavy metals, Steel slag, Waste management, Wheat



Crop Response Assessment in Degraded Soil

How to cite: Khokhar, S.K., V. Goyal, N. Kumar, K. Usha, V. Pandey, J. Sharma, C.K. Gupta and B. Singh: Enriched Linz-Donawitz (LD) slag application for improving grain yield and quality of nutritionally poor degraded soil. *J. Environ. Biol.*, **45,** 666-675 (2024).

Introduction

The ever increasing land degradation is one of the most pressing environmental problems limiting global food production (Jinger *et al.,* 2023). While 60% of the global land area is degraded (Pimentel, 2006), the value stands at 29.7% (97.8 M ha) for India (SAC, 2021; Mosier *et al.,* 2021) and the situation is expected to worsen with the rising demand for food production. Land degradation can exacerbate the effect of climate change and threaten agricultural productivity. The major cause of land degradation is soil erosion which is further aggravated by phenomena like salinization, acidification and other physical degradation processes like deterioration of natural structure and composition, water logging and mining activities (Jinger *et al.,* 2023). Reclamation of degraded land and restoring its fertility is necessary to ensure global food security. However, utilization of degraded lands for agricultural production requires management practices and other interventions to enable high-yielding food production (Mosier *et al.,* 2021).

For reclamation of degraded lands, several amendments like microbial, organic and inorganic soil conditioners have been used conventionally, however, they entail a variety of risks for environment and human health due to the presence of persistent pollutants and pathogens (Jaskulak and Grobelak, 2021). Moreover, their availability and the cost for large scale application can be another major constraint in their use (Das *et al.,* 2019). Steel slag, a byproduct of steel manufacturing process, can be a potential and economical alternate for reclamation of degraded soils (Tozsin and Oztas, 2023). It works as liming/conditioning material due to high alkalinity and essential plant nutrients required for growth and development. Steel slag is rich in iron, magnesium, manganese, calcium, and phosphorus (Song *et al.,* 2021; Guo *et al.,* 2018; Fisher and Barron, 2019). Apart from essential plant nutrients, steel slag is also rich in silicon, which has beneficial effect on crops like rice and sugarcane (Das *et al.,* 2019; O'Connor *et al.,* 2021).

Depending on the process from which they are generated or the type of furnace used, steel slags are generally classified as blast furnace iron slag (BF), basic oxygen furnace slag or Linz-Donawitz converter slag (BOF or LD), electric arc furnace slag (EAF), and refined slag or ladle furnace (LF) slag (Piatak *et al.,* 2015). Irrespective of the processes through which steel slags are generated, it contains high amount of heavy metals like chromium, cadmium, nickel and lead (Gao *et al.,* 2023), which are harmful and sometimes lethal for plant as well as humans (Mitra *et al.,* 2022). These heavy metals affect ion uptake in plants by causing nutrient deficiency, oxidative stress and altered metabolic processes, inhibiting the overall growth and development of plants. Thus, there is a need to reduce the level of toxic heavy metals in steel slag before using it for agricultural purposes. Moreover, strategies need to be developed to enrich steel slag by blending it with other agricultural inputs for improving its nutrient value. Wheat, being one of the most important crops in the world, is grown more extensively than any other crop. It is grown on more than 218 million ha area worldwide and is staple source of nutrients for approximately 40% of the global population (Khalid *et al.,* 2023). The effect of raw steel slag on wheat crop has been recently reported by Errouh *et al.* (2023) which showed a reduction in yield and other growth attributes. Raw slag may also lead to accumulation of heavy metals in soil, which makes it unsuitable for long-term agricultural application (Das *et al.,* 2019).

Reports suggest that slag should not be applied directly in the farmlands without any pretreatment for reducing harmful heavy metal pollutants in order to ensure soil health and environmental quality as these heavy metals leach out from the soil and contaminate air and water affecting the quality of the ecosystem and environment (Wang *et al.,* 2020). Thus, in the present study, the impact of steel slag based valorized products on wheat crop yield and nutritional characteristics of degraded soil was investigated.

Materials and Methods

Experimental site and sample collection: Steel slag based products were prepared by augmentation with microbial consortia and organic amendments at the Division of Environment Science, ICAR-IARI, New Delhi and same were tested in wheat crop at the Central Research Farm of CCSHAU, Hisar having semi-arid climate with 443 mm annual rainfall and Typic Haplustepts type of soil characterized by sandy loam texture and alkali in reaction. The experimental plots are situated at 29.15° N latitude and 75.7057° E longitude, and 254 m above mean sea level.

Development and characterization of steel slag based products: Linz-Donawitz (LD) slag was collected from TATA Steel Limited, Jamshedpur and analyzed for various elements using X-ray fluorescence analyzer (Olympus, USA). LD slag was preferred over other slag types owing to its availability in larger quantity as the BF/BOF processes contribute more than 70% of global steel production. LD slag was valorized using different natural organic sources of macronutrients, particularly N, P, K and S in different ratios. In a total 11 organically amended slag based products (SPs) were prepared as per the following details: SP1 (N enrichment); SP2 (P enrichment); SP3 (K enrichment); SP4 (P and K enrichment, 0.5:0.5); SP5 (S1 enrichment); SP6 (S1 and P enrichment, 1:1); SP7 (S1 andK enrichment, 1:1); SP8 (S1,P andK enrichment, 1:0.5:0.5); SP9 (P and K enrichment, 1:1); SP10 (S1, P and K enrichment, 1:1:1); and SP11 (S2, P and K enrichment, 1:1:1), where S1 and S2 are two different sources of sulfur. The pH and organic carbon of the products was estimated by the methods described by Jackson (1973) and Walkley and Black (1934). The elemental analyses of slag and slag based products were determined by handheld X-Ray Fluorescence (XRF) analyser (Olympus, USA). The dried samples were finely ground and passed through 0.2 mm mesh sieve before XRF analysis.

Application of steel slag based products: Wheat cv. WH 1105 was grown in rabi season during two consecutive years, *i.e.,* 2021-2022 and 2022-23 in grow bags (50×50 cm) with three replications in a completely randomized block design. The first

year (2021-2022) experiment was used as screening experiment and selected six products were used as treatments for the second year study. The recommended dose of fertilizer (RDF) was applied @ 150N:60P:60K and the products (SPs) were applied at two levels, *i.e.,* 1 t ha^{-1} and 2 t ha^{-1} with 80% RDF. The products were applied in two splits, i.e., 50% at the time of sowing and 50% one week after sowing. 0% RDF (F0), 80% RDF (F_{80}) and 100% RDF (F_{100}) were also maintained as controls. In 0% RDF control, the plants received no slag and no NPK fertilizer, while in 80% RDF and 100% RDF control only 80% and 100% of the RDF was applied. Another nutrient omission experiment was also conducted where the products SP1-11, depending on P, K and S enrichment status, the quantity of P, K and S being supplied from products were further subtracted from 80% RDF. The products were applied at two doses, *i.e.,* 1 and 2 t ha^{-1}.

Plant growth and yield attributes: Plant height (cm) was determined during reproductive stage (80 DAS) and the biological yield (g m^{-2}), grain yield (g m^{-2}), spikes m^{-2} or ear bearing tillers (EBT), grains $spike^{-1}$ and 1000 grain weight (g) were recorded after crop harvest.

Soil sampling and analysis: Soil samples were collected at 0-15 cm depth immediately after crop harvest, air-dried, ground and sieved through a 0.2mm sieve before analysis. EC and pH of the soil was measured in 1:2 soil-water suspension (Jackson, 1973) and soil organic carbon (OC) was determined by wet oxidation method (Walkley and Black, 1934). Soil available nitrogen (N) was determined by Kjeldhal-distillation method (Subbiah and Asija, 1956) and available phosphorus was extracted by 0.5M sodium bicarbonate solution (pH 8.5) and estimated following the method of Olsen *et al.* (1954). Available potassium was extracted with 1N neutral ammonium acetate and estimated with flame photometer (Jackson, 1973). Soil heavy metals were extracted through DTPA and estimated by atomic absorption spectrometry (Lindsay and Norvell, 1978).

Statistical analysis: The experiment was laid out in randomized block design in triplicate and data was subjected to analysis of variance (ANOVA) using SPSS 16.0 software at 5% level of significance ($p<0.05$).

Results and Discussion

Organically amended steel slag based products were rich in macronutrients (N, P, K, Ca, S), micronutrients (Fe, Cu, Mn, Zn), and microbial load while having heavy metal concentration within the permissible limit (Table 1). In the year 2021-2022, the application of eleven LD slag based products increased the growth and yield parameters of wheat significantly ($p<0.05$) as compared to 80% RDF control. Plant height was increased by 1.0% to 5.4%, biological yield by 0.8 to 11.2%, (Table 2) and grain yield by 1.1 to 14.4% (Table 3). The number of grains per spike and test weight (1000 grain weight) was not significantly affected, while the spikes m^{-2}, *i.e.,* ear bearing tillers increased by 0.1 to 6.7% over 80% RDF treatment control (Table 2).

The maximum growth and yield attributes of wheat, *i.e.,* biological yield, grain yield, spikes per meter square and grains per spike was found in SP3 treated plants whereas test weight and plant height were maximum in SP1 and SP5 treatments, respectively. The absolute control plants (F_0) without any RDF application showed the lowest values among all the growth and yield parameters. The response of crop to these products was dose dependent and the growth and yield increased when higher dose of SPs @2 t ha^{-1} was applied. Combining the observations of growth and yield attributes of wheat, treatments where slag based enriched products were applied under 80%RDF (F_{80}) showed beneficial results as compared to F_0 and F_{80} controls. Slag application has previously been implicated to improve the soil biological status by enhancing soil microbial biomass and enzyme activities which further help in nutrient uptake by plants and improve the crop yield (Das *et al.,* 2020a). The slag based

Table 1: Generic profile of organically amended steel slag in comparison to raw steel slag

Nutrients/ Heavy metals	Raw steel slag	Amended steel slag (SP1-SP11)	Nutrients/ Heavy metals	Raw steel slag	Amended steel slag (SP1-SP11)
Physico-chemical and Biological characteristics			Micronutrients (mg kg^{-1})		
pH	11.7	8.34-8.98	Fe	122840.7	3.51-4.17
OC (%)	0.129	1.79-3.17	Zn	35.5	0.04-0.05
TMC* (Log_{10} CFU g^{-1})	0.0	7.88-8.89	Mn	8025.3	783.1-1478.6
Macronutrients			Cu	55.6	13.0-25.0
N (mg kg^{-1})	0.0	63.5-105.8	Toxic heavy metals**(mg kg^{-1})		
P (mg kg^{-1})	2813.0	56.7-82.5	Ni	28.0	9.5-17.1
K (mg kg^{-1})	0.0	1495.0-6720.0	Cd	82.6	0.06-0.27
S (mg kg^{-1})	0.0	40.0 -630.0	Cr	380.3	115.8-176.0
Ca (%)	17.8	2142.0-2864.1	Pb	6.0	4.58-7.96
Mg (%)	0.0	0.0	Co	247.0	2.31-3.95

*TMC is total microbial count and determined through serial dilution method. **Permissible limit for heavy metals in fertilizer are: Ni- 62 mg kg^{-1}, Cd- 3 mg kg^{-1}, Cr- 150-210 mg kg^{-1}, Co- 34 mg kg^{-1} and Pb- 50-150 mg kg^{-1} (Brinton, 2000; Standard for microbial organic fertilizers, NY 884-2012, China, 2012; FAO).

Table 2: Effect of organically amended steel slag based products (SP1-SP11) on plant growth and yield attributes of wheat (WH 1105) grown under 80% level of recommended dose of fertilizer (RDF, F_{80}) in comparison to absolute control (F_0) and 100% RDF (F_{100}) on degraded soil in *rabi* season of 2021-2022

Treatments	Plant height (cm)			Biological yield (g m^{-2})			Grain yield (g m^{-2})		
	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean
Control (F_0)	67.4		67.4	257.2		257.2	86.8		86.8
F_{80}	84.3		84.3	676.6		676.6	276.2		276.2
F_{100}	100.8		100.8	748.8		748.8	325.8		325.8
$F_{80}SP_1$	84.5	85.8	85.2	671.4	694.2	682.8	260.6	320.4	290.6
$F_{80}SP_2$	82.1	85.2	83.7	705.0	763.2	734.2	294.4	326.2	310.4
$F_{80}SP_3$	86.0	88.3	87.2	728.6	776.4	752.6	310.2	321.6	316.0
$F_{80}SP_4$	87.6	88.5	88.1	672.2	741.8	707.0	271.8	319.6	295.8
$F_{80}SP_5$	87.3	90.4	88.9	686.4	788.0	737.2	289.6	339.6	314.6
$F_{80}SP_6$	86.0	91.3	88.7	688.6	675.6	682.2	301.2	308.2	304.8
$F_{80}SP_7$	87.7	88.8	88.3	694.2	721.2	707.8	297.6	303.0	300.4
$F_{80}SP_8$	82.4	86.0	84.2	685.0	703.0	694.0	276.6	282.0	279.4
$F_{80}SP_9$	87.5	87.2	87.4	665.6	723.0	694.4	274.2	298.2	286.2
$F_{80}SP_{10}$	83.1	88.8	86.0	684.2	700.6	692.4	278.4	290.6	284.6
$F_{80}SP_{11}$	83.8	87.1	85.5	670.4	770.6	720.6	262.6	325.0	293.8
Mean of products	85.3	87.9	86.7	686.6	732.6	709.6	283.4	312.2	297.9
SE (m)	2.9	1.4	-	6.5	7.1	-	4.3	3.8	-
CD (5%)	8.1	NS	-	NS	22.4	-	13.4	12.1	-

Table 3: Effect of organically amended steel slag based products (SP1-SP11) on yield attributes of wheat (WH 1105) grown under 80% level of recommended dose of fertilizer (RDF, F_{80}) in comparison to absolute control (F_0) and 80% RDF (F_{80}) on degraded soil in *rabi* season of 2021-2022

Treatments	Grains per spike			Spikes m^{-2}			1000 grain wt (g)		
	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean
Control (F_0)	52.7		52.7	116.8		116.8	36.4		36.4
F_{80}	57.5		57.5	370.4		370.4	40.2		40.2
F_{100}	60.1		60.1	437.8		437.8	42.6		42.6
$F_{80}SP_1$	48.4	56.5	52.5	377.6	400.5	389.3	41.0	41.5	41.3
$F_{80}SP_2$	51.4	59.1	55.3	392.9	415.8	404.6	38.0	40.6	39.3
$F_{80}SP_3$	55.9	58.6	57.3	405.6	426.0	415.8	40.9	40.9	40.9
$F_{80}SP_4$	53.6	59.4	56.5	375.0	408.2	391.8	39.6	39.5	39.6
$F_{80}SP_5$	52.5	59.4	56.0	357.1	423.5	390.3	35.9	39.1	37.5
$F_{80}SP_6$	54.4	53.4	53.9	408.2	405.6	407.1	35.1	40.0	37.6
$F_{80}SP_7$	52.0	54.9	53.5	367.3	375.0	371.4	40.8	39.4	40.1
$F_{80}SP_8$	52.6	55.3	54.0	352.0	364.8	358.7	37.9	40.5	39.2
$F_{80}SP_9$	53.1	55.3	54.2	380.1	392.9	386.7	35.3	40.6	38.0
$F_{80}SP_{10}$	50.6	49.6	50.1	359.7	369.9	364.8	39.6	41.9	40.8
$F_{80}SP_{11}$	48.6	52.6	50.6	377.6	408.2	392.9	38.9	40.6	39.8
Mean of products	52.1	55.8	54.0	377.6	399.1	388.5	38.5	40.4	39.5
SE(m)	2.2	3.5	-	1.2	1.5	-	2.1	1.0	-
CD (5%)	NS	NS	-	3.9	4.9	-	NS	NS	-

products used in this study were also rich in microbial content besides many essential nutrients, thus showing positive response even when applied with F_{80}. Slag based fertilizers also improved the growth and yield of treated plants by increasing the translocation of nutritional elements from root to shoot and grain (Islam *et al.,* 2022). In the year 2022-2023, six promising amended steel slag based products were evaluated again. The results showed that the application of products increased the plant height significantly by 0.9 - 1.9 %, biological yield by 3.5 - 11.9% and grain yield by 16 - 36% as compared to 80% RDF

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Table 4: Field performance of selected amended steel slag products on plant growth and yield attributes of Wheat (WH 1105) raised under 80% RDF when compared with absolute control (F_0) and 100% RDF (F_{100}) on degraded sandy soils of in rabi season of 2022-2023

Treatments	Plant height (cm)			Biological yield (g m^{-2})			Grain yield (g m^{-2})		
	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean
Control (F_0)	73.0		73.0	295.5		257.2	96.1		86.8
F_{80}	84.6		84.6	681.1		676.6	229.6		276.2
F_{100}	97.8		97.8	728.3		748.8	302.8		325.8
$F_{80}SP_3$	82.9	84.9	84.9	637.8	715.2	676.6	259.6	298.8	279.2
$F_{80}SP_4$	83.7	88.0	88.0	690.6	719.1	704.8	286.2	304.4	295.4
$F_{80}SP_5$	85.7	87.3	87.3	690.6	751.6	721.2	277.4	310.4	294.0
$F_{80}SP_6$	84.1	89.1	89.1	721.6	802.2	762.0	297.0	327.8	312.4
$F_{80}SP_9$	84.4	86.9	86.9	663.4	694.0	678.8	261.4	280.6	271.0
$F_{80}SP_{10}$	80.2	85.2	85.2	638.4	664.4	651.4	248.4	287.0	267.8
Mean of products	83.5	86.9	86.9	673.7	724.4	699.1	271.6	301.5	286.6
SE(m)	4.0	3.1	-	19.3	15.2	-	2.3	3.1	-
CD (5%)	25.3	19.8	-	NS	23.8	-	11.3	25.7	-

Table 5: Field performance of selected amended steel slag products on yield attributes of wheat (WH 1105) raised under 80% RDF when compared with absolute control (F_0) and 100% RDF (F_{100}) on degraded soils of rabi season of 2022-2023

Treatments	Grains per spike			Spikes m^{-2}			1000 grain wt (g)		
	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean
Control (F_0)	51.0		51.0	130.1		130.1	37.2		37.2
F_{80}	54.7		54.7	414.3		414.3	42.6		42.6
F_{100}	58.1		58.1	488.8		488.8	43.7		43.7
$F_{80}SP_3$	53.9	61.1	57.5	377.6	423.5	400.5	37.9	39.4	38.7
$F_{80}SP_4$	53.4	58.9	56.2	396.9	453.1	425.0	38.2	39.8	39.0
$F_{80}SP_5$	54.2	62.0	58.1	366.3	432.7	399.5	38.1	37.9	38.0
$F_{80}SP_6$	55.2	60.3	57.8	422.4	471.9	447.4	37.4	39.1	38.3
$F_{80}SP_9$	52.6	58.3	55.5	372.4	418.4	395.4	37.2	39.3	38.3
$F_{80}SP_{10}$	49.6	57.0	53.3	379.1	407.1	393.4	35.8	37.7	36.8
Mean of products	53.15	59.6	56.4	385.8	434.4	410.2	37.4	38.8	38.2
SE(m)	2.9	0.9	-	12.7	13.9	-	1.3	2.0	-
CD (5%)	NS	3.1	-	NS	NS	-	NS	NS	-

control (Table 4). No significant difference was recorded for test weight and number of spikes m^{-2}, while the number of grains per spike increased significantly (Table 5).

Among six products, the plant height, biological yield and grain yield was maximum for SP6 (89.1 cm, 762.0 g m^{-2} and 312.4g m^{-2}, respectively), followed by SP5 and SP4. Grains per spike were highest in SP5 followed by SP6. Spikes per meter square and grain test weight were highest in SP6 and SP3 treated plants, respectively, however, the difference was not significant as compared to other treatments. These findings are in line with the previous investigation where a higher yield of wheat was reported by the application of steel slag at @ 5 t ha^{-1} (Mihalache *et al.,* 2016). Slag based products are rich in Si which has been implicated to support more number of spikes per plant in crops (Helala *et al.,* 2022). Other nutrients available in Sps, especially micronutrients (Mn, Cu and Zn) contribute towards higher seed count and weight (Saquee *et al.,* 2023). The results of two years experiment showed that the application of LD slag based products improved the growth and yield attributes of wheat by increasing essential nutrients in soil under 80% level of recommended dose of fertilizer as compared to absolute control (F_0) and 80% RDF (F_{80}) control.

The improvement in growth parameters such as plant height and biomass may be attributed to the fact that the plants quickly absorb mineral elements present in the slag to maintain their life cycle and encourage notable development (Radić *et al.,* 2022). Also, slag application favors the increase in soil pH affecting nutrient absorption by the roots, thus favoring overall

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Table 6: Effect of organically amended steel slag based products (SP1-SP11) on growth and yield attributes of wheat (WH 1105) grown under 80% level of recommended dose of fertilizer (RDF(-P), F_{80}) in comparison to absolute control (F_0) and 100% NK (F_{100}NK) on degraded soil in rabi season of 2021-2022

Treatments	Plant height (cm)			Biological yield (g m^{-2})			Grain yield (g m^{-2})		
	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean
Control (F0)	87.7		87.7	521.6		521.6	154.4		154.4
F_{80}NK	89.2		89.2	498.8		498.8	174.8		174.8
F_{100}NK	90.9		90.9	623.6		623.6	201.2		201.2
$F_{80}SP_1$	82.4	85.0	83.7	617.6	554.4	586.0	194.8	191.2	193.0
$F_{80}SP_2$	90.3	85.4	87.8	624.4	541.2	582.8	170.4	179.2	174.8
$F_{80}SP_3$	85.0	85.1	85.0	595.6	593.6	594.6	202.8	181.6	192.2
$F_{80}SP_4$	90.8	91.0	90.9	626.4	581.6	604.0	212.8	190.4	201.6
$F_{80}SP_5$	86.1	89.6	87.8	588.8	672.0	630.4	155.6	214.4	185.0
$F_{80}SP_6$	89.1	89.5	89.3	603.2	630.0	616.6	207.2	180.4	193.8
$F_{80}SP_7$	88.3	88.1	88.2	664.0	593.2	628.6	218.4	212.8	215.6
$F_{80}SP_8$	88.4	82.0	85.2	586.8	604.8	595.8	188.4	196.8	192.6
$F_{80}SP_9$	86.7	90.1	88.4	624.4	650.4	637.4	205.2	195.6	200.4
$F_{80}SP_{10}$	88.6	85.5	87.05	675.6	592.8	634.2	221.2	181.6	201.4
$F_{80}SP_{11}$	89.7	83.0	86.35	631.6	584.4	608.0	195.6	172.4	184.0
Mean of products	87.8	86.8	87.3	621.7	599.9	610.8	197.5	190.6	194.0
SE(m)	3.2	2.1	-	7.3	7.9	-	2.0	3.0	-
CD (5%)	NS	NS	-	NS	23.8	-	9.3	11.7	-

growth and yield of the crops (Deus *et al.,* 2018). Improvement in soil fertility, increased nutrient uptake, leaf area enhancement due to application of slag based products have also been reported by Antoniadis *et al.* (2015) and Koutroubas *et al.* (2014). Further, an increase in grain yield can be attributed to increased number of spikes and number of grains per spike in treated plants, which can be corroborated withthe previous results of White *et al.* (2017) and Errouh *et al.* (2023). The effect of LD slag based products on the growth and yield attributes of wheat grown under 80% RDF (-P) and (-K), evaluated in the year 2021-2022 are given in Table 6, 7, 8 and 9. In the phosphorus omission experiment (RDF(-P), F_{80}), the biological yield ranged from 586.0 to 637.4 g m^{-2} and grain yield from 184.0-215.6 g m^{-2}, while these values were 498.8 g m^{-2} and 174.8 g m^{-2} respectively for 80% control (F_{80} NK).

The increase in biological yield and grain yield was 16.8-27.8% and 5.3-23.3% compared to 80% control (F_{80} NK). The number of spikes per meter square on products treated plants in the P omission experiment was in the range 237.2-312.5, which was 8.1-42.4% high as compared to 80% control (F_{80} NK). The plant height, grain number per spike and grain test weight in the P omission experiment didn't show significant effect with the application of slag based products (Table 6, 7). Similarly, in the potassium omission experiment (RDF(-K), F80), biological yield ranged from 490.9 to 563.8 g m^{-2} and grain yield from 146.0-194.1 g m^{-2}, while these values were 498.8 g m^{-2} and 174.8 g m^{-2} respectively for 80% control (F_{80}NK). The increase in biological yield and grain yield was 2.6-13.0% and 10.4-11.0% compared to 80% control (F_{80}NK). In the K omission experiment, the number of spikes per meter square on products treated plants was in the range 267.9-288.3 and grain per spike was in the range 39.6-50.2, while these values were 219.4 and 43.4 respectively for 80% control (F_{80}NK). The grain test weight in the K omission experiment did not show significant changes with the application of slag based products (Table 8, 9).

The perusal of data showed that the products SP1-11 having different P, K and S enrichment status performed well under conditions where the enriched element getting supplied from them were excluded from NPK fertilizer recommended for wheat. Omission of P and K nutrient during fertilizer application resulted in significant difference in biological yield and grain yield (Table 6 and 8). This suggests that costs towards N, P, K or S towards crop fertilizer recommendation can be saved by using organically amended steel slag based nutrient supplementing products in agriculture.

Effect of LD slag based products on soil properties: The soil analysis is presented in Table 10. The results showed that there was no change in the composition of sand, silt and clay with application of steel slag based products, while the soil physico-chemical properties at 0-15 cm depth significantly changed after two successive years of experiment over initial values. Soil pH changed from 8.6 to 8.8, EC from 0.18 to 0.20 dSm^{-1} and soil organic carbon increased to 0.24% from 0.22%. Available macronutrients NPK were found 130, 13, 125 kg ha^{-1} and showed an increasing trend as compared to initial values. The data showed that the Co, Ni, Cd and Pb content increased with the application of steel slag based products, but the increase was

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Table 7: Effect of organically amended steel slag based products (SP1-SP11) on yield attributes of wheat (WH 1105) grown under 80% level of recommended dose of fertilizer (RDF(-P), F_{80}) in comparison to absolute control (F_0) and 100% NK (F_{100}NK) on degraded soil in rabi season of 2021-2022

Treatments	Grains per spike			Spikes m^{-2}			1000 grain wt (g)		
	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean
Control (F_0)	40.3		40.3	188.8		188.8	24.4		24.4
F_{80}NK	43.4		43.4	219.4		219.4	26.0		26.0
F_{100}NK	47.3		47.3	301.0		301.0	29.0		29.0
$F_{80}SP_1$	54.0	46.2	50.1	267.9	311.2	289.5	32.5	27.9	30.2
$F_{80}SP_2$	47.3	26.3	36.8	273.0	288.3	280.6	31.7	29.1	30.4
$F_{80}SP_3$	42.3	39.5	40.9	239.8	280.6	260.2	31	29.5	30.25
$F_{80}SP_4$	50.5	41.2	45.85	275.5	273.0	274.2	27.4	29.6	28.5
$F_{80}SP_5$	42.7	50.3	46.5	257.7	216.8	237.2	30.2	31.5	30.85
$F_{80}SP_6$	33.5	45.5	39.5	260.2	265.3	262.8	29.7	25.6	27.65
$F_{80}SP_7$	40.8	41	40.9	306.1	318.9	312.5	32.9	32.4	32.65
$F_{80}SP_8$	44.7	39.2	41.95	283.2	267.9	275.5	29.3	28.3	28.8
$F_{80}SP_9$	44.5	41.7	43.1	260.2	301.0	280.6	31.1	41.2	36.15
$F_{80}SP_{10}$	47.3	41.5	44.4	270.4	273.0	271.7	32.5	27.9	30.2
$F_{80}SP_{11}$	42.7	51.7	47.2	255.1	275.5	265.3	31.7	29.1	30.4
Mean of products	44.6	42.2	43.4	268.1	279.2	273.7	30.9	30.2	30.6
SE(m)	3.9	4.2	-	11.3	17.5	-	1.9	2.2	-
CD (5%)	NS	NS	-	35.8	43.5	-	NS	NS	-

Table 8: Effect of organically amended steel slag based products (SP1-SP11) on growth and yield attributes of wheat (WH 1105) grown under 80% level of recommended dose of fertilizer (RDF(-K), F_{80}) in comparison to absolute control (F_0) and 100% NP (F_{100}NP) on degraded soil in rabiseason of 2021-2022

Treatments	Plant height (cm)			Biological yield (g m^{-2})			Grain yield (gm^{-2})		
	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean
Control (F_0)	87.7		87.7	321.6		321.6	154.4		154.4
F_{80}NP	89.2		89.2	498.8		498.8	174.8		174.8
F_{100}NP	90.9		90.9	623.6		623.6	201.2		201.2
$F_{80}SP_1$	89.0	86.2	87.6	509.6	531.2	520.4	196.8	191.4	194.1
$F_{80}SP_2$	65.9	67.2	66.5	511.0	525.4	518.2	102.4	111.2	106.8
$F_{80}SP_3$	65.3	70.2	67.7	510.2	513.2	511.7	198.2	107.8	153.0
$F_{80}SP_4$	68.9	64.3	66.6	517.4	552.0	534.7	198.4	101.6	150.0
$F_{80}SP_5$	65.4	61.2	63.3	537.8	589.8	563.8	102.6	192.8	147.7
$F_{80}SP_6$	68.3	68.1	68.2	507.0	474.8	490.9	104.6	191.0	147.8
$F_{80}SP_7$	59.4	60.7	60.0	543.4	466.8	505.1	199.6	187.4	193.5
$F_{80}SP_8$	64.2	66.5	65.3	475.2	510.4	492.8	113.4	199.4	156.4
$F_{80}SP_9$	57.6	60.4	59.0	512.4	478.8	495.6	199.4	188.6	194.0
$F_{80}SP_{10}$	63.0	55.3	59.1	506.2	475.8	491.0	193.2	192.6	192.9
$F_{80}SP_{11}$	69.6	59.5	64.5	560.8	470.2	515.5	101.2	190.8	146.0
Mean of products	66.9	65.4		517.4	508.0		155.4	168.6	
SE(m)	1.2	2.5	-	37.5	31.6	-	1.9	2.6	-
CD (5%)	4.7	NS	-	71.0	63.8	-	5.3	4.1	-

within the permissible limit of heavy metals in soil as recommended by WHO/FAO (FAO/WHO, 2001; Adekiya *et al.,* 2018). General improvement in the soil properties of poor degraded soil due to application of slag and slag based product has been previously reported (Das *et al.,* 2020b; Galgo *et al.,* 2024 and Mihalache *et al.,* 2016), but owing to higher content of heavy metals in pure slag its use in agricultural soil without any amendment is not suggested (Wang *et al.,* 2020; Tozsin and Oztas, 2023). Previous studies have also showed that the application of steel slag based fertilizer increases soil pH, and

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Table 9: Effect of organically amended steel slag based products (SP1-SP11) on yield attributes of wheat (WH 1105) grown under 80% level of recommended dose of fertilizer (RDF(-K), F_{80}) in comparison to absolute control (F_0) and 100% NP (F_{100}NP) on degraded soil in rabi season of 2021-2022

Treatments	Grains per spike			Spikes m^{-2}			1000 grain wt (g)		
	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean	1 t ha^{-1}	2 t ha^{-1}	mean
Control (F_0)	40.3		40.3	188.8		188.8	24.4		24.4
F_{80}NP	43.4		43.4	219.4		219.4	26.0		26.0
F_{100}NP	47.3		47.3	301.0		301.0	29.0		29.0
$F_{80}SP_1$	37.2	43.3	40.2	318.9	247.4	283.2	53.0	52.5	52.7
$F_{80}SP_2$	51.7	38.5	45.1	283.2	270.4	276.8	51.2	49.6	50.4
$F_{80}SP_3$	38.3	42.8	40.5	303.6	270.4	287.0	57.0	52.3	54.6
$F_{80}SP_4$	37.7	41.5	39.6	283.2	273.0	278.1	51.3	31.8	41.5
$F_{80}SP_5$	44.7	44.5	44.6	295.9	250.0	273.0	30.7	30.1	30.4
$F_{80}SP_6$	41.2	45.3	43.2	336.7	239.8	288.3	30.8	30.6	30.7
$F_{80}SP_7$	43.7	41.8	42.7	273.0	265.3	269.1	30.8	33.1	31.9
$F_{80}SP_8$	47.7	43.3	45.5	278.1	280.6	279.3	28.0	31.5	29.7
$F_{80}SP_9$	44.7	55.8	50.2	298.5	250.0	274.2	31.6	30.6	31.1
$F_{80}SP_{10}$	40.5	42.8	41.6	288.3	247.4	267.9	33.0	32.5	32.7
$F_{80}SP_{11}$	46.0	38.3	42.1	293.4	250.0	271.7	31.2	29.6	30.4
Mean of products	43.0	43.45	43.2	295.7	258.6	277.1	38.9	36.7	37.9
SE(m)	2.8	1.2	-	11.4	14.3	-	2.1	2.5	-
CD (5%)	6.9	5.7	-	75.1	93.2	-	NS	NS	-

Table 10: Effect of steel slag based products (SP1-SP11) on different properties of degraded soil after two crop growing seasons

Components	Values
Mechanical composition of soil (%)	
Sand	80
Silt	5
Clay	15
Chemical properties of soil	
pH	8.8 (8.6)
EC (dSm^{-1} at 25°C)	0.20 (0.18)
Organic Carbon (%)	0.24 (0.22)
Available Nitrogen (kg N ha^{-1})	130 (126.0)
Available Phosphorus (kg P_2O_5 ha^{-1})	13 (8.0)
Available Potassium (kg K_2O ha^{-1})	125 (100.0)
Heavy Metals (mg kg^{-1})*	
Pb	0.013 (0.01)
Cd	0.09 (0.06)
Ni	0.06 (0.05)
Co	0.71 (0.59)

*Permissible limit for heavy metals in soil are: Ni-50-75 mg kg^{-1}, Cd- 3 mg kg^{-1}, Co- 50 mg kg^{-1} and Pb- 100 mg kg^{-1} (Adekiya *et al.,* 2018). Values given in parenthesis are initial values recorded before applying treatments to the soil.

there was no significant increase in availability of heavy metals like cadmium and lead in the soil (Ning *et al.,* 2016). The enhanced soil pH and available Si may contribute in reducing metal mobility and bonding metals into more stable fractions, thus decreasing the uptake of heavy metals by plant roots (Ning *et al.,* 2016). Mihalache *et al.* (2016) reported that steel slag application at different rates (1 to 5 t ha^{-1}) increased the wheat yield, and translocation of heavy metals to grains was within the permissible limits. Das *et al.* (2020b) and Fan *et al.* (2018) reported that the heavy metals taken up by the plants mostly remain accumulated in roots and there is very low translocation in grains/fruits. Reports also suggest that application of steel slag may help in immobilization of heavy metals in soil (Schlögl *et al.,* 2023), and bioavailability of these metals generally depends on its chemical form and plants capacity to absorb from the soil (Branca and Colla, 2012).

The organically amended steel slag produced in the present study showed quite low level of heavy metals having values well within the permissible limits. These products significantly improved the crop growth and economic yield of wheat even with 80% of the recommended fertilizer dose. Further, our study also suggests that the amended steel slag may be suitable for the reclamation of degraded soil by improving its physico-chemical properties. Although the use of organically amended steel slag in agriculture may help in improving the global food production while address the pressing issue of industrial waste management in steel sector, it is imperative to have a continuous monitoring of heavy metal bioaccumulation in the plant tissues as well as in the soil to determine the long term implications of steel slag based nutrient supplements in agriculture.

Acknowledgments

Authors wish to thank the Director, ICAR-IARI for providing the facilities for conducting the research; Ministry of Steel, Government of India for providing the research funding

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support and the Tata Steel Limited Jamshedpur for providing LD Steel Slag for conducting research experiments.

Authors' contribution: S.K. Khokar: Conceptualization, methodology, supervision, data curation; **V. Goyal:** Data collection and curation; **N. Kumar:** supervision; **V. Pandey:** Writing, revising and editing; **J. Sharma:** Writing; **C. K. Gupta and K. Usha:** Supervision and editing; **B. Singh:** Conceptualization, methodology, supervision, data curation, revising and editing, funding acquisition.

Funding: This work was supported by the Ministry of Steel, Government of India (Grant no. 24-774).

Research content: The research content of manuscript is original and has not been published elsewhere.

Ethical approval: Not applicable.

Conflict of interest: The authors declare no competing interests.

Data availability: Not applicable.

Consent to publish: All authors agree to publish the paper in *Journal of Environmental Biology.*

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