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Utilization of Steel Slag as a Soil Amendment and Mineral Fertilizer in Agriculture: A Review

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ABSTRACT

The gradual increase in industrial wastes allowed the utilization of these wastes in different areas. Steel slag, one of the industrial wastes, is formed during the reduction of molten crude iron to molten crude steel in basic oxygen furnaces or scrap to molten crude steel in electric arc furnaces and induction furnaces. Removal, storage, or disposal of steel slag is an important environmental and economic problem. Steel slag offers opportunities to be used as an alternative material in various areas and contributes to the national economies through recycling. This research provides information about the studies and application examples on the use of steel slag as a soil amendment and mineral fertilizer in the world. This usage allows reducing the consumption of natural resources and providing great agricultural, environmental, and economic gain by minimizing the negative environmental effects of steel slag.

Keywords: Steel slag, Basic oxygen furnace (BOF), Electric arc furnace (EAF), Induction furnace (IF), Soil amendment, Mineral fertilizer

1. Introduction

The use of steel slag in the remediation of acidic soils and the improvement of plant nutrient availability of infertile soils is a cost-effective and environmentally friendly approach that helps reduce waste issues. Therefore, the use of steel slag as agricultural lime material and/or mineral fertilizer is of great importance (Hemalatha 2013; Wen et al. 2020). The slag formed as a result of the steelmaking process can be successfully used as a soil amendment for the neutralization of soil pH in the reclamation of acidic soils as an alternative to natural agricultural lime material (limestone or dolomite) (Manso et al. 2013; Deus et al. 2018; Mamatha et al. 2018). On the other hand, since steel slag contains essential plant nutrients such as P, S, Mn, Fe, and Mo at various concentrations, it is possible to contribute to soil fertility as mineral fertilizer. Steel slag, with its calcium silicate content, can be used as an important source of nutrients for some plants sensitive to silicon, such as wheat, rice, and sugar cane, and as a material to improve disease resistance in many cultivated plants (Ito 2015; Yang et al. 2018; Das et al. 2019; O'Connor et al. 2021).

There are many studies and successful applications in different parts of the world which explicitly demonstrate that steel slag can be effectively used in the reclamation of acidic soils as an alternative liming material and is an economical soil amendment material (Proctor et al. 2000; Hemalatha 2013; Mamatha et al. 2018). On the other hand, steel slag has the potential to contribute to soil fertility and thus to crop yield as it has a significant amount and variety of essential plants. Steel slag can be used directly as a fertilizer, or it can be used more effectively by mixing and preparing compost with vegetable and animal wastes (Reuter et al. 2004; Winkler 2011; Manso et al. 2013).

This review has been prepared to pay attention on use of steel slag produced as a by-product of steel making industry, which has very high production value for Turkey in terms of plant nutrition and soil reclamation purposes.

2. Steel Slag Formation

Basic oxygen furnace slags (BOFS), electric arc furnace slags (EAFS), and induction furnace slags (IFS) are referred to as steel slags (TSPA 2015). Since the amount of production in IF is low, the amount of slag is also negligible. Steel slags, which are the by-products resulting from the oxidation of impurities in molten steel during steelmaking, primarily contain CaO, SiO_2, Al_2O_3, MgO, MnO, Fe_2O_3 and P_2O_5 (Proctor et al. 2000; Reuter et al. 2004; Yi et al. 2012; Guo et al. 2018; Fisher & Barron 2019; Song et al. 2021). The general chemical compositions of BOFS and EAFS is given in Table 1.

Table 1 - Chemical compositions of BOFS and EAFS (wt, %) (Yi et al. (2012))

Slag type	*CaO*	*SiO_2*	*Al_2O_3*	*MgO*	*MnO*	*Fe_2O_3*	*P_2O_5*
BOFS	45-60	10-15	1-5	3-13	2-6	3-9	1-4
EAFS	30-50	11-20	10-18	8-13	5-10	5-6	2-5

The pH of steel slag generally changes between 8 to 10 but depending on the limestone content, it increases up to 12 (NSA 2021). Steel is classified as high, medium, and low carbon-based on its carbon content. During production, the amount of oxygen blown must be changed in order to change the carbon content (FHWA 2017). Wang et al. (2021) found that carbon content of steel slag was 0.87%. After the blast furnace melting process in integrated plants, the scrap is added to the molten iron and processed in the BOF. At this stage, 10-15% of BOFS is obtained per ton of crude steel produced as a by-product (Cebeci & Sonverdi 2012). EAFS is produced as a by-product in steelmaking from scrap. Because the resulting molten steel is not of sufficient quality for direct use, the molten steel is taken into the crucible and subjected to additional processes. Undesirable elements in the molten steel are removed in the form of oxides by the oxidation process (Yonar 2017). IF uses alternating current flowing through a coil to create a magnetic field within the metal. The induced current provides rapid heating and melting. Since the metal is not in contact with the heating elements, the setting must be well controlled to produce molten metals of high quality and purity. Despite the lower capacity than other furnaces, the greatest advantage of IF is their lower investment cost compared to other melting furnaces. Since it operates at a low capacity, the amount of IFS is relatively less (GDH 2017).

3. Disposal Methods and Usage Areas of Steel Slag

More than 400 million tons of steel slag is produced in the world every year (Carvalho et al. 2017). The World Steel Association aims to achieve zero waste in the steel industry by reusing and recycling steel slag. Using the slag in other areas reduces the amount of waste, disposal costs, and energy use. In the notice published by the American National Slag Association (NSA 2003), it is stated that steel slag is a suitable aggregate material that can be used in residential, agricultural, industrial, and construction applications. Application areas and rates of steel slag in Europe in 2012 are given in Table 2. According Euroslag (2021) 68% of the steel slag was used in various application areas in 2012, while 19% was stored temporarily for later use, and only 13% was finally stored. The primary area of application of steel slag is aggregate production in road construction with a rate of 43%. While the rate of internal use for metallurgical purposes is 11%, it is used in cement production, hydraulic structures, and fertilizer production by 3 to 5% (Table 2).

Table 2 - Application areas and rates of steel slag in Europe in 2012 (Euroslag (2021))

Application areas	*Application rates (%)*
Road construction	43
Temporary storage	19
Final storage	13
Metallurgical usage	11
Cement production	5
Hydraulic structures	3
Fertilizer production	3
Others	3

Steel slag is a suitable aggregate material that can be used in residential, agricultural, industrial, and construction applications (NSA 2003; He et al. 2012; Mengxiao et al. 2015; Xue et al. 2016; Poulikakos et al. 2017). The slags have been tested following the USEPA and ASTM procedures, and it has been stated that slag applications are an environmentally friendly approach. Since slags are formed at very high temperatures, they do not contain organic, semi-organic, or volatile compounds but contain calcium, iron, silicon, aluminum, magnesium oxides and calcium silicate, aluminosilicate, and aluminoferrite compounds. According to the risk assessment analyses and the Human Health and Ecological Risk Assessment, the use of steel slag in residential, agricultural, industrial, and construction applications do not pose a threat to human health and the environment. A study conducted in Sweden investigated the suitability of ladle slags, by-product of secondary steel treatment, and EAFS for landfill cover, considering that large amounts of mineral materials were required by the landfills to be closed, and it was very costly to fulfill this need from natural resources. The opportunities to use EAFS and ladle slags from 4 different sources were investigated. Accordingly, regarding these slags with different particle sizes, it was determined that slags in the range of 16-32 mm could be used in the drainage layers, and finer slags could be used in the impermeable layer (Andreas et al. 2005).

Uibu et al. (2011) stated that EAFS could be used for CO_2-sorbent. Their study indicated that the EAFS are suitable for mineral carbonization in the liquid phase due to their Mg and Ca contents and that they can be used for CO_2-sorbent to reduce

CO_2 emissions. Moreover, it has been determined that steel slag has 95-100% removal efficiency in arsenic removal in aqueous systems (Yi et al. 2012). Kim et al. (2008) investigated the removal mechanisms of copper using steel slag. Many studies show that steel slag can be an effective material in phosphate adsorption from wastewater. When used as filter material in constructed wetlands, BOFS is found to be effective in the removal of phosphate (Park et al. 2017). Regarding the use of slags in wastewater treatment, there are phosphate removal applications, especially in domestic wastewater, by passing the wastewater through a tank filled with slag after biological treatment (Okochi & Mcmartin 2011). It has also been proven that steel slag can be used as ballast material on roads and railways as well as being used as backfill material in coastal structures (Unal et al. 2014; GDH 2017; Tozsin et al. 2023).

In Turkey, as of 2018, there are 34 established crude steelmaking facilities, 3 of which are BOF, 25 EAF, and 6 IF. The total crude steel production amount of these plants in 2018 was 37.311.733 tons, and the amount of slag formed was 5.562.018 tons (Table 3) (TSPA 2018).

Table 3 - The amounts of crude steel production and steel slag formed in Turkey in 2018 (TSPA (2018))

Slag type	*Crude steel*	*Steel slag*
	(tons)	
BOF	11.513.194	1.692.237
EAF	25.079.946	3.761.992
IF	718.593	107.789
TOTAL	37.311.733	5.562.018

For each ton of steel produced, 120-150 kg of slag is obtained. It is known that 100-140 million tons of slag have been obtained from iron and steel production in Turkey until now, most of this by-product has been disposed of or kept in storage areas in an inactive state, and around 4-5 million tons of slag is added to this idle pile every year (GDH 2017). The use of steel slag in different areas allows savings from natural resource consumption while minimizing the adverse effect on the environment by safely removing a material occurring in large masses under normal conditions and being kept in storage areas (Uysal & Bahar 2018). In Turkey, it is seen that steel slag is;

- regularly/irregularly stored in the fields,
- sold in the market as road filling material after being recycled in recycling facilities (iron in the slag is removed using magnetic separators, then processed in the crushing-screening facilities and sold as aggregate),
- used as raw material in cement and sinter plants.

4. Soil Application of Steel Slag

Steel slag has an important potential to be used as a mineral fertilizer as well as a good soil amendment. Therefore, steel slag can be used as an environmentally friendly application as a fertilizer or soil amendment in order to promote plant growth, regulate the structural properties of the soil, and increase crop yield (Lopez et al. 1995; Pistocchi et al. 2017; Jafer et al. 2018). Steel slag, which is a by-product of an industrial process, offers significant cost advantages over commercially produced limestone. In addition, steel slag is not only a liming material, but also contributes to the structural development of the soil due to its Ca, Mg, and Fe content and significantly reduce fungal infections. Slag is used as a soil amendment due to its high Ca and Mg content, and on the other hand, it is used directly as a raw material for the production of silicon fertilizer or phosphorus fertilizer in order to increase the resistance of plants against diseases and pests (Shi 2004; Branca et al. 2014; Das et al. 2019). Chand et al. (2015) stated in their study on the use of BOFS in agriculture that slag can be successfully used instead of limestone to neutralize soil acidity, and it may be possible to utilize it as a fertilizer material. Likewise, Das et al. (2007) pointed out that slag can be used safely and effectively as fertilizer and soil amendment.

Pinto et al. (1995), investigating the possibilities of using slag, a by-product of the iron and steelmaking industry and containing 29% Ca, 21% Fe, and 5% Mg, as a dolomitic liming material in pasture soils, indicated that soil pH increased significantly and linearly with slag application (0, 1, 1.5, 3, 5, and 7.5 t ha^{-1}), and pasture yield increased by 41% with the application of 3 tons of slag per hectare. Munn (2005) used steel slags as liming material for the improvement of agricultural and acidic mining areas in Ohio State (USA) and examined the effects of slag application on plant growth in these areas with a 3-year greenhouse trial. Steel slag and $CaCO_3$ were applied to acid soil with pH 3.5 in the ratio of 12.5 and 25 g $CaCO_3$ kg^{-1} equivalent. Selected plants, oat (*Avena sativa* L.), wheat (*Triticum aestivum* L.), corn (*Zea mays* L.) and soybean (*Glycine max* (L.) *Merr.*) were grown and harvested at the seedling stage. It was determined that the steel slag and $CaCO_3$ application increased the yield at the $P<0.01$ level compared to the control. Depending on the application, it was determined that the Ca and Mg content of the soil and all studied plants increased. Mihalache et al. (2016) reported that steel slag application at different doses (control, 1 t ha^{-1}, 2 t ha^{-1}, 3 t ha^{-1}, 5 t ha^{-1}) increased the wheat yield.

Steel slag is effectively used as a soil amendment to stabilize rice production, reduce greenhouse gas emissions in paddy fields, and most importantly, increase soil productivity in countries where rice production is vital, such as Korea, Japan, Bangladesh, and China. Wang et al. (2018a) stated that steel slag is very rich in terms of Fe and other nutrients and noted that if it is applied to the soil, the acidic soil pH can be increased, especially in paddy fields, the methane emission occurring in these areas can be reduced, the soil quality can be improved, and a significant increase in paddy yield can be achieved. Wang et al. (2018b) also determined that depending on the application of steel slag, Ca and Si concentrations in the soil as well as N and P concentrations in leaf and root increased significantly. They stated that the rice yield increased depending on the increase in the P, Ca, Si, N and P concentrations. As a result, it was determined that the application of steel slag to the paddy fields promoted the use of nutrients, increased plant growth and yield, and regulated soil and plant chemistry. In the same study, Wang et al. (2018b) investigated the effects on soil organic carbon stock by applying steel slag and biochar both separately and together as a soil amendment. They found that the amount of organic carbon in the 30 cm topsoil layer increased by 28.7-42.2% depending on the application at a rate of 8 t ha^{-1}. In this study, it was determined that the application of steel slag reduced the soil fungus population by 62.8% compared to the control soil. Makela et al. (2012) stated that the compost obtained by mixing steel slag with pulp and paper industry solid wastes gives very successful results in the improvement of acidic soils, and therefore, it can be substituted with commercial fertilizers.

Agricultural lime material used in the reclamation of acidic soils is generally reapplied every 3-5 years. The low solubility of limestone can ensure that the desired soil pH remains stable during this time. The situation in the application of steel slag is slightly different. The $Ca(OH)_2$ produced when CaO in the slag reacts with soil moisture causes a spike in soil pH, but this is temporary, and the desired pH is created when the poorly soluble calcareous components in the slag react with the soil. Therefore, the frequency of applying steel slag to the soil for liming depends on the time the slag can maintain the desired soil pH, which can be determined by monitoring the soil reaction at intervals of several years. The amount of salt added to the soil together with the steel slag is one of the most important issues to be considered in terms of the slag being used as agricultural lime material. Since agricultural lime has low solubility in water, the amount of soluble salts accumulated in the soil by the use of these materials does not pose a serious risk. However, the water-soluble salt content of steel slag is much higher than that of limestone. CaO and MgO in the slag react with water to form $Ca(OH)_2$ and $Mg(OH)_2$, respectively. The water solubilities of these hydroxides are 1.20 g L^{-1} and 0.009 g L^{-1}, respectively, and it is much higher compared to $CaCO_3$ (0.014 g L^{-1}) and $MgCO_3$ (0.013 g L^{-1}) (NLA 1990; Beck & Daniels 2008). However, soluble salts are not a problem in rainy areas and well-drained soils when the slag is applied in optimum doses to neutralize the soil pH. Beck & Daniels (2008) report that the soluble salt contents of fine and coarse steel slag are 3.68 and 2.55 dS m^{-1}, respectively. Considering that plants can tolerate soil salinity up to 2dS m^{-1}, serious problems with soil soluble salts should not be expected with the application of steel slag. However, in areas where high doses of steel slag are applied, it is recommended to monitor soluble salts and soil salinity.

It is absolutely required to monitor the amount of heavy metals added to the soil along with the steel slag. Studies show that the amount of heavy metal added to the soil by steel slag is generally well below the permissible limits. If steel slag is used as a liming material, there is no risk for conditions where soil pH is neutral as metals such as Al, Cr, Pb, Cd, Ni, Co, Be, Ba, and Sr have low soil solubility and bioavailability levels (Dimitrova & Mehanjiev 2000; He et al. 2017).

Since steel slag contains a high amount of fertilizer components such as CaO, SiO_2, and MgO, it is used as calcium silicate fertilizer in many regions of the world. Steel slag also includes essential plant nutrient elements such as Fe_2O_3, MnO and P_2O_5 (Shi 2004; Yildirim & Prezzi 2011; Das et al. 2019). Therefore, it has the potential to be used effectively as a fertilizer in cultivated and pasture areas. Studies have shown that steel slag, which is an important environmental problem, can be used as an inorganic fertilizer (Delil et al. 2017). Due to its alkalinity, steel slag is successfully used in agricultural soils instead of limestone to neutralize the acidity of the soil and create more suitable chemical and biological conditions agronomically (Yi et al. 2012; Chand et al. 2015). It has been reported that plant nutrient balance can be achieved rapidly, especially among Si, Fe, Ca, Mg, P, Mn and B in soils where steel slag is applied as calcium silicate fertilizer (Wang et al. 2018b; Das et al. 2020). Although Si is not an essential plant nutrient, it has great importance in promoting photosynthesis, root activity and stem resistance, and preventing yellowing of lower leaves and burn formation in many cultivated plants. For this reason, there are significant increases in yield in terms of quality and quantity, and especially dry matter production and grain yield increase depending on the calcium silicate application. In addition, it is reported that the product yield increases due to Fe, Mn and P supplementation, and the negative effects that lead to product loss, especially root rot and leaf burn, are eliminated (Kostura et al. 2005; Das et al. 2020).

Steel slags are categorized as silicate fertilizer, lime fertilizer, phosphate fertilizer, or Fe-added special fertilizer based on their Ca, Si, Mg, P, Mn, and Fe contents (Ito 2015). In studies on the determination of the efficiency of using steel slag as Fe fertilizer, it has been revealed that very significant increases in yield and plant Fe intake are achieved depending on the application dose in calcareous soils with Fe deficiency. Xian & Qingsheng (2006) applied steel slag directly and in the acidified form to calcareous soil in two different doses (10 and 20 g kg^{-1}) and determined that there were statistically significant increases in the dry matter ratio and plant Fe content of the corn plant at the end of the application.

The Indian Ministry of Agriculture has approved the product, which is obtained by enriching steel slag with nutrients such as Ca, P and Fe and produced by the Indian Fertilizer Association, to be used as a soil amendment. It was determined that the product gave very successful results in acidic soils, and the yield increased by at least 25% (Chand et al. 2015). In their study in Italy and Germany, where they shared long-term field trial results on the use of slag as a mineral fertilizer in agriculture, Branca et al. (2014) compared BOFS with reference liming material and commercial mineral fertilizers and reported that long-term slag application significantly increased the product amount and feed quality and that no negative effects on soil fertility occurred.

Steel slag can be used directly as a fertilizer, or it can be used more effectively by mixing and preparing compost with vegetable and animal wastes. Composted animal manure is used as a source of N and P. Very successful results can be obtained by mixing steel slag with animal manure and applying it to the soil as a compost enriched with N and P as well as Ca, Si, Mg, Mn, Fe, and other elements (Ito 2015). In the study, Ito (2015) underlined that the temperature of the compost prepared by mixing 15% slag with cattle manure based on weight increased up to 70 ºC at a depth of 20 cm from the surface; in the control group, this temperature could only rise to 58 ºC; even it was mixed every 10 days, the temperature was stabilized at 65-70 ºC after a short decrease; and therefore, the use of slag in composting accelerates the process and compost can be obtained in a shorter time. In the same study, it was determined that compost mixed with slag provided more than 80% germination and increased yield significantly. Therefore, the slag could be successfully used to correct soil acidity, increase soil physical and chemical properties and soil fertility.

5. Considerations in the Use of Steel Slag as a Soil Amendment and Mineral Fertilizer

The most important physical property of steel slag is its particle size distribution. The finer the slag to be used as a liming material in agriculture, the more reactive it will be, and thus, the more its effectiveness in neutralizing soil acidity will increase. In terms of particle size distribution, it is recommended that 90% of the slag passes through a 20 mesh (900 microns) sieve. The bulk density and specific gravity of steel slag are relatively higher than that of agricultural lime material. This situation is directly related to the amount of metal contained in the steel slag. The bulk density of steel slag ranges from 1.6 to 1.9 cm^{-3} while that of agricultural lime material ranges from 1.4 to 1.5 g cm^{-3}. Similarly, the specific gravity of steel slag varies between 3.2 - 3.6 g cm^{-3} while that of agricultural lime material varies between 2.7-2.9 g cm^{-3} (NSA 2021).

The main purpose of applying steel slag to the soil as mineral fertilizer is to provide nutrients to the plant. However, these wastes should not have negative effects on the environment, human, animal, and plant health. Therefore, in order to ensure more effective and sustainable use of steel slag in agriculture, it is necessary to carefully monitor the soil health and groundwater quality due to heavy metal and salt content while examining the effects on yield. Instead of limestone, steel slag has been successfully used for many years to neutralize soil acidity in agricultural soils with high efficiency and low cost. To ensure more effective and sustainable use of steel slag in agriculture, Chand et al. (2015) stated in their study on the behavior and immobilization of heavy metals in steel slag in soil that heavy metal accumulation in the soil was below the permissible limit values depending on the slag application. Wang et al. (2015) stated that steel slag could be used as an effective soil amendment to increase the paddy yield and to decrease the CH_4 and N_2O emission occurring in paddy fields without leading to heavy metal accumulation at concentrations which may produce adverse effects in soils and plants.

It is important in terms of fertilization that the fertilizer produced from steel slag contains nutrients such as Ca and Mg, which are consumed excessively by plants, as well as micro plant nutrients such as Fe and Mn. However, it should not be expected that the fertilizer produced from slag will completely eliminate the deficiency of N, P, and K, which are considered essential nutrients for plants and needed at the macro level. Because the N and K content of the slag is very low, and the P content is not in the amounts that can meet the plant's demands at the optimum level. Therefore, it is clear that it would be much more beneficial to use the fertilizer to be produced together with some N-P-K fertilizer (Ito 2015; Das et al. 2020).

The amount of lime to be added to the soil may vary significantly depending on the characteristics of the lime material used, the thickness of the soil layer to be improved, the soil characteristics, especially the texture and the initial pH of the soil, and the requirements of the product to be grown. The CaO content and particle size of the lime material are very important. As the CaO content of the lime material increases, the amount of lime material to be applied to the unit area decreases. The small particle size will lead to higher chemical efficiency due to the increase in the specific surface area. The thickness of the soil layer to which the lime material will be applied is generally considered as 15-20 cm. This depth is the soil depth where 80% of the root density of many cultivated plants is located, where water and plant nutrients are used intensively, and microbial activity is the highest (USDA 1999; Anderson et al. 2013).

6. Evaluation and Conclusions

Many industrialized countries consider steel slag not as a waste but as a by-product with economic value and use as a liming material in the reclamation of acidic soils and as plant nutrients. The use of slag, which is a by-product of steelmaking facilities, as a soil amendment and mineral fertilizer is of great importance in terms of agriculture, environment, and economy.

Studies on the use of steel slag as a soil amendment and mineral fertilizer indicate that steel slag;

- can be used as an effective and economical soil amendment material in the reclamation of acid soils as an alternative to agricultural lime,

- promotes nutrient uptake, increases plant growth and yield by creating more suitable chemical and biological conditions in acid soils,
- can be used as direct fertilizer since it has a significant amount and variety of essential plant nutrients (P, S, Mn, Fe and Mo), or it can be applied more effectively by mixing and preparing compost with vegetable and animal wastes,
- can be used directly as a calcium and magnesium silicate due to its high amount of CaO, SiO_2, and MgO contents,
- has the potential to be widely used as a source of Si, which has significant effect on quality and quantity of some plants by stimulating photosynthesis in many cultivars, increasing root activity, preventing yellowing of lower leaves, increasing stem strength, and preventing burn formation,
- can increase the crop yield when applied as a mineral fertilizer,
- has the potential to be used as lime fertilizer, phosphate fertilizer, and Fe-containing special fertilizer,
- although it contains certain amounts of heavy metals, the amount of these metals that can be loaded into the soil or taken from the soil by plants is below the maximum allowable amounts.

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