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Review Article

Can steel slag remediate the key problems of Rice-Wheat Cropping systems in India?

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Abstract

Sustaining the plant nutrition demand and meeting the present challenges of increasing micro nutrient deficiencies, biotic and abiotic stress as well as bringing economics in cultivation are major challenges of the Rice Wheat cropping system in India which extends for over 10 mha in India. Utilization of the industrial waste is one of the several strategies for giving comprehensive solution to these problems. Steel slag provides a low-cost opportunity which has potential to address these challenges. Steel slag is indispensable waste generated during the steel manufacturing process and its disposal is major problem for the industry and environment too. However, steel slag is rich in nutrients including Si, Ca, Mg, P, Fe, Mn and S and makes it a good alternative nutrient supplement with fertilizers. Iron acts as alternate electron acceptor, thus, can reduce the generation of methane in rice fields. The silica content in slag can be beneficial in reducing the sodium stress and heavy metal stress in contaminated soils. It is also been reported to reduce the biotic stress in crop plants.

Keywords: Rice-Wheat Cropping System, micronutrients, greenhouse gases, disease, insects, abiotic stress, steel slag

1. Introduction

Plant nutrition is one among the several factors having positive correlation with the food grain production. Fertilizers are essential for replenishing the soil nutrient pool as well satisfying the current season crop requirement. However, the fertilizer usage in India is associated with several problems including imbalanced nutrition, rising micro nutrient deficiency, reducing reserve position, import dependency and rising cost. In 2022-23, the total consumption of fertilizer (N+P2O5+K2O) stood at 29.84 MT with marginal growth of 0.2% over previous year, in spite of the increase in N and P2O5 consumption of 4% and 1.2%, respectively, as there has been reduction in K2O consumption by 32.2% in same period (FAI, 2023). This has implication on the NPK use ratio and balanced fertilization in India. The resultant deficiency of other nutrients (including micronutrients) appears either apparent under the exhaustive cropping system or there may be the "hidden hunger" in crop. Sulphur and micronutrient deficiency in crops is primarily due to the high intensity cropping and use of high analysis fertilizers (Shukla *et al.*, 2021). The availability of resources in terms of raw material and finished fertilizers also pose a challenge for satisfying the fertilizer requirement. High grade rock phosphate reserves are projected to last for 50-175 years (Dhillon *et al.*, 2017; Biswas *et al.*, 2023), for which India is dependent almost 100% on the imports. The restricted resource availability to few countries of the world and emerging geopolitical conflicts in recent times increases the vulnerability of importing nations including India for the availability of fertilizers. Russia-Ukraine war and recent situations in Israel can lead to the increased potash prices. The demand of fertilizers in India is met by the domestic production and imports, both has increased in the first quarter of 2023-24 (Fertiliser India, 2023). All these have implications in form of rising nutrient subsidy in India which has increased 2.5 times in past decade (Press Information Bureau, 2023a). In view of this, the alternate and innovative sources of plant nutrition can be effective in resolving these issues. PM-PRANAM (PM Programme for Restoration, Awareness, Nourishment and Amelioration of Mother Earth) yojana was launched by Government of India to promote alternate sources and balanced nutrition in agriculture. Rice Wheat cropping system (RWCS) is one of the main contributors of food security in India and one of the most extensive cropping systems in Asia covering an area of 24 mha of which, 13.5 mha belong to South Asia (Anonymous 2009; Nawaz *et al.* 2019). In addition to the food security, the system is providing employment to millions of rural poor (Dhanda *et al.* 2022). RWCS contributes to 58% area and more than 75% of the national food grain production in India thus, contributing substantially to food security (Mahajan *et al.* 2008; Pawar *et al.* 2018; Trethowan *et al.* 2018). For the past two decades (2000-2021), RWCS is important as rice and wheat has primary position in terms of area and production (Fig 1). However, at present the system is facing several challenges pertaining to its sustainability. Inadequate and imbalanced nutrient application leading to rising micronutrients deficiency, reduced factor productivity and decline in nutrient use efficiency and organic carbon content in soil, increase in greenhouse gases emission and heavy metal problems in certain areas (Gupta *et al.* 2016; Pawar *et al.* 2018; Setia *et al.* 2021). This has implication for the sustainability of the soil health in these areas. Also, the rising costs of fertilizers and diminishing mineral resources call for the exploration of alternative sources of plant nutrition especially in the intensively cultivated zones like RWCS in India (Mahajan and Gupta, 2009). Industrial waste provides an opportunity as an alternative that can be utilized in the agriculture production, provided these are rich in plant nutrients. Besides enriching the soil fertility, these are important in reducing the carbon footprints in utilization of the fertilizers. However, this needs to economically viable, no hazardous impact on user, crop yield and quality.

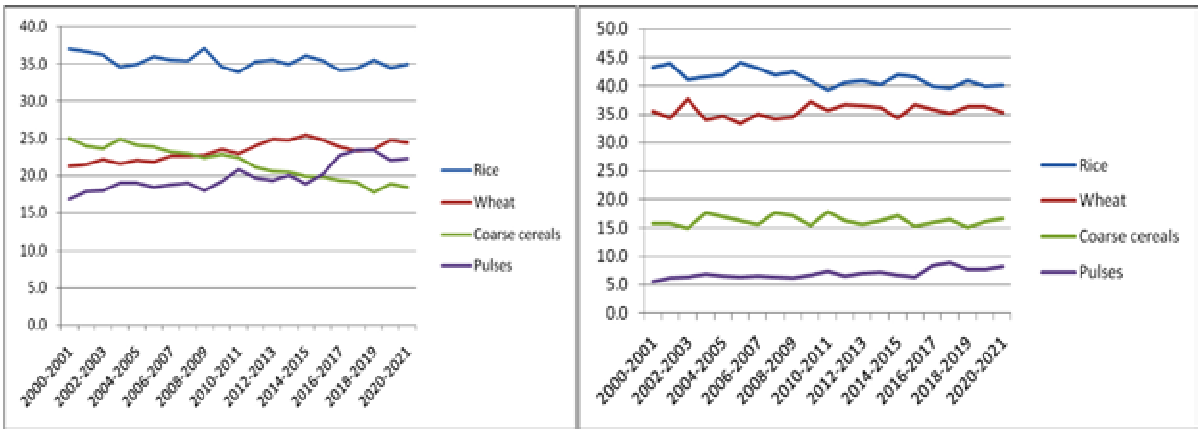

Fig 1: Area and production Rice, wheat, coarse cereals and pulses as percentage of total food grain production. The share of rice area stands highest among all components and for wheat there is increasing trend though the area under pulses is also increasing since 2014-15, still below the share of wheat (GRAPH ON LEFT SIDE). In terms of production, the share of both rice and wheat stands at 75-80% of the total food grain production (GRAPH ON RIGHT SIDE) (Data sourced from Indiastat, 2022).

Steel slag is one such industrial waste laden with good amount of nutrients and can help to ensure the balanced nutrition along with other benefit like carbon sequestration, heavy metal sequestration and disease resistance (Fig 2). The rising economic growth coupled with the increased consumer demand had led to the rise in steel production in India. Consequently, there is increase in the steel slag emission from these industries. It is generated during the conversion of iron ore to the molten steel, and the composition of the steel slag varies with the nature of ore and production methods. Around 15 MT steel slag is generated in India annually (Press Information Bureau, 2023b). Dumping of the waste in open area is an environmental challenge which not only deteriorate the soil and water quality of the surrounding area, but also harm the aesthetic values. The management of this huge waste is emerging as major challenge to the steel producers. The major utilization of steel slag is in the cement manufacturing industries. Recently, it has also been utilized the road construction in various states. However, the higher content of lime restrict its usage which leads to the piling of huge waste with steel industries. In general, steel slag is source of calcium, magnesium, sulphur, phosphorus, silicon, iron and manganese, which can be harnessed for agriculture. Higher content of the calcium and magnesium and higher pH enables it to replace the lime for the neutralization of acidic soils. Steel slag has also property to immobilize the heavy metals in the soil. The silicon content in the steel slag imparts the disease and pest resistance properties in plants. Thus, slag can be utilized for developing the specialty fertilizers. A lot of research work has been carried out in various countries regarding its utilization in agriculture. The research work on utilization of steel slag in India is still in nascent stage which need to be widened so as to develop effective products as well as measures to utilize it in crop production. Following review has been done regarding the multi-dimensional utilization of steel slag in crop production.

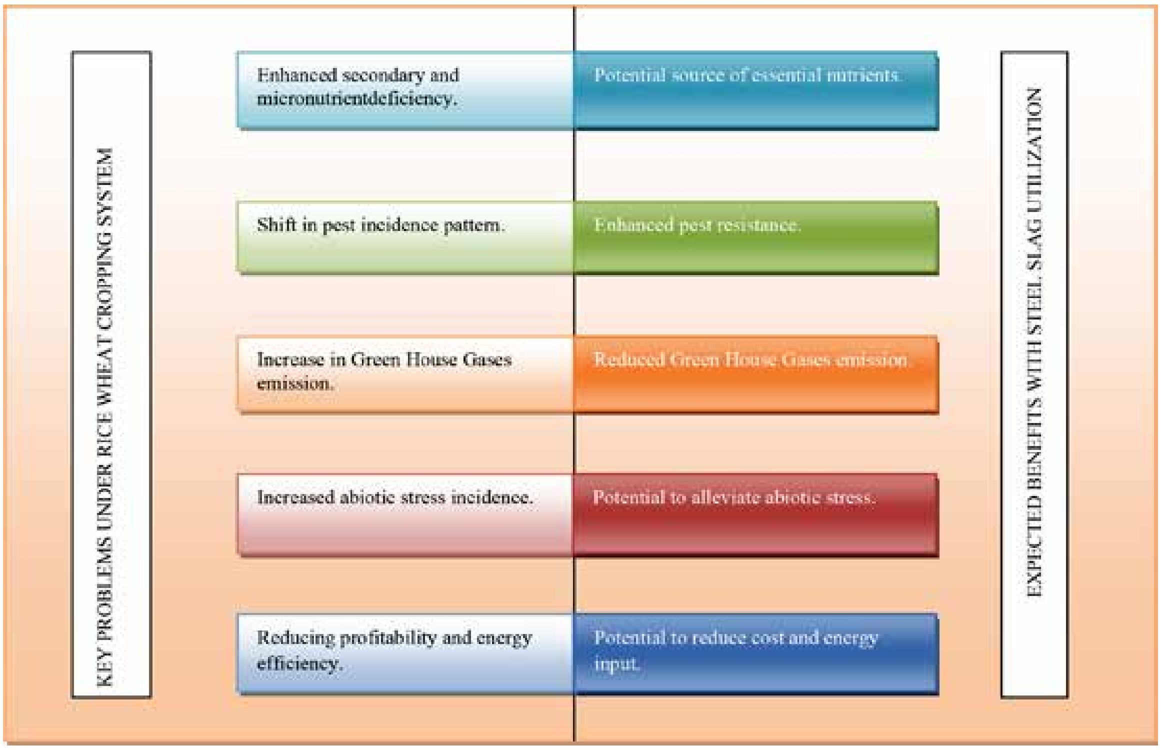

Fig 2: Steel slag utilization has potential to address the key problems of Rice Wheat Cropping System in India.

2. Problems under Rice-Wheat Cropping Systems

RWCS is an exhaustive cropping system which leads to negative balance in nutrients in soil (Dhaliwal *et al.* 2013). There has also been reporting of secondary and micro-nutrient deficiency like of manganese and iron in Punjab and Boron in West Bengal in particular and other are zinc, copper and molybdenum in general (Nayyar *et al.* 2001; Pingali and Shah 2001; Timsina and Connor 2001; Shukla *et al.* 2012; Bhatt *et al.* 2016; Nawaz *et al.* 2019; Nadeem and Farooq 2019; Saha *et al.* 2020). Zinc deficiency is more common in rice and manganese deficiency is prevalent in wheat (Ullah *et al.*, 2021). Micronutrient export from soil increases with higher dose of macronutrients in these crops (Fig 3). It is reported that in intensive RWCS areas where Zn is regularly applied for past 15-20 years, deficiency of Mn and Fe is emerging (Shukla *et al.* 2012). New pest build up, their activity as well as increased severity of earlier known minor pest like army worm, case worm and leaf folder is getting common in RWCS areas (Pingali and Shah 2001; Timsina and Connor 2001; Bhatt *et al.*, 2016; Nawaz *et al.* 2019). Cross migration of the pest like rice shoot fly (Antherigona oryzae) and pink stem borer (Sesamia inferens) to wheat crop; Helminthesporium sativum (Spot Blotch) in wheat and build up of soil pathogen like Sclerotinium, Rhizoctonia and Fusarium is taking place (Pingali and Shah 2001; Timsina and Connor 2001). Changing pattern of pest attack has been observed like blast and stem borer earlier restricted to long duration basmati has also been severe in short duration one; sheath blight in rice earlier restricted to border area covers the full field now; false smut causing larger loss to rice crop (Bhatt *et al.* 2016). Emergence of Brown plant hopper (Nilaparvata lugens) is becoming major yield limiting factor especially after green revolution of 1960s (He *et al.* 2015).

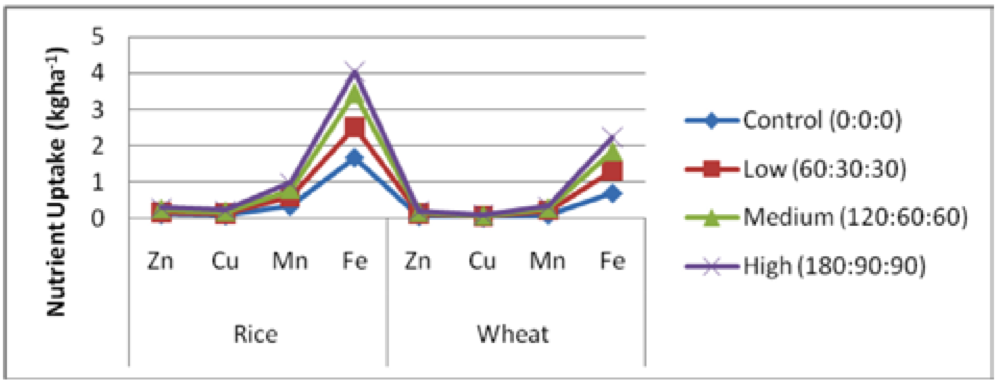

Fig 3: Increased fertility levels lead to higher uptake of micronutrients owing to increase in dry matter in both rice and wheat crops. This can lead to micronutrient deficiency deficiency if not replenished properly (Data sourced from Nayyar et al. 2001).

Intensive nature of RWCS has led to increased GHG emissions (Ullah *et al.* 2021). Owing to intensive nature of two crops in terms of cultivation practices and sub-tropical climatic conditions of their growing areas in India, the system is prone to carbon losses from soil. The estimated Global warming potential of GHGs from Rice-Wheat cropping system of Indo-Gangetic plains is 13-26 Mg CO2ha-1year-1(Sapkota *et al.* 2015). It is estimated that production of 1 kg of rice returns 0.71 kg CO2 equivalent to the atmosphere compared to 0.27 kg CO2 equivalent for other cereal crops (Kumar *et al.* 2021). Rice cultivation is contributing to the 20% of the global methane emission (Ullah *et al.* 2021) and 28% of the total methane emission from agriculture sector in India (Datta *et al.* 2011). Among the major crops grown in North West India, Rice recorded highest methane emission; nitrous oxides emission was highest for upland crops depending on the season and nitrogen application rates (Jain *et al.* 2016). The methane emission also varies with the cultivation practice as it is more under continuous flooded than intermittent one (Gupta *et al.* 2015) whereas nitrous oxides emission were reported more under intermittent flooding and drying than continuous flooded irrespective of N management practices (Pathak *et al.* 2002).Burning of crop residues or their removal for various other purposes leads to the loss of soil organic carbon in these areas and consequent nutrient supply is impacted (Timsina and Connor 2001). Sharp decline in soil carbon has been witnessed, both qualitatively and quantitatively (Dey *et al.* 2020).

The major abiotic stresses in RWCS include physical i.e. crop lodging, low and high temperature and drought stress and chemical i.e. salinity and heavy metal stress and these are responsible for the reduction of 20-30% wheat yields in developing countries (Jinger *et al.* 2020; Hossain *et al.* 2021). Secondary salinization is emerging as major problem due to excess irrigation in these areas. Increased use of fertilizers and pesticides for higher production has led to the increased circulation of heavy metals in food chain. Cadmium (Cd) toxicity under Rice is an emerging problem. The major features of rice plant favoring Cd uptake are fibrous root system having higher surface area, release of chelating agents, solublization of Cd by cell wall mediation process thus, able to enter the food chain even at low concentration (Sebastian and Prasad 2014; Rizwan *et al.* 2016). The major sources of cadmium in rice fields are Cd containing fungicides, phosphatic fertilizers, Cd contaminated irrigation water and sewage sludge application which has catastrophic effect on human health in form of cancer, anaemia, hypertension, cataract and renal disorders (Sebastian and Prasad 2014. Rizwan *et al.* 2016). Arsenic is another heavy metal of which pesticides and arsenic contaminated irrigation water are major source and are responsible for several disorders and finds its way in the crops like rice and wheat which is becoming a major problem (Patel *et al.* 2005; Bhattacharya *et al.* 2013). In a study carried out in Rice wheat growing areas of flood plains of Sutlej basin, it had been reported that Pb, Co and Cd content in grain has exceeded the permissible limit in both rice and wheat, and among all carcinogenic risk is highest for Cd (Setia *et al.* 2020).

The losing relevance of the agronomic practices which revolutionized the production in RWCS areas; increased difference between cost of production and prices and reducing total factor productivity has led to declining profitability in these areas (Kumar *et al.* 1998; Chauhan *et al.* 2012; Dhanda *et al.* 2022). There has been rise of inorganic fertilizers use upto 400 kg/ha which share 15% of total cost next to land and human labor in Punjab (Kumar *et al.* 1998). Fertilizer use has substantial share in terms of per hectare cost, irrespective of the soil type (Ullah *et al.* 2021). Simultaneously fertilizers constitute the highest energy share followed by irrigation, machinery etc on Rice-Wheat cropping system (Chaudhary *et al.* 2009). Fertilizers share 45% of the total input energy in wheat crop in Rice-Wheat cropping system (Singh *et al.* 2021).

Steel slag

Slag is basically a waste generated whenever the metal is extracted from the rock. Steel slag is one of the slags which is the byproduct of steel industry. More than 400 mT of steel slag is generated worldwide. In India, 150-200 kg steel slag is generated for 1 ton of steel production in India (Chand *et al.* 2015; IBM 2018). The global steel production stands at 1951 mT in 2021, which has seen an increase of around 27% over 2011, for India, it remained at 118.2 MT 2021 with increase of 60% for same period (WSA, 2022). Various types of slag are generated during the steel manufacturing (Fig 4). The blast furnace slag is generated during the conversion of iron ore to pig/ molten iron which is utilized in cement industry. Basic oxygen furnace (BOF)/ Linz Donowitz (LD) converter is utilized for conversion of pig iron into steel. In the basic oxygen furnace, 99 per cent pure oxygen is charged at supersonic speed which causes intense oxidation to remove impurities and carbon content is lowered by conversion to carbon monoxide causing temperature to rise upto 1600 -1700°C and lime and dolomite are added as flux agents during the process to remove other unwanted elements (Yildrim and Prezzi 2011; O'Connor *et al.* 2021). Electric arc furnace (EAF) slag, which is generated when steel scraps are utilized for steel manufacturing. It utilizes electric arc instead of oxidizing agents (O'Connor *et al.* 2021). Ladle Furnace (LF) slag is generated during the further refining of steel wherein, desulphurization, degassing of nitrogen, oxygen, and hydrogen, impurities removal and final decarburization is done so as to obtain refined steel (Yildrim and Prezzi 2011; O'Connor *et al.* 2021). Globally, BOF process shares 60-70% and EAF shares 30% of the total steel production (Branca and Colla 2012).

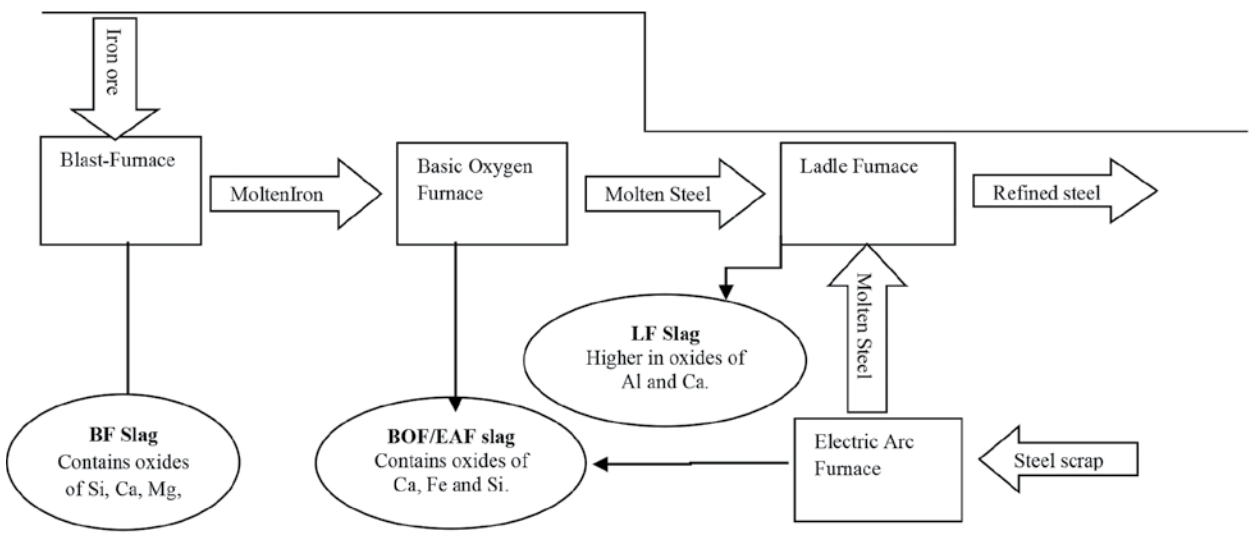

Fig 4: Depiction of generation of various types of slag at various steps and their composition. Blast Furnace (BF) slag is generated when iron ore is converted to molten/ pig iron which is further fed to Basic oxygen furnace (BOF) and there is generation of BOF slag. Electric arc furnace (EAF) utilizes the steel scrap as raw material and EAF slag is generated. Further refining of steel through ladle furnace (LF) leads to generation of LF slag.

Table1: Composition of various types of slag (Yildrim and Prezzi 2011; Yi et al. 2012).

Oxides (%)	CaO	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	MnO	P_2O_5	SO_3	TiO_2
BOF slag	45-60	10-15	1-5	3-9	7-20	3-13	2-6	1-4	0.1-0.3	0.4-2
EAF slag	30-50	11-20	10-18	5-6	8-22	8-13	5-10	2-5	0.1-06	0.5-0.8
LF slag	30-60	2-35	5-35	0.9-3.3	0-15	1-12.6	0-14	0-0.4	0.1-1	0.3-0.9

Lower content of lime in the EAF slag makes it stable and suitable for use in asphalt without any problem (Branca and Colla 2012). BOF slag generated finds its use partly in manufacturing of steel again and some of it is utilized in the construction; however, higher content of free lime makes it difficult to be used in construction industries. In countries like USA, Japan and European countries it is > 80 per cent, however for the countries like China and India, it is < 30 per cent (Das *et al.* 2020a). Thus, a large amount of steel/ BOF slag finds its way in the landfill sites and or stored in the steel mills. Land filled with slag imposes a major cost on the human health and vegetation through air, soil and water pollution (Das *et al.* 2019). The nutrient content of steel slag (Table 1) shows that it can be utilized as potential nutrient source in agriculture.

Steel slag as nutrient source

Slag is rich source of silicon and is source of calcium, iron, phosphorus and manganese (Ning *et al.* 2016; Das *et al.* 2020a; Gao *et al.* 2020). It can be utilized for the preparation of various specialty fertilizers (Table 2). Higher silica content in slag has synergistic interaction with phosphorus in soil towards its availability to the crop as it competes for binding sites to Fe, Al and Mn oxides and also enhances the uptake and translocation of essential nutrients (Humaria 2014; Deus *et al.* 2018; O'Connor *et al.* 2021). It is estimated that rice yield of 1 to 5tonnes ha-1 removes 130 to 470 kg ha-1 Si twice as much as combined NPK (Ning *et al.* 2014; Han *et al.* 2015). The major effects of steel slag as source of plant nutrient and yields in Rice and wheat crop are given in Table 3. Steel slag has been found to increase the rice yields and the uptake of P, K, Mn and Fe uptake (Branca and Colla 2012). Higher content of iron and manganese oxides in slag gives vitality to rice roots (Humaria 2014). It is reported that steel slag contains Copper (30 mgkg-1), zinc (70 mgkg-1) and Nickel (3 mgkg-1) in addition to the various nutrients as mentioned in Table 1 (Deus *et al.* 2018). Slag application in soil influences the soil-microbial interaction which causes the increased nutrient availability through direct release of nutrients by it, increased root exudates from plants supplying adequate carbon and nutrients to the microbes, improving soil pH and immobilizing toxic heavy metals (Das *et al.* 2019). Slag application along with the green manuring and Blue Green Algae has reported the yield increase in rice upto 40% and found to increase plant iron content in corn when applied along with sewage and sludge (Das *et al.* 2020a).

Steel slag for disease and pest resistance

The silica content of steel slag is important for imparting disease resistance in crop plants. Role of silica in imparting disease resistance in rice was established against Rice blast early in 1917 (Mehrag and Mehrag 2015). Silica in slag have biochemical role in mediating enhanced resistance to pathogens as well leads to enhanced cell silicification and more elaborate and large papillae formation

Table 2: Roles of various fertilizers that can be developed from steel slag (Humari, 2014; Das et al. 2019; Das et al. 2020a)

Types of slag fertilizer	Effects in plant system
Silicate fertilizers	Photosynthesis increment; Increased microbial activity by allocating carbon to soil through exudates; Highly useful for silica accumulating crop like rice; Boosting root activity, reduces wilting, creating strong stem for healthy rice crops. It also promotes the dry matter production, increasing kernel weight, improved appearance quality and promotes ripening to improve flavor in rice.
Lime fertilizers	Alleviates soil acidity and protect plants from pathogen; Ca makes root strong and promote K absorption.
Slag Phosphate fertilizers	Improves plant growth and fruiting; Cheaper alternative to non-renewable rock phosphate reserve utilized for phosphatic fertilizer synthesis.
Iron matter of specialized fertilizer	Mitigates heavy metals toxicity in soil and plant; serves as cheaper source of iron compared to costly Fe-chelate fertilizers.

Table 3: Performance of steel slag (based products) as the nutrient source and their effect on Greenhouse gases mitigation.

CROP	EXPERIMENTAL LOCATION	TYPE OF EXPERIMENT	SOIL pH	SLAG DOSE	YIELD INCREASE	GREEN HOUSE GASES MITIGATION	REFERENCE
Rice	Republic of Korea	Pot Experiment	5.6	Slag was added @ 2Mgha-1 along with recommended fertilizers.	+15.2% (Japonica) +13.63% (Indica)	Soil organic carbon increased by 11.6% (Japonica) and 14.6% (Indica)	Das et al. 2020b
Rice	China	Pot Experiment	Red soils	Steel slag applied equivalent to 0.5M HCl soluble Si- 0 (CK), 400 (Si1), 800 (Si2) and 1200 (Si3) 1600 (Si4), 2000 (Si5) mg SiO2 per kg soil. Basal fertilizers were added as per recommendation	+11.9% (1600mg SiO_2 per kg of soil) and +13.9% (2000mg SiO2 per kg of soil) for timely sown. +14.3% (1600mg SiO2 per kg of soil) and +16.7% (2000mg SiO2 per kg of soil) for late sown.	NA	Ning et al. 2016
Rice	China	Field Experiment	6.5	Steel slag was applied @ 0(Control), 2, 4 and 8 Mgha-1. Other fertilizers were applied at recommended rates.	+1.6%, +3%, +4% (First Early Rice crop); +0.4%, +8.3%, +9.1% (Late Rice); -1.1%, +0.8%, -0.4% (Second early rice) with 2, 4 and 8 Mgha-1 compared to control in Early Rice crop.	-36.3, 52.1 and 56.0% reduced mean CH4 emission compared to control. -42.4, 41.2 and 98.8% lower mean N2O emission compared to control.	Wang et al., 2014; Wang et al., 2015
Rice	Indonesia	Field Experiment	6.40	Steel slag applied @0, 1 and 2 Mgha-1. Fertilizers were applied at recommended rates.	+4.8% increase in rice yields at both doses.	-9.1% and -10.7% reduced CH4 emission. -2.8% and -3.4% reduction in N2O emission.	Susilawati et al. 2015
Rice	Republic of Korea	Field Experiment	5.6	LD slag applied @ 2Mgha-1	+10.7% and +10.3% increase for indica and japonica rice, respectively.	-24 and -17.8% reduction in CH4 emission in indica and japonica respectively	Gwon et al. 2018
Rice	China	Field Experiment	slightly acidic soil	Four treatments with control slag and biohar separately and together each @ 8 Mgha-1. Fertilizer was added with recommended rates.	+9.2% and +7% increase in yields with steel slag along with biochar in early and late paddy, respectively.	-41.9 to 51.6% reduction in CO2 emission in early paddy season. +28.7% higher SOC with steel slag+biochar; -30.1 and -25.8% lower LOC with steel slag alone and with biochar.	Wang et al., 2018a; Wang et al., 2020

Rice	South Korea	Field Experiment	6.1	Silicate iron slag applied @ 0, 1, 2 and 4 Mgha-1.	+2.4%, 6.2% and 13.4% increase in grain yield compared to control.	-16 to -20% reduction in CH_4 emission at 4Mg ha-1.	Ali et al. 2008
Rice	South Korea	Field Experiment (Long term for 28 years).	6.3	Blast Furnace Slag was applied @ 1.5Mgha-1.	+14% average increase in rice yields.	…	Lim et al. 2022
Rice	China	Field Experiment	6.5	7 treaments with straw alone and with other industrial byproducts including steel slag @ 8Mgha-1.	+3.1% increase in yield with straw+steel slag compared to straw alone.	-31.7% reduction in Green house gas intensity;-29.5% reduction in global warming potential	Lin et al. 2022
Rice	Japan	Pot experiment	4.7	Chicken manure and steel slag in ratio of 1:1, 1:1.5 and 1:2.5 were applied compared to conventional (only fertilizer treatment).	Highest grain yield for conventional and increasing trend of yield with increasing ratio of chicken manure with slag.	Cumulative CH_4 emission lowest for conventional. Hihest for 1:1 and decreasing trend with increasing ratio. Lowest N_2O emission for 1:1.5.	Fauzan et al. 2021
Rice	China	Field Experiment	6.5	Steel slag was applied @ 8 Mgha-1 along with other wastes in different treatments. Mineral fertilizers was applied at recommended levels.	+7.1%	-20.2% CO_2 emission; -53.8% CH_4 emission; -26.6% reduction in Global warming potential.	Wang et al. 2018b
Rice	China	Field Experiment	6.5	Steel slag was applied @ 8 Mgha-1	+8%	-66.1% mean CH_4 emission; -67.8% reduction in Global warming potential	Wang et al. 2016
Wheat	USA	Field Experiment	..	Two N rates i.e. 101 and 145 kg N ha-1 and five steel slag rates 0, 1, 2, 4.5 and 9 Mgha-1	+25.4% (101 kg N ha-1) and +9.0% (145 kg N ha-1) with slag @ 9 Mg ha-1.	…	White et al. 2017
Wheat	Romania	Field Experiment	5.2-5.4	LF slag was applied @ 0,1, 2, 3 and 5 tha-1.	+6.8%; +21%; +28.2%; +38.1% increase respectively	..	Mihalache et al. 2014

providing resistance to fungal infection ,promotes callose production, silica deposition on the epidermis of the leaf blade and sheath forms cuticle silica double layer leading to herbivory resistance, indirectly affecting the molecular defense associated signaling responses, through phenolic production and regulation of ethylene pathways (Provance-Bowley *et al.* 2010; Ning *et al.* 2014; Mehrag and Mehrag 2015; Han *et al.* 2015). Addition of steel slag reported upto nil incidences of brown spot at anthesis stage of rice with application of steel slag compared to control where it was found upto 39.7% in control showing strong correlation with slag application (Ning *et al.* 2014). Silica content in rice reduced the sheath blight lesion progress curve significantly by 34.2% compared to the rice without silica content (Schurt *et al.* 2014). Brown plant hopper emergence, their weight increase and survival rate were found significantly lower with silica treated rice plants compared to control (He *et al.* 2015). Si application in rice led to the reduced larval and pupal weight and net reproduction rate of Rice leaf folder (Han *et al.* 2015). Basal application of steel slag @ 500kgha-1 in rice resulted in significant reduction in dead heart, white ear incidence and feeding tunnels of Rice stem borers (Tripathy and Rath 2016). In a three year study, application of calcium silicate slag by product resulted in reduced incidence of lesions in flag leaf due to powdery mildew and found to be associated with its silica content (Provance-Bowley *et al.* 2010). Lowest foliar disease severity was observed in wheat with application of slag (Pereira Báez and Grabowski Ocampos 2015).

Steel slag for reducing Greenhouse gases emission

Steel slag utilization in agriculture holds potential for reducing the emission of greenhouse gases. The electron acceptors in form of Mn4+, Fe3+, SO42- decreases the CH4 emission as iron reducing bacteria are stimulated at cost of methanogens and higher silica content contributes to the better plant growth and yields and aerenchyma enlargement in rice plant, thus, enhanced transport of oxygen to rhizosphere which causes oxidation of the methane (Ali *et al.* 2008; Susilawati *et al.* 2015; Das *et al.* 2019; Kumar *et al.* 2020) (Fig 5). The CO2:CH4 production ratio under anaerobic wetland conditions is higher with terminal electron acceptors like NO3-, Mn (III, IV), Fe (III) and SO42- which are energetic favourable and slowly there is increase in CH4 production with consumption of these (Keller *et al.* 2013). Thermodynamically, Fe3+ prove to be favourable electron acceptor than H2/ acetate for anaerobic degradation of the organic matter, thus, reducing the methane emission from rice fields (Wang *et al.* 2014; Kumar *et al.* 2020). Formation of iron plaque on rice roots with application of slag limits the transport of material between the root and soil, thus, limiting the gas release to the atmosphere (Wang *et al.* 2018b). Various studies conducted with the application slag have shown that there is reduction of emission of green house gases with application steel slag (Table 1). Though there has been reported reduction of nitrous oxides with application of slag, however, the complete understanding on the effect of slag on N2O emission is missing as some studies has also shown an increase in its emission with slag application (Wang *et al.* 2016; Das *et al.* 2019; Kumar *et al.* 2020). Nitrous oxides are associated with Fe3+ oxidation under anoxic conditions (Kumar *et al.* 2020). Silica fertilization promotes nitrous oxides production by lowering decomposition of soil carbon, thus reducing N immobilization and making more of it available for the nitrification and denitrification; improving soil pH and Eh in favor of denitrification, however, higher number of electron supplied by Fe2+ leads to complete denitrification to nitrogen, thus, reducing nitrous oxide emission (Das *et al.* 2019).

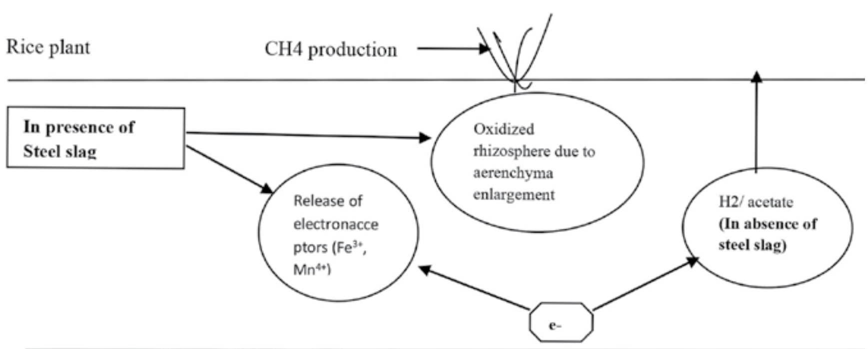

Fig5: Application of steel slag releases electron acceptors and increases oxidation of rhizosphere, therefore, methane production is reduced, otherwise in absence of steel slag there is emission of methane.

Steel Slag for Abiotic Resistance

The silicon present in the steel slag plays vital role in imparting the abiotic resistance in crops. Silicon imparts resistance to abiotic stress such as drought, salinity, flooding, lodging and heavy metal toxicity. The major mechanisms of the stress tolerance are presented in the table 4. In a three year lysimetry study carried out by Pistocchi *et al.* (2017) with wheat and tomato crops, it was reported that application of slag doses 3.5g kg-1 and 7 g kg-1reduced exchangeable sodium percentage by 40-45% possibly due to supply of Ca and Mg. The alkaline nature of slag and its promotion of soil redox potential reduce the bioavailability of heavy metals to the crop; increased silica supply is antagonistic to the arsenic uptake; heavy metals are precipitated on surface by Ca, Mg and Si (Mehmood *et al.* 2021). He *et al.* (2016) reported the reduction of cadmium uptake in brown rice by 45% with application of 4 tonnes slag ha-1. Similar results were reported by Gu *et al.* (2011) where the slag application upto 6 gkg-1 of soil in pot experiment reported reduction of Cd uptake by 99%. Similar results of reduced Cd uptake and translocation were reported (He *et al.*2016; Ning *et al.* 2016; Cao *et al.* 2018; He *et al.* 2020).

Table 4: Tolerance mechanism promoted by silica in plant against various types of stress (Mehrag and Mehrag 2015; Malhotra and Kapoor 2019; Sarto et al. 2019).

Stress type	Tolerance Mechanism
Salinity	Inhibit Na^+ uptake by reducing root membrane permeability, improving structure and stability of root cells, promoting Na^+ export from cell and mediating root plasma membrane ATPase. Provides binding sites for the salt, thus, reducing their uptake.
Drought	Cell wall deposition of silica reduces transpiration and increases internal water balance; Hydrophilic nature of $SiO_2.2H_2O$ maintains water in plants; Increases Ca concentration and thus, membrane stability; Maintaining higher level of K^+; Increased root elongation; Abscisic acid signaling system promotion.
Heat	Silica deposition on xylem vessels prevents their compression under high transpiration conditions; Reduced wilting; Higher production RuBP carboxylase promoting CO2 metabolism, Increased activity of SOD.
Heavy Metal	Silica deposition causes thickening of casparian strips in endodermis and cell wall of xylem hampering metal transport in plants; stimulation of root exudates production; co-precipitation of heavy metal ions; stimulation of anti-oxidant defense mechanism, changing leaf morphological characteristics including leaf length, leaf area, leaf number etc.
Lodging	Deposition of silica in the cell wall provides strength and rigidity to the plants.

Challenges in utilization of steel slag

The major challenge in utilization of steel slag in agriculture is of its heavy metal content especially chromium (Cr) and vanadium (Vn) and higher pH. Cr (VI) is more soluble form of chromium which get reduced to Cr (III) and thus, which is comparatively lesser soluble and bioavailable to the crops. Concentration of oxide of Cr (III) in slag is upto0.105- 0.37% (Yildrim & Prezzi 2011; Das *et al.* 2021). The concentration of chromium (III) and vanadium in slag varies from 760-1707 mgkg-1 and 299-634 mgkg-1, respectively (Chand *et al.* 2015). There are contrasting reports on the accumulation of Cr on the long term application of slag as fertilizer (Mehmood *et al.* 2021). It is demonstrated that application of slag doesn't increase the bioavailable Cr content in soil or its uptake by plants in short term and there are possibilities of its accumulation in the long term, however, contrasting results are also obtained with long term trials (Das *et al.* 2019). Soil amended with 10 tonnes slag acre-1 reported to had small but non-environmentally important increase in Cr (III) concentration in soil (Chand *et al.* 2015). Toxicity characterization leaching potential (TCLP) and American Standards for Testing Material (ASTM) water leachate of chromium in the steel slag was found to be lower than hazardous limits showing it is less soluble and less likely to effect the ground water quality (Chand *et al.* 2015; Gwon *et al.* 2018). Application of slag has resulted in their accumulation in the top soil and was not leached down and in crop plants; these were concentrated in roots and almost negligible in leaves and fruits (Pistocchi *et al.*2017; Annunziata *et al.* 2019). However, the risk of chromium accumulation in soil due to continuous application cannot be ruled out which is needed to be studied further. Higher pH of the slag is another major challenge which can lead to the reduction in bioavailability of the nutrients to the crop. However, treating slag with suitable amendment not only bring down the pH which can increase the phyto-availability of nutrients but can also lead to the considerable reduction in chromium content reducing its uptake by the plant (Scattolin *et al.* 2021).

Conclusion

In addition to aforementioned advantages with respect to potential utilization of slag in Rice Wheat Cropping System in India, it is pertinent to note that additional advantages can come in form of economic and energy efficiency. This becomes more important in view of declining resources and more protectionist approach of countries witnessed in present times. Fertilizer production accounts for the 1.2% of the global energy consumption (Wood and Cowie 2004). Though the content of essential nutrients in slag is not comparable with the high analysis fertilizers, its supplementation with fertilizers can bring down the cost of fertilizer use in agriculture. The chromium content in slag is a major challenge in its utilization, however, the extensive studies are required for its verification regarding its persistence, entry in the food chain and consequent impact on human health. It is to be noted that the steel slag has been utilized as raw material for crop fertilizers extensively in countries of Japan, China and Korea (Das *et al.* 2019). Thomas Phosphate fertilizer in Germany by utilizing slag was started in 1960 and it was successfully commercialized as phosphatic fertilizers and there was also successful production of slow relase potassium silicate fertilizers in Japan (Das *et al.* 2020a). In India also Tata steel launched Growell, a soil conditioner and lime fertilizer for the acidic soils and had beneficial effect on plant growth and yields. More research need to be conducted for development of such products in future.It is undeniable fact that there is increased requirement of food grains in the future. Rice Wheat cropping system areas in India is one of the important granaries of the world which is not only satisfying the food grain requirement but also the employment to a large rural sector. In such situations it is essential to analyze the various problems of these areas and find the low cost and sustainable solutions to these. The major problems pertaining to these are rising multi nutrient deficiencies, GHG emission, increased biotic and abiotic stress and reduced economic and energy efficiency due to intensive use of high cost inputs. Utilization of the industrial wastes with suitable modifications can not only increase the economy and energy use efficiency but certain waste due to their inherent composition can address the major problems of these areas. Steel slag utilization is one such industrial waste whose utilization has multiple advantages. Utilization of steel slag in agriculture has potential to increase sustainability and transform economy into circular through promotion of close loop production system.

Author contributions

All authors contributed equally for preparing the final version of the manuscript.

Conflict of Interest

Authors declare no conflict of interest.

Ethical Approval

The article doesn't contain any study involving ethical approval.

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