

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**UNLOCKING THE POTENTIAL OF STEEL SLAG FOR
SUSTAINABLE AGRICULTURE: A STUDY ON WHEAT AND
LETTUCE**

RIFAT BUĞRA BİLDİRİ

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF BIOTECHNOLOGY

ADVISOR: ASST. PROF. BAHAR YILDIZ KUTMAN

JULY 2025

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LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

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*to Nursu,
as precious as light
as essential as water
for me*

ABSTRACT

Sustainable waste management strategies necessitate efficient valorization of industrial by-products across different fields, including but not limited to agriculture. Steel slag, a by-product of steel manufacturing, appears to be a promising material as fertilizer and soil amendment due to its mineral composition and physicochemical characteristics. The main concern regarding the use of steel slag in agriculture is its heavy metal content which can adversely affect both plant tissues and soil environments. Based on the hypothesis that steel slag may affect plant growth, yield, and nutritional status of tissues, wheat and lettuce grown under greenhouse conditions were subjected to various slag treatments in alkaline and acidic soil types under different fertilization regimes in this study. In addition, an independent soil experiment was conducted to determine the effect of steel slag on soil pH, electrical conductivity (EC), and extractable element concentration. Steel slag amendment notably improved wheat growth by up to 78% over control in acidic soil with a significant increase in shoot phosphorus (P), potassium (K), zinc (Zn), and boron (B) levels. Furthermore, grain yield and nutritional quality positively responded to ground doses of slag amendment under acidic conditions. Lettuce growth, on the other hand, was drastically elevated compared to control in response to slag application in acidic soil. Nutritional status of edible lettuce parts was also enhanced by slag amendment in terms of K, calcium (Ca), and Zn concentrations. No significant increase in the concentrations of potentially toxic metals such as cadmium (Cd), chromium (Cr), vanadium (V), or lead (Pb) observed in any of the crops upon steel slag treatment in either type of soil. Moreover, 31% and 60% decreases in shoot Cd concentration were achieved in alkaline and acidic soil environments, respectively. These findings revealed that steel slag could enhance the growth, yield, and nutritional status of the crops through improvements in soil properties. Overall, this study suggested the considerable potential of steel slag as a promising approach for sustainable agriculture and a potential alternative to chemical fertilizers, whose production and long-term use may cause soil pollution and elevated CO₂ emissions. Future studies investigating the long-term impact of steel slag on soil and various plant species should be carried out to test the safety of the material, particularly under field conditions.

Keywords: Electric-Arc-Furnace Slag, Soil Amendment, Fertilization, Circularity, Sustainability

ÖZET

Sürdürülebilir atık yönetimi stratejileri, endüstriyel yan ürünlerin tarım da dahil olmak üzere çeşitli alanlarda etkili bir şekilde değerlendirilmesini gerektirmektedir. Çelik üretiminin bir yan ürünü olan çelik cürufu, mineral içeriği ve fizikokimyasal özellikleri sayesinde gübre ve toprak düzenleyici olarak öne çıkmaktadır. Ancak tarımda çelik cürufu kullanımına yönelik temel endişe, cürufun bitki dokularını ve toprağı olumsuz etkileyebilecek ağır metal içeriğidir. Çelik cürufunun bitki gelişimi, verimi ve dokuların besin içeriği üzerinde etkili olabileceği hipotezinden hareketle, bu projede sera koşullarında yetiştirilen buğday ve marul farklı gübreleme rejimlerinde, alkali ve asidik toprak tiplerinde muhtelif cüruf uygulamalarına tâbi tutulmuştur. Buna ek olarak, çelik cürufunun toprağın pH'ı, elektriksel iletkenliği (EC) ve yarayışlı element konsantrasyonu üzerindeki etkisini ortaya koymak amacıyla bağımsız bir toprak inkübasyon denemesi de kurulmuştur. Asidik toprakta yapılan cüruf uygulamalarında, buğday gelişimi kontrol grubuna göre %78 oranında artmış, sürgün dokularındaki fosfor (P), potasyum (K), çinko (Zn) ve bor (B) düzeylerinde anlamlı bir artış sağlanmıştır. Ayrıca, dane verimi ve besin kalitesi de asidik koşullarda ince partiküllü cüruf dozlarının uygulamasından olumlu etkilenmiştir. Asidik toprakta yapılan uygulamalarda marul gelişimi kontrol grubuna göre büyük bir artış göstermiştir. Marulun yenilebilir kısımlarındaki K, kalsiyum (Ca) ve Zn konsantrasyonları açısından da cüruf uygulaması dokuların besin içeriğini zenginleştirmiştir. Cüruf uygulaması hiçbir toprak tipinde bitkilerin kadmiyum (Cd), krom (Cr), vanadyum (V) veya kurşun (Pb) gibi potansiyel toksik metallerin konsantrasyonlarında anlamlı bir artışa yol açmamıştır. Dahası, sürgün Cd konsantrasyonlarında alkali ve asidik toprakta sırasıyla %31 ve %60 oranında azalma sağlamıştır. Bu bulgular, çelik cürufunun toprak özelliklerini iyileştirmek suretiyle bitkilerin büyüme, verim ve besin içeriğini artırabileceğini ortaya koymuştur. Bu çalışma ile çelik cürufunun sürdürülebilir tarımda ve üretimi ile uzun vadeli kullanımı toprak kirliliğine ve yüksek CO₂ salımına neden olabilen kimyasal gübrelere alternatif olarak kullanımının önemli bir potansiyele sahip olduğu ortaya konmaktadır. Çelik cürufunun, özellikle tarla koşullarında, toprak ve farklı bitki türleri üzerindeki uzun vadeli etkisini değerlendiren çalışmaların yapılması gerekmektedir.

Anahtar Kelimeler: Elektrik Ark Ocağı Cürufu, Toprak Düzenleyici, Gübreleme, Döngüsellik, Sürdürülebilirlik

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LIST OF SYMBOLS AND ABBREVIATIONS

μg	: Microgram
μS	: Microsiemens
M	: Molar
mM	: Milimolar
μM	: Micromolar
cm	: Centimeter
cm^2	: Square centimeter
cm^3	: Cubic centimeter
%	: Percent
$^{\circ}\text{C}$	: Celcius degree
g	: Gram
h	: Hour
kg	: Kilogram
mg	: Miligram
min	: Minute
ml	: Mililiter
nm	: Nanometer
mm	: Milimeter
rpm	: Revolutions per minute
ppm	: Parts per million
sn	: Second
As	: Arsenic
B	: Boron
BOF	: Basic oxygen furnace
C	: Carbon
Ca	: Calcium
CaCl_2	: Calcium chloride
$\text{Ca}(\text{NO}_3)_2$	: Calcium nitrate
CaCO_3	: Lime
$\text{Ca-Mg}(\text{CO}_3)_2$	: Dolomitic lime
CaO	: Calcium oxide
$\text{Ca}(\text{OH})_2$	: Calcium hydroxide
Cd	: Cadmium
CH_4	: Methane
CO_2	: Carbon dioxide
Cr	: Chromium
Cu	: Copper
cv.	: Cultivar
DAS	: Days after sowing
dH ₂ O	: Deionized water
ddH ₂ O	: Double deionized water
DTPA	: Diethylenetriaminepentaacetic acid
DW	: Dry weight
EAF	: Electric-arc-furnace
EC	: Electrical conductivity
Fe	: Iron
Fe_2O_3	: Iron (III) oxide

FW	: Fresh weight
GHGs	: Greenhouse gases
H ₂ O ₂	: Hydrogen peroxide
HCl	: Hydrochloric acid
HNO ₃	: Nitric acid
HSD	: Tukey's honestly significant difference
ICP-OES	: Inductively coupled plasma optical emission spectrometry
K	: Potassium
KH ₂ PO ₄	: Mono potassium phosphate
LD	: Linz-Donawitz
Mg	: Magnesium
MgO	: Magnesium oxide
Mn	: Manganese
Mo	: Molybdenum
N	: Nitrogen
Na	: Sodium
NBI	: Nitrogen balance index
n.d.	: Not detected
NH ₄ HCO ₃	: Ammonium bicarbonate
NH ₄ OAc	: Ammonium acetate
Ni	: Nickel
P	: Phosphorus
P ₂ O ₅	: Phosphorus pentoxide
Pb	: Lead
S	: Sulfur
SEM	: Scanning electron microscope
SMS	: Steelmaking slag
Si	: Silicon
Sn	: Tin
V	: Vanadium
var.	: Variety
Zn	: Zinc
FAO	: Food and Agriculture Organization

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1. INTRODUCTION

The evaluation of waste products obtained across different industries and sustainable waste management systems have gained increased attention in recent years [Bisinella et al., 2017; Hajam et al., 2023; Um, 2025]. The effective recycling of various by-products is essential for industries to improve the efficiency of their sustainability programs. Waste management strategies of industrial companies is critical in terms of ensuring long-term profitability and competitive advantage [Winkler, 2011].

Valorization of industrial by-products is important issue for saving money, energy, and environment due to concerns related to global waste generation, which is expected to double by 2050 when compared to 2016 [Kaza et al., 2018]. It can also be effective in improving the relationship between different industries and establishing the network that provides interdisciplinary projects and collaborative studies. Each component of different industries, therefore, have a tendency to consider cost-beneficial impacts of recycling programs in terms of circular economy [Winkler, 2011; Ferronato et al., 2019; Um, 2025]. Although implementing recycling, reducing or reusing strategies appears to have a positive impact on sustainability, it is critical to evaluate trade-offs between circulation of waste materials and economic and environmental aspects of sustainability [Haupt and Hellweg, 2019; Blum et al., 2020; Kulakovskaya et al., 2023].

Steel slag is one of the most important materials considered as waste forming during steel production. In recent years, its potential to be used in agriculture has attracted researchers to investigate steel slag and explore its beneficial effects in terms of plant nutrition and soil health [O'Connor et al., 2021]. The mineral content and physicochemical properties of steel slag are the primary factors that make researchers recognize its potential in agricultural activities. The essential minerals in steel slag demonstrate the fertilizer role of the material, and its high pH and other physicochemical properties exhibit the potential of steel slag for soil amendment purposes [National Slag Association, 2011].

Soil amendments and fertilizers play a key role in improving soil productivity, structure, and nutrient bioavailability, which are crucial for enhancing crop growth and

ensuring food security. Fertilizers provide essential macro- and micronutrients required for plant development. Soil amendments, on the other hand, are employed to improve the physicochemical and biological properties of the soil, such as pH balance, nutrient availability, and microbial activity. There is growing interest in alternative soil management strategies that directly contribute to sustainability and resource efficiency. The incorporation of industrial by-products as soil amendment presents a promising strategy by providing soil neutralization impact, supplying essential nutrients, and potentially reducing the reliance on chemical fertilizers. This integrated approach can not only improve crop performance but also promote sustainable waste valorization, aligning agricultural practices with circular economy principles.

1.1. Steel Slag

Steel slag, a by-product of steel-making industry, is composed mainly of Ca, magnesium (Mg), and iron (Fe). Steel slag also contains various concentrations of other plant nutrients such as P, sulfur (S), manganese (Mn), Zn, B, and molybdenum (Mo) [Yildirim and Prezzi, 2011]. As a co-product of steel production process, steel slag includes low ranges of heavy metals such as Pb, Cd and V, which can pose significant risks to both environment and human health [Ito, 2015]. The changing concentrations are due to differences in manufacturing processes such as varied melt compositions and furnace conditions [Yang et al., 2018; Gwon et al., 2018]. Steel slag contains Cr higher than any other potentially toxic non-essential element. Due to Cr content of steel slag that can adversely affect plant growth and development, it is the primary factor that raises concern about the utilization of this material in agricultural activities. Although it contains some elements that can negatively affect plant growth, essential macro- and micronutrients in steel slag might outweigh the damaging effects of these stress-related elements over a short period due to their low concentration and bioavailability. Therefore, the potential of steel slag to be used in agricultural practices appears to be promising.

1.1.1 Steel Slag Production

Almost all steel is manufactured using the basic oxygen furnace (BOF) or electric arc furnaces (EAF) in the steel-making industry. In both production processes, flux

materials such as lime (CaCO_3) and dolomitic lime ($\text{Ca-Mg}(\text{CO}_3)_2$) are placed in furnace [Ilyushechkin et al., 2012]. In the BOF route, oxygen is injected into the furnace by lance with high-pressure. Oxygen released into the furnace reacts with carbon and non-iron impurities to form various oxidized compounds. These oxidized compounds, in turn, carry out a number of reactions with lime and dolomitic lime, resulting in formation of slag. Electric-arc-furnace route, on the other hand, relies mainly on steel scraps as raw material, and electricity to generate energy required for operating the processes [National Slag Association, 2011].

Slag forming during the steel-making process floats on top of the molten steel. The liquid steel is obtained from the furnace, and remaining slag is poured into separate vessels. The by-product of transforming iron ore to steel in blast furnace which utilizes basic oxygen process-related steel-making route, or in electric arc furnace which melts the scrap metal is described as steel slag [O'Connor et al., 2021].

Slags are named based on the production type and the furnaces used for the generation. The main types of steel slag produced from steel industry can be classified as BOF slag, EAF slag, and ladle slag [Yildirim and Prezzi, 2011]. BOF and EAF slags have similar chemical compositions, differing mainly in the ratio of some compounds such as CaO , Fe_2O_3 , and P_2O_5 .

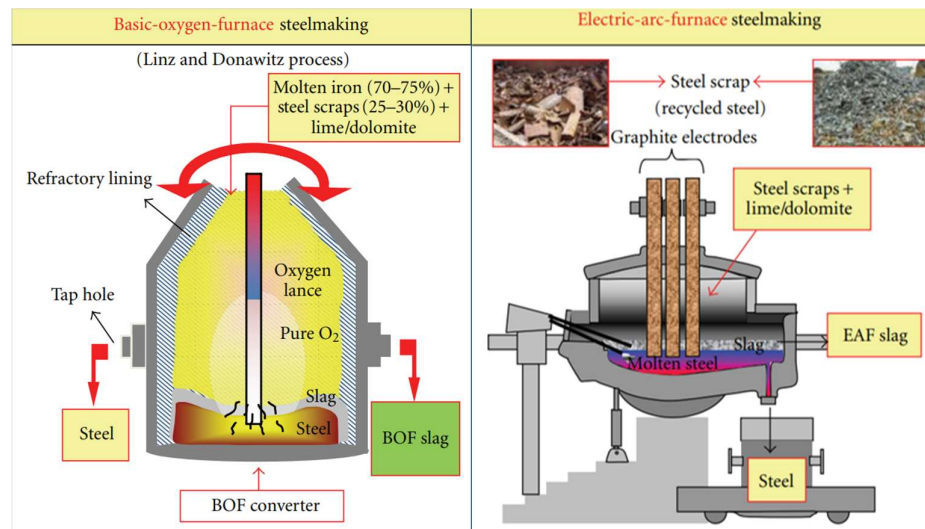


Figure 1.1: Schematic representation of basic oxygen furnace (BOF) and electric-arc-furnace (EAF) processes [Yildirim and Prezzi, 2011].

1.1.2 Characteristics of Steel Slag

There are different types of steel slag generated during steel-making process. Steel slags obtained from different stages of the production can vary in terms of structure, composition, and physicochemical properties [O'Connor et al., 2021]. General flow of steel production determines important characteristics of steel slag. Its composition can be affected by the parameters such as temperature, gas environment, quality of flux, cooling rate, and impurities present in raw material [Ilyushechkin et al., 2012; Dhoble and Ahmed, 2018]. Changes in these parameters cause difference in slag nutrient contents, toxic element concentrations, pH, and other physicochemical properties such as electrical conductivity, surface area, and porosity [O'Connor et al., 2021]. Although various parameters cause steel slags to have a range of chemical and mineralogical composition or textural properties, they share common characteristics such as possessing acid-neutralising capacity and containing essential nutrients for plants.

Particle size of the material is one of the most important factors that indicates if steel slag can be used for agricultural liming material. Physical characteristics of steel slag are crucial for its effective utilization. Particle size distribution and fineness of steel slag exhibit the reactivity of the material which, in turn, increases the neutralizing capacity of steel slag in soil environments. Steel slag has high specific gravity (3.2-3.6 g/cm³) and high bulk density (1.6-1.9 g/cm³) that originate from residual metals found in the composition [National Slag Association, 2011]. Porous structure of steel slag used in this thesis studies was shown in **Figure 1.2**.

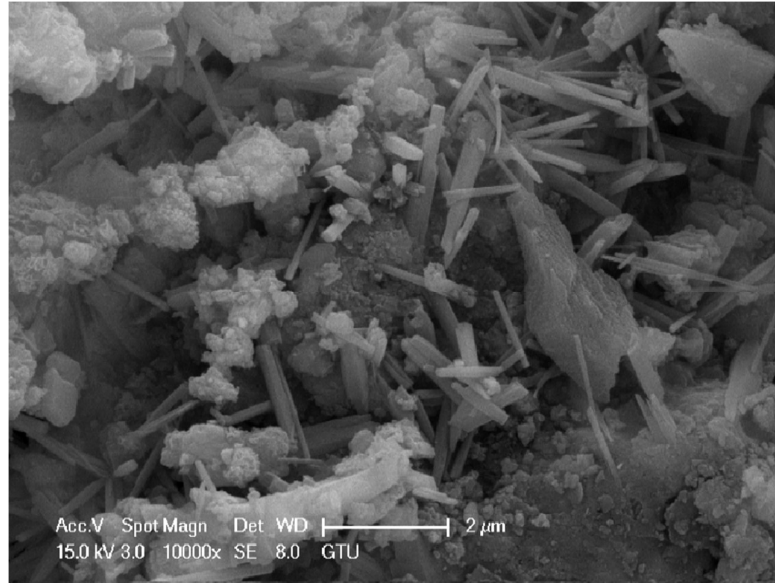


Figure 1.2: Scanning electron microscope (SEM) image of steel slag

The content of steel slag depends mainly on the production process, kind of raw material, and the specific stage in which the material is obtained [Yıldırım and Prezzi, 2011]. It generally contains significant concentrations of Ca and Mg. These elements occur as silicates, ferrites, aluminates, oxides, and some free CaO and MgO [Waligora et al., 2010]. The high content of Ca and Mg makes steel slag an alkaline material that has pH in the range of 8-10. The pH range of 10-12 can also be possible in case of higher concentrations of free CaO since it can react with water that forms Ca(OH)_2 which has a maximum pH of 12.5. Ca(OH)_2 can rapidly react with water found in soil, whereas less soluble silicate compounds slowly react with the soil acidity, providing long-term buffering of soil pH [Ning et al., 2016; Mayes et al., 2018]. Soil acidity can therefore be corrected by use of steel slag which makes it attractive resource in terms of soil amendment purposes. Alkaline nature of steel slag indicates its function in neutralizing the acidic soils, which provides optimum soil pH levels in order for plants to grow and develop properly. Alteration in bioavailability of essential elements and changing activities of microbial community in soil as a response to elevated pH level are the main results of steel slag application [Das et al., 2019].

1.1.3 Utilization of Steel Slag for Alternative Sectors

The utilization of steel slag has increased in several countries due to the efforts related to enhancing the recycling programs [Gao et al., 2020]. According to the report by US Geological Survey, US produces nearly 10 million tons of steel slag which is generally used for road surfaces or asphaltic concrete [US Geological Survey, 2017]. In Europe, nearly 18.4 million tons of steel slag produced is generally utilized for road construction and metallurgical use [EUROSLAG, 2016]. It has been reported that steel slag is recycled at 77.3% in Australia and is mostly used for cementitious materials and road construction [Australasian Iron and Steel Slag Association, 2020]. Japan produces approximately 14.1 million tons of steel slag and recycles steel slag at 98.4% which is the highest recycling ratio among others. The recycled steel slag is primarily used for road construction, civil engineering, internal recycling, and other uses in Japan [Nippon Slag Association, 2016]. The disposal rate of steel slag is around 70.5% in China. Although China manufactures almost half of the steel worldwide, its recycling programs are not efficient in terms of evaluation of steel slag. Limited recycled steel slag is primarily utilized for road construction and civil engineering in China [Guo et al., 2018].

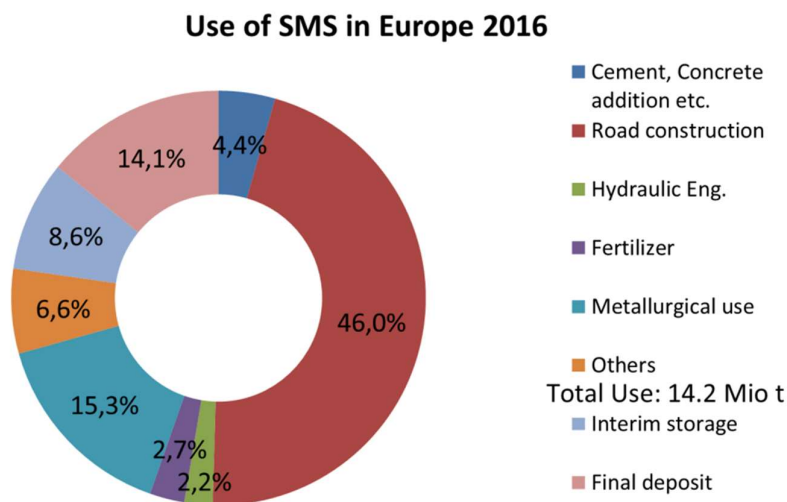


Figure 1.3: The rate of steelmaking slag (SMS) uses in different areas in Europe [EUROSLAG, 2016].

In most countries, steel slag is generally evaluated in road construction and civil engineering. However, the studies investigating the potential of steel slag use in agricultural activities has increased in recent years due to its physicochemical properties and mineral composition [O'Connor et al., 2021].

1.1.4 Beneficial Use of Steel Slag in Agricultural Production

Steel slag can be utilized in agriculture because of its beneficial properties in terms of providing major nutrients, remediating soil, reducing leachate potential of heavy metals, increasing pH in acidic soils, and elevating CO₂ sequestration [O'Connor et al., 2021]. There are limited studies investigating the effects of steel slag application on different plants, focusing mainly on the bioavailability of the elements and metal stabilization in contaminated soils. In a study about the effect of steel slag on rice, it has been revealed that steel slag treatment increased the bioavailability of N, P, Ca, and Si in soil, which results in increased biomass and nutrient content of rice [Wang et al., 2018]. The positive effects observed as a result of steel slag application were reported to be attributed to its function in increasing the bioavailability of some essential elements. Although Si is known as one of the beneficial elements in plant growth, it is an essential element when it comes to rice growth and yield, which could partially explain the positive effects observed in biomass and nutrient content improvements in rice [Pavlovic et al., 2021]. In a study, they found that steel slag application significantly increased P, K, Ca, Mg, Fe, and Si bioavailability in soil, which provided considerable improvement in rice straw and root biomass, nutrient contents, photosynthetic rate, and grain yield in *Japonica* and *Indica* cultivars [Das et al., 2020]. Another research examined the impact of steel slag on maize plant and they revealed that EAF slag significantly increased net photosynthesis, maize growth, and Fe, K, N, Mn, Mg and P uptake, which implied promising role of steel slag as nutrient supplier and soil amendment [Radic et al., 2013]. Metal immobilization property of steel slag is another beneficial effect of the material in terms of alleviating heavy metal-related toxicities in plants. It has been demonstrated that steel slag application notably decreased the uptake of Cd, Cu and Pb by rice plant thanks to the function of steel slag to immobilize some heavy metals through pH regulation [Gu et al., 2011]. In another study investigating impact of steel slag on bioavailability of As, it was found that 0.5% of steel slag significantly reduced As bioavailability in soil by 89%, which

could be achieved through providing competition between As and specific elements, and pH increase [Nejad et al., 2017].

Different studies were also carried out to investigate the effect of steel slag on yield parameters of various plants. It has been showed that steel slag treatment in Cd-contaminated soil increased rice grain yield by 36-45% [He et al., 2017]. A significant decrease in extractable soil Cd was another result of the study that indicated reduced Cd-related toxicity in rice plant. These benefits provided by steel slag amendment were reported to be associated with elevated pH level and extractable Ca and Si content in the soil. In parallel, steel slag amendment improved crop yield by 9.1% in late rice crops, which could be associated with increased bioavailability of some nutrients such as silicates and calcium found in steel slag [Wang et al., 2015]. It has been demonstrated that specific doses of steel slag (0.2% to 1.0%) significantly boosted *Brassica rapa* var. *periviridis* and *Spinacia oleracea* L. growth, which could be resulted from elevated levels of Ca, Mg and Fe uptake [Islam et al., 2022]. In another study, it was concluded that 1% and 2% of converter slag application into tea garden soil and rice field soil elevated the shoot dry yield and P uptake of maize plant over control group [Ali and Shahram, 2007]. They have also explored the potential of steel slag to be used as soil amendment in decreasing greenhouse gas emissions, especially in subtropical paddy fields. In another study investigating the effect of basic slag application on *Phaseolus vulgaris* L. showed that addition of basic slag into Cu-contaminated soil considerably boosted the soil pH, soil electrical conductivity, and plant growth compared to untreated soil [Negim et al., 2010]. It has been demonstrated that application of steel slag had a significant effect in enhancing rice grain yield and percentage of ripened grain, which could be provided by the increased bioavailability of silicate and manganese [Wang et al., 2014]. They have also found that steel slag was a functional material in reducing CH₄ emission originated from paddy fields. The incorporation of sewage sludge stabilized with steel slag was reported to be effective in improving wheat growth in different types of soil through significant increase in available N and P over control [Samara et al., 2017]. The comparison between different particle sizes of slag demonstrated that 100-micron particle size of Linz-Donawitz (LD) slag ensured 50% improvement in the foliage yield of spinach [Mulodia et al., 2024].

1.1.5 Food Safety and Environmental Concerns Regarding Steel Slag Use

Steel slag can contain metal contaminants such as Cd, Cr, arsenic (As), V, and Pb depending on the type of steel production process [Gwon et al., 2018]. The main concern related to evaluation of steel slag in terms of environment is possibility of heavy metal leaching [Teo et al., 2020]. Oxidation states and ratios of elements can affect bioavailability and mobility of heavy metals [Reuter et al., 2004]. The concerns associated with heavy metal leaching are generally associated with Cr, Cd, and V trace elements, differing in their leachability [Chaurand et al., 2007]. Bioavailability and solubility of cationic metals such as Cr, Pb, and Cd are lower in neutral soils than oxyanion trace elements such as V, tin (Sn), and Mo. Chromium is generally found in non-toxic form (Cr^{3+}) and has low solubility in water, which can be oxidized at pH levels greater than 9 into toxic Cr^{+6} species [Zachara et al., 1989; Rakshit et al., 2018]. Vanadium, on the other hand, is mostly present in V^{+3} and V^{+4} forms in BOF slag [Chaurand et al., 2006]. Vanadium has higher release capacity in soil compared to Cr. It has been showed that there is no significant Cr or V uptake by crop although steel slag application elevated Cr and V solubilities in 3-year-old period which exhibits the long-term impact of steel slag on soil [Morillon et al., 2015]. Carbonation of V and other heavy metals, therefore, increases their release rate and leachability in soil.

Steel slag can cause an impact on environment by elevating soil pH due to the high reactivity of Ca and Mg elements. Addition of steel slag into alkaline soil can reduce the bioavailability of trace elements due to further pH levels in soil. As observed in lime-induced problems originated from excessive increase in soil pH, steel slag can also cause some troubles such as iron chlorosis [Bolan et al., 2003]. Moreover, pH level higher than 8.6 limited plant growth due to the fact that Cr^{3+} to Cr^{+6} conversion is induced in high pH environment, causing oxidative stress in plants derived by Cr^{+6} toxicity [Scattolin et al., 2021].

Toxic metal content of steel slag is the most important aspect that the risk assessment studies need to take into consideration. Other factors such as repetition number, application frequency and dose/rate of steel slag are also needed to further assess the long-term effect of the treatment. Different studies reported short-term impact of steel slag that shows no significant risk on soil [Gu et al., 2011; He et al., 2017; Nejad et al., 2017]. The long-term risks related to the application of steel slag includes release

and accumulation of toxic metals in soil which, in turn, has the possibility to involve the food chain [Mehmood et al., 2021]. Entrance of toxic metals into the food chain can severely affect human health [Wang et al., 2021]. It has been reported that the levels of heavy metals upon slag application were below the critical toxicity levels in dry matter of maize [Caetano et al., 2016]. The risk assessment studies of steel slag utilization are therefore required to focus particularly on addressing safety of the material as long-term fertilizer or soil amendment. Since steel industry has growing interest in sustainable valorization of steel slag, more comprehensive data associated with long-term impact and possible consequences of wide scale soil application of steel slag need to be pursued to alleviate environmental concerns as well as food safety issues.

1.2. Wheat

Wheat (*Triticum aestivum*) is a monocot crop extensively consumed by developing countries such as Turkiye, where it constitutes a major part of the daily diet by providing nearly half of the average caloric intake [Curtis, 2002; Cakmak, 2008]. Over the past decades, advancements in agricultural practices, genetic improvement through breeding, and improved crop management have considerably increased global wheat production, even though the total area under cultivation has remained relatively unchanged. This progress is not sufficient to meet the increasing demands driven by the growing population, which necessitates further yield improvements on existing agricultural lands to prevent potential food crises. The additional increases in yield of the cultivated land are therefore required to be able to reduce the concerns related to food security issues.

Wheat cultivation necessitates precise agricultural practices and appropriate management strategies to enhance both yield and quality parameters. Wheat was reported to grow optimally on soil with a pH of 6-7.5, salinity below 4 EC_e dS m⁻¹, and bulk density below 1.3 g cm⁻³ [Gooding and Shewry, 2022]. Soil organic carbon content should be more than 1% to sustain soil productivity. These parameters are essential not only for maximizing yields but also for enhancing grain quality, which has direct implications on human nutrition. As a monocot, wheat utilizes Strategy II for nutrient uptake, which facilitates their transport into roots through the secretion of

phytosiderophores, especially in chelating Fe^{3+} ions. This mechanism is effective in alkaline soils where Fe availability is limited. These adaptive strategies ensure wheat to efficiently take up essential nutrients across different soil types.

Growing demand and necessity for wheat production emphasize the increasing importance of sustainable production techniques which can be achieved by improvement of fertilizer use efficiency or cost-efficient evaluation strategies of the wastes promising for agricultural use [Barlog et al., 2023]. The nutritional and economic importance of wheat and wheat-based products predominantly consumed by developing countries attracts researchers to make investigations into developing more efficient production systems that can ensure sustenance to people worldwide. This aligns with the circular economy principles in agriculture, where industrial by-products such as steel slag may contribute to sustainable soil amendment practices. Therefore, advancing wheat production through sustainable and resource-efficient practices is critical in ensuring long-term global food security and agricultural resilience.

1.3. Lettuce

Lettuce (*Lactuca sativa* L.) is an annual, cool-climate, dicot plant with broad green leaves that can be grown in a wide variety of geographical and climatic conditions, particularly in temperate and subtropical regions. Raw vegetables like lettuce are widely used due to their ready accessibility and ease of consumption. The global popularity of lettuce is largely attributed to its role in human nutrition and health. Lettuce is one of the leafy vegetable crops that is an important source of vitamin A, vitamin C, vitamin K, polyphenols, and fiber as well. These nutritional components contribute to its antioxidant properties and its relevance in promoting digestive health, cardiovascular well-being, and immune function.

Globally, lettuce is a significant crop both in production volume and economic value. China has the largest lettuce production in the world, followed by the US, India, Spain, and Italy [Mou, 2008; FAO, 2024]. Although China alone provides about half of all lettuce production in the world, the majority of this production is utilized for domestic consumption. Spain and US are the two leading exporters of lettuce globally. Before the late 20th century, Western Europe and North America had the highest lettuce

production, which, in turn, changed due to the large-scale cultivation of different varieties of lettuce around the world [Shatilov et al., 2019].

Optimal soil conditions in growing lettuce were reported to have a pH between 6.1-6.6, sufficient N and P levels, and low soil organic matter to avoid disease susceptibility [Hemphill and Jackson, 1982; Costigan, 1986]. Lettuce cultivation requires the implementation of suitable agricultural practices and management strategies. Lettuce is highly responsive to nutrient availability and soil pH, making it sensitive to suboptimal soil conditions, particularly in acidified or degraded soils. As a dicot, lettuce employs Strategy I for nutrient uptake, particularly for Fe. This strategy is characterized by the acidification of rhizosphere through H^+ release, the reduction of Fe^{3+} iron through ferric-chelate reductase enzyme, and the release of phenolic compounds that can increase the solubilization of Fe in soil [Marschner, 2012].

The use of industrial by-products, such as steel slag, should be considered for their potential contribution to sustainable crop production, particularly through their ability to enhance fertilizer use efficiency and neutralize soil environments. Incorporating such waste-derived materials not only helps in environmental waste management but also supports more resilient and cost-effective agricultural models. Thus, exploring the effects of steel slag on lettuce cultivation is critical to developing innovative, sustainable solutions that can enhance crop productivity and food quality while mitigating environmental impacts.

2. PURPOSE OF THE STUDY

In the present study, based on the hypothesis that steel slag may ensure beneficial effects on sustainable crop production, wheat and lettuce grown under greenhouse conditions were subjected to various slag treatments in alkaline and acidic soil types under different fertilization regimes. Greenhouse conditions were provided to ensure a controlled environment to avoid external factors that could negatively impact the observations.

Wheat, as a monocot, and lettuce, as a dicot, were selected to represent two major model crops differing in root morphology and nutrient uptake strategies. Alkaline and acidic soil types were chosen to reveal the behavior of EAF slag across different pH environments. The reason behind two different fertilization regimes was to assess the fertilization requirements of slag-treated soils, which could indicate the fertilizer-use-efficiency of the material.

The crop experiments were conducted to investigate how different particle sizes and doses of EAF slag affects the growth, yield and nutritional status of the crops, and soil properties. The shoot dry biomass was documented to reveal the growth of wheat and yield of lettuce. Grain parameters, e.g. grain number, grain yield, were determined to exhibit the changing yield of wheat in response to various slag amendments. The mineral composition of shoot and grain parts were also investigated to assess the nutritional status of plants with a special emphasis on food safety.

An independent soil experiment was also established to reveal the effect of steel slag on soil pH, EC, and extractable element concentration, which are of critical importance in terms of soil productivity. This experiment addressed the mechanism behind soil behavior in response to EAF slag as a soil amendment. This study also pointed out the environmental concern and food safety issues regarding the use of steel slag.

3. MATERIALS AND METHODS

3.1. General Information on Materials

3.1.1. Plant Materials

In the wheat and lettuce experiments documented here, Nusrat, a Turkish bread wheat cultivar (*Triticum aestivum* cv. Nusrat), and Papyon, a Turkish curly lettuce cultivar (*Lactuca sativa* L. cv. Papyon), were used.

3.1.2. Steel Slag Materials

The steel slag material used in the wheat, lettuce, and soil incubation experiments documented here was provided by the Materials and Testing Innovation Laboratories Company (MATIL). The obtained steel slag was classified as EAF slag. Electric-arc-furnace slag used in our experiments was shown in **Figure 3.1**.



Figure 3.1: Ground (0-2 mm) and non-ground (0-4 mm) EAF slag used in all experiments

3.2. Plant Growth Facility

All experiments documented here were conducted in a Venlo-type greenhouse with geographic coordinates of 40°48'24.3"N 29°21'46.9"E. The greenhouse has an evaporative cooling system and a heating system, which can maintain the temperature between 15-25 °C in the environment.



Figure 3.2: Inside view of the greenhouse where the experiments have been conducted

3.3. Soil Properties

Two different soil types were used in all experiments conducted under controlled glasshouse conditions. Alkaline (pH 7.67 in a 1:5 soil-water extract) and acidic (pH 5.52 in a 1:5 soil-water extract) soils were used. Alkaline soil is loamy soil with low

lime (3.2%) and low organic matter (1.0%) while acidic soil has a clay-loam structure with low lime (2.4%) and sufficient organic matter (3.5%), as shown in **Table 3.1**.

Table 3.1: Characteristics of alkaline and acidic soil types used in all experiments

Soil Characteristics	Alkaline Soil	Acidic Soil
pH (1:5 w/v dH ₂ O)	7.67	5.52
Lime (%)	3.2	2.4
Organic matter (%)	1.0	3.5

3.4. Experiments

3.4.1. Soil Incubation Experiment

In the soil incubation experiment, acidic and alkaline soil types were used under controlled conditions in a greenhouse. There were three pot replicates for each treatment. In the experiment, 42 pots in total [(2 types of soil x 2 different particle sizes of steel slag x 3 different doses of steel slag x 3 replicates) + (3 control pots for acidic soil + 3 control pots for alkaline soil)] have been established. There were six different steel slag treatments applied as described in **Table 3.2**. In control groups, no steel slag application was made. Prior to the first sampling collected at the beginning of the experiment, steel slag was mixed with the soils.

Table 3.2: The abbreviations that indicate two different particle sizes and three different doses of steel slag used in soil incubation experiment

Particle Size	Dose	Abbreviation
Ground (0-2 mm) Steel Slag	0.5% of steel slag (5 g kg ⁻¹ dry weight of soil)	G-0.5%
	1.0% of steel slag (10 g kg ⁻¹ dry weight of soil)	G-1.0%
	2.0% of steel slag (20 g kg ⁻¹ dry weight of soil)	G-2.0%
Non-Ground (0-4 mm) Steel Slag	0.5% of steel slag (5 g kg ⁻¹ dry weight of soil)	NG-0.5%
	1.0% of steel slag (10 g kg ⁻¹ dry weight of soil)	NG-1.0%
	2.0% of steel slag (20 g kg ⁻¹ dry weight of soil)	NG-2.0%

The pots in the soil incubation experiment were irrigated within a certain volume of water according to the water-holding capacity of each soil type. In the soil incubation experiment, soil samples were collected in three times (July, October, and January). At the beginning of the experiment, newly incorporated soil samples were collected (t0). Two other samplings (t1 and t2) were carried out three and six months after the establishment of the experiment, respectively. The soil samples were dried at room temperature and sifted using a 0-2 mm-scale sieve. Dried soil samples were used to determine the physicochemical properties and extractable element concentrations.

3.4.2. Wheat Experiments

In both wheat experiments, 150 ppm N in the form of $\text{Ca}(\text{NO}_3)_2$ and 40 ppm P in the form of KH_2PO_4 were used for 1X-NP fertilization and 300 ppm N in the form of $\text{Ca}(\text{NO}_3)_2$ and 75 ppm P in the form of KH_2PO_4 were used for 2X-NP fertilization. Chemical fertilizers were incorporated into the soils by thorough mixing prior to seed sowing. When the plants were at the pre-anthesis stage in the wheat experiments, additional fertilization was performed at half concentration of the initial fertilization dose.

In the first wheat experiment, bread wheat (*Triticum aestivum* cv. Nusrat) plants were grown on acidic or alkaline soil types under controlled conditions in a greenhouse. Four pot replicates were established, and 13 seeds were sown per pot. The plants were thinned to 8 plants approximately 14 days after sowing (DAS). The experiment was established with a total of 112 pots [(2 different fertilization regimes x 2 types of soil x 2 different particle sizes of steel slag x 3 different doses of steel slag x 4 replicates) + (8 control pots for acidic soil + 8 control pots for alkaline soil)]. There were six different steel slag treatment applied as described in **Table 3.3**. No steel slag was applied to the control groups. Prior to sowing the seeds, steel slag and fertilizers were mixed with the soils.

Table 3.3: The abbreviations that indicate two different particle sizes and three different doses of steel slag used in first wheat experiment

Particle Size	Dose	Abbreviation
Ground (0-2 mm) Steel Slag	0.5% of steel slag (5 g kg ⁻¹ dry weight of soil)	G-0.5%
	1.0% of steel slag (10 g kg ⁻¹ dry weight of soil)	G-1.0%
	2.0% of steel slag (20 g kg ⁻¹ dry weight of soil)	G-2.0%
Non-Ground (0-4 mm) Steel Slag	0.5% of steel slag (5 g kg ⁻¹ dry weight of soil)	NG-0.5%
	1.0% of steel slag (10 g kg ⁻¹ dry weight of soil)	NG-1.0%
	2.0% of steel slag (20 g kg ⁻¹ dry weight of soil)	NG-2.0%

In the second wheat experiment, bread wheat (*Triticum aestivum* cv. Nusrat) plants were grown on acidic or alkaline soil types under controlled conditions in greenhouse. There were four pot replicates, and 13 seeds were sown per pot. The plants were thinned to 8 plants about 14 DAS. A total of 48 pots were used in the experimental setup [(2 different fertilization regimes x 2 types of soil x 2 different particle sizes of steel slag x 4 replicates) + (8 control pots for acidic soil + 8 control pots for alkaline soil)]. Two different steel slag treatments were selected based on a previous wheat experiment (**Table 3.4**). In control groups, no steel slag application was made. Prior to sowing the seeds, steel slag and fertilizers were mixed with the soils.

Table 3.4: The abbreviations that indicate two different particle sizes and the selected dose of steel slag used in second wheat experiment

Particle Size	Dose	Abbreviation
Ground (0-2 mm) Steel Slag	2.0% of steel slag (20 g kg ⁻¹ dry weight of soil)	G-2.0%
Non-Ground (0-4 mm) Steel Slag	2.0% of steel slag (20 g kg ⁻¹ dry weight of soil)	NG-2.0%

In both wheat experiments, plants were harvested at two different times. The first harvest was carried out at pre-anthesis stage, and four plants were collected from each pot. The obtained shoot parts were dried and weighed to measure the dry biomass. The

mineral element concentrations of the harvested shoots were determined as described below. The final harvest was performed at the maturation stage of the plants. The grains and straw of the plants were collected and weighed to determine the yield. The mineral concentration of the grains was determined as described below. In both wheat experiments, among eight plants in each pot, four of them were collected at the pre-anthesis stage and dried at 65 °C to measure dry shoot biomass. Dried shoot samples were then ground for elemental analysis. The spikes of the remaining four plants in each pot were harvested and dried at 50 °C for grain yield determination and element analysis. The grains were obtained from the spikes using laboratory-sized thresher.

3.4.3. Lettuce Experiment

In the lettuce experiment, 100 ppm N in the form of $\text{Ca}(\text{NO}_3)_2$ and 50 ppm P in the form of KH_2PO_4 were used for 1X-NP fertilization and 200 ppm N in the form of $\text{Ca}(\text{NO}_3)_2$ and 100 ppm P in the form of KH_2PO_4 were used for 2X-NP fertilization. The incorporation of chemical fertilizers into the soils were achieved by thorough mixing prior to sowing of the seeds.

In lettuce experiment, curly lettuce (*Lactuca sativa* cv. Papyon) plants were grown on acidic or alkaline soil types under controlled conditions in a greenhouse. There were four pot replicates established. The plants were germinated in cocopeat substrate before being transplanted into the soil. The experiment was conducted by using 112 pots in total [(2 different fertilization regimes x 2 types of soil x 2 different particle sizes of steel slag x 3 different doses of steel slag x 4 replicates) + (8 control pots for acidic soil + 8 control pots for alkaline soil)]. There were six different steel slag treatment applied as described in **Table 3.5**. In control groups, no steel slag application was made. Prior to sowing the seeds, steel slag and fertilizers were mixed with the soils.

Table 3.5: The abbreviations that indicate two different particle sizes and three different doses of steel slag used in lettuce experiment

Particle Size	Dose	Abbreviation
Ground (0-2 mm) Steel Slag	0.5% of steel slag (5 g kg ⁻¹ dry weight of soil)	G-0.5%
	1.0% of steel slag (10 g kg ⁻¹ dry weight of soil)	G-1.0%
	2.0% of steel slag (20 g kg ⁻¹ dry weight of soil)	G-2.0%
Non-Ground (0-4 mm) Steel Slag	0.5% of steel slag (5 g kg ⁻¹ dry weight of soil)	NG-0.5%
	1.0% of steel slag (10 g kg ⁻¹ dry weight of soil)	NG-1.0%
	2.0% of steel slag (20 g kg ⁻¹ dry weight of soil)	NG-2.0%

The plants were harvested two months after transplantation at the heading stage. The obtained harvestable parts of the lettuce were dried and weighed to measure the dry biomass. The mineral element concentration of the harvested parts was determined as described above. In the lettuce experiment, plants were harvested and dried at 70 °C to measure dry biomass. The dried lettuce samples were then ground for elemental analysis.

3.5. Element Analyses

3.5.1. Element Analysis of Steel Slag

Element analysis of the steel slag samples was carried out by modifying the mineral analysis method of Ceylan et al. [Ceylan et al., 2016]. Ground (0-2 mm), non-ground (0-4 mm), and powder (~100µ) steel slag samples were mixed with 8 ml Aqua regia and kept in fume hood for 40 min at room temperature. Steel slag samples were subjected to acid digestion using microwave system (MarsExpress; CEM Corp., Matthews, NC, USA). The vessels containing acid-digested steel slag samples were then cooled down at room temperature and final sample volume was completed to 20 ml using double-deionized water. The digested plant samples were filtered using analytical filter papers (Macherey-Nagel, Ø 110 mm). The concentrations of macro- (P, K, Ca, Mg, and S) and micronutrients (Fe, Zn, Mn, Cu, B, Mo, and Ni), and potentially toxic non-essential elements (Cr, Cd, V, and Pb) in digested steel slag samples were determined by ICP-OES (Agilent ICP-OES 5800, NC, USA).

3.5.2. Element Analysis of Plant Samples

Element analysis of plant samples was carried out using the mineral analysis method described by Ceylan et al. [Ceylan et al., 2016]. Dried wheat shoots and lettuce samples were ground into ground powders using a coffee mill machine (Bosch TSM6A011W; Germany). The wheat grains were not ground. The acid digestion of plant samples was carried out (~0.2 g sample in 2 ml of 30% H₂O₂ and 5 ml of 65% HNO₃) using microwave system (MarsExpress; CEM Corp., Matthews, NC, USA). The vessels containing acid-digested plant samples were cooled to room temperature and the final sample volume was completed to 20 ml using double-deionized water. Digested plant samples were filtered using analytical filter paper (Macherey-Nagel, Ø 110 mm). Concentrations of macro- (P, K, Ca, Mg, and S) and micronutrients (Fe, Zn, Mn, Cu, B, Mo, and Ni), and potentially toxic metals (Cr, Cd, V, and Pb) in digested plant samples were determined by ICP-OES (Agilent ICP-OES 5800, NC, USA). The N concentrations of the shoot and grain samples obtained from the second wheat experiment were determined using the LECO TruSpec C/N Analyzer.

3.5.3. Extractable Element Analysis of Soil Samples

3.5.3.1. Extractable P Determination

Dried soil samples collected from the soil incubation experiment were sieved for Olsen analysis [Olsen et al., 1954]. 5 gr soil sample was dissolved in 50 ml 0.5M NH₄HCO₃ (pH: 8.5) and incubated in shaker for 30 min at 250 rpm. After incubation, samples were filtered using analytical filter paper (Macherey-Nagel, Ø 110 mm). Extractable P concentration of filtered samples was determined by ICP-OES.

3.5.3.2. Extractable K, Ca, Mg and Na Determination

Dried soil samples collected from the soil incubation experiment were sieved for ammonium acetate (NH₄OAc) analysis [Mehlich, 1984]. 5 gr soil sample was dissolved in 50 ml 1N NH₄OAc and incubated in shaker for 30 min at 250 rpm. After incubation, samples were filtered using analytical filter paper (Macherey-Nagel, Ø 110

mm). Extractable K, Ca, Mg, and Na concentration of filtered samples were determined by ICP-OES.

3.5.3.3. Extractable Fe, Zn, Mn, Cu and Ni Determination

Dried soil samples collected from the soil incubation experiment were sieved for diethylenetriaminepentaacetic acid (DTPA) analysis [Lindsay and Norvell, 1978]. 10 gr soil sample was dissolved in 20 ml 0.005M DTPA, 0.01M CaCl₂ and 0.1M triethanolamin mix and incubated in shaker for 2.5 h at 250 rpm. After incubation, samples were filtered using analytical filter paper (Macherey-Nagel, Ø 110 mm). Extractable Fe, Zn, Mn, Cu, and Ni concentration of filtered samples were determined by ICP-OES.

3.5.3.4. Extractable B Determination

Dried soil samples collected from the soil incubation experiment were sieved for hot-water incubation analysis [McGeehan et al., 1989]. 10 gr soil sample was mixed with 20 ml 0.01M CaCl₂ and incubated at 100 °C hot water for 10 min. After hot water extraction, samples were filtered using analytical filter paper (Macherey-Nagel, Ø 110 mm). Extractable B concentration of filtered samples was determined by ICP-OES.

3.6. Chlorophyll Content and Nitrogen Balance Index Measurements

Chlorophyll content and nitrogen balance index (NBI) of wheat leaves were measured non-destructively by a portable sensor (DUALEX SCIENTIFICTM) (FORCE-A, Orsay, France).

3.7. Statistical Analysis

All crop experiments documented here were established using a full factorial design with four replicates in each treatment group. The soil incubation experiment has been established in a full factorial design with 3 replicates in each treatment group. The JMP software (version 17.2) was utilized for all statistical analyses. Significant differences

between mean values were determined using Tukey's honestly significant difference (HSD) test at a 5% significance level.

4. RESULTS

4.1. Characterization of Steel Slag Material for the Dose Determination in Crop and Soil Experiments

Two different particle sizes of steel slag (0-2 and 0-4 mm) were determined to establish the experiments described below. The extractable element concentrations and physicochemical properties of steel slag used in our studies were shown in **Table 4.1**. Both ground and non-ground slags were observed to have similar pH levels, showing their highly-alkaline nature. Ground slag was showed to have higher EC value compared to non-ground slag. The extractable mineral concentration of ground slag had higher values in general. In contrast, the extractable Fe, B, Cu, and Zn concentrations were higher in non-ground slags.

Table 4.1: Extractable element concentrations and physicochemical properties of ground (0-2 mm) and non-ground (0-4 mm) EAF slag used in all experiments

Slag Properties	Ground Slag (0-2 mm)	Non-Ground Slag (0-4 mm)
pH (1:5 w/v dH ₂ O)	9.89	9.83
EC ($\mu\text{S cm}^{-1}$)	803	365
Extractable P (mg kg^{-1})	17.2	9.6
Extractable Ca (g kg^{-1})	3.2	1.3
Extractable K (mg kg^{-1})	103	45
Extractable Mg (mg kg^{-1})	72	31
Extractable Na (g kg^{-1})	1.3	0.7
Extractable Fe (mg kg^{-1})	46.1	95.3
Extractable Zn (mg kg^{-1})	16.1	21.7
Extractable Mn (mg kg^{-1})	49.4	40.6
Extractable Cu (mg kg^{-1})	2.5	3.0
Extractable B (mg kg^{-1})	1.9	3.1

The mineral composition of the steel slag used in our study was also determined as shown in **Table 4.2**. Total element analysis was performed to reveal the mineral composition of EAF slag used in our study. It has been showed that EAF slag contains the majority of essential macro- and micronutrients. The total element concentrations were higher than the extractable element concentrations in general.

Table 4.2: Total element concentrations of ground (0-2 mm) and non-ground (0-4 mm) EAF slag used in all experiments

Macroelement Concentrations (g kg⁻¹)					
Particle Size	P	K	Ca	Mg	S
Ground	1.5	0.8	185	10.0	1.6
Non-Ground	1.6	0.8	184	9.5	1.7

Microelement Concentrations (mg kg⁻¹)							
Particle Size	Fe	Zn	Mn	Cu	B	Mo	Ni
Ground	247	832	30	448	78	26	71
Non-Ground	289	713	28	635	99	47	156

Potentially Toxic Non-Essential Element Concentrations (mg kg⁻¹)				
Particle Size	Cr	Cd	V	Pb
Ground	2140	3.5	472	35
Non-Ground	2362	2.7	469	23

4.2. The Effect of Different Slag Doses on the Extractable Mineral Composition and Physicochemical Properties of Soil over a Six-Month Period

The effect of steel slag amendment on soil pH was investigated in the incubation experiment (Table 4.3). Three different soil samples were collected at t0 and at

subsequent intervals over a six-month period. According to results, all slag amendments further elevated the alkaline soil pH in all sampling times. In July, at t0 sampling time, the highest dose of ground slag and the lowest dose of non-ground slag application into alkaline soil achieved remarkable increase compared to control, reaching at 8.2. At t1 sampling time, the same treatment groups ensured significant increase in pH of alkaline soil over control. The pH of soil samples collected at t2 sampling time significantly improved in response to slag treatment, regardless of the slag particle size and dose. In acidic soil, on the other hand, steel slag amendment did not affect the soil pH significantly at t0 sampling time. However, it considerably boosted the soil pH in the samples collected at t1 sampling time over control, reaching at 6.12 from 5.12 in the highest dose of ground slag treatment group. The medium and the highest dose of ground slag amendment notably elevated the pH of acidic soil samples collected at t2 sampling time.

The effect of steel slag application on soil electrical conductivity (EC) was also investigated in the incubation experiment (**Table 4.4**). No significant change was reported in soil EC in response to steel slag application in alkaline soil samples collected at t0 and t1 sampling times. At t2 sampling time, however, significant improvement in the pH of F-1.0% slag-treated alkaline soil was reported, resulting in a 26% increase over control. All slag applications into acidic soil elevated the soil pH in the samples collected at t0 over control. At t2 sampling time in January, the medium dose of non-ground slag significantly reduced the soil EC by 46% compared to control whereas there was no significant change observed upon slag amendment at t1.

Table 4.3: Changes in pH of subsequently collected alkaline and acidic soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	pH (1:5 w/v dH ₂ O)								
	Alkaline Soil					Acidic Soil			
	t0	t1	t2	t0	t1	t2	t0	t1	t2
Control	7.84 ± 0.10 c	8.12 ± 0.31 b	7.34 ± 0.17 c	5.52 ± 0.26 ab	5.12 ± 0.06 d	5.40 ± 0.29 b			
G-0.5%	7.96 ± 0.05 bc	8.53 ± 0.02 a	7.81 ± 0.04 b	5.32 ± 0.01 ab	5.40 ± 0.07 c	5.37 ± 0.02 b			
G-1.0%	8.12 ± 0.04 ab	8.40 ± 0.07 ab	7.80 ± 0.03 b	5.35 ± 0.07 ab	5.79 ± 0.04 b	5.88 ± 0.07 a			
G-2.0%	8.23 ± 0.03 a	8.66 ± 0.04 a	8.15 ± 0.03 a	5.60 ± 0.11 a	6.12 ± 0.11 a	6.23 ± 0.03 a			
NG-0.5%	8.20 ± 0.01 a	8.50 ± 0.05 a	7.98 ± 0.05 ab	5.22 ± 0.04 b	5.51 ± 0.13 c	5.42 ± 0.16 b			
NG-1.0%	8.07 ± 0.11 ab	8.42 ± 0.02 ab	8.05 ± 0.06 a	5.20 ± 0.07 b	5.33 ± 0.09 cd	5.42 ± 0.09 b			
NG-2.0%	8.09 ± 0.01 ab	8.44 ± 0.06 ab	8.16 ± 0.03 a	5.35 ± 0.06 ab	5.51 ± 0.04 c	5.44 ± 0.04 b			

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.4: Changes in electrical conductivity (EC) of subsequently collected alkaline and acidic soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	EC ($\mu\text{S cm}^{-1}$ 1:5 w/v dH ₂ O)											
	Alkaline Soil						Acidic Soil					
	t0		t1		t2		t0		t1		t2	
Control	256 ± 27	a	215 ± 57	ab	178 ± 30	b	117 ± 38	c	177 ± 5	ab	198 ± 37	ab
G-0.5%	240 ± 12	ab	143 ± 24	b	153 ± 7	b	130 ± 6	b	176 ± 45	ab	179 ± 23	a-c
G-1.0%	250 ± 14	ab	261 ± 50	a	225 ± 15	a	122 ± 6	bc	126 ± 11	b	140 ± 26	bc
G-2.0%	252 ± 13	a	172 ± 7	ab	188 ± 12	ab	152 ± 12	a	167 ± 19	ab	201 ± 26	ab
NG-0.5%	213 ± 7	b	174 ± 22	ab	176 ± 7	b	123 ± 4	b	150 ± 5	ab	130 ± 36	bc
NG-1.0%	238 ± 14	ab	197 ± 8	ab	178 ± 4	b	120 ± 4	bc	199 ± 13	a	107 ± 12	c
NG-2.0%	244 ± 16	ab	217 ± 18	ab	180 ± 5	b	129 ± 4	b	186 ± 15	a	230 ± 20	a

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Soil macronutrient bioavailability was investigated in response to steel slag amendment in the soil incubation experiment (**Table 4.5; 4.6; 4.7; 4.8**). According to results, extractable P concentration of alkaline soil was non-responsive to slag application in July (t0) and October (t1) whereas the lowest and the highest dose of ground slag amendment elevated the extractable P level significantly in the alkaline soil samples collected at t2 sampling time (**Table 4.5**). Among others, the highest dose of ground slag amendment was the most effective one, achieving 77% increase in the same parameter over control. P availability of acidic soil samples was considerably affected by slag application, irrespective of the particle size and dose (**Table 4.6**). The highest dose of ground and non-ground slag amendment ensured over 69% increase in extractable P level in acidic soil samples collected at t0 in July. At subsequent sampling times in October and January, however, no significant alteration was reported in response to slag treatment. The soil K availability tended to decrease upon slag application in alkaline conditions in all sampling times (**Table 4.5**). The highest decrease in extractable K concentration was observed in the soil treated with the highest dose of non-ground slag, causing 62% decrease over control at t0. At other sampling times, K availability generally did not respond to steel slag amendment in alkaline soil. There was no significant difference between control and slag treatment groups in acidic soil in terms of extractable K level (**Table 4.6**).

The soil extractable Ca concentration reduced in all slag-treated alkaline soil samples (**Table 4.7**). The highest dose of ground and non-ground slag application into alkaline soil resulted in 33% and 69% decrease in the Ca availability over control in July (t0), respectively. Ground slag amendment at highest dose also decreased the extractable Ca concentration in alkaline soil by up to 33% compared to control at the final sampling. In acidic soil, however, Ca bioavailability generally tended to improve upon slag application in all sampling times (**Table 4.8**). Ground slag amendment at highest dose, for instance, enhanced the extractable Ca level in acidic soil by 26%, 48%, and 26% over control at the consecutive sampling times, respectively. Non-ground slag treatments in alkaline soil significantly reduced the Mg availability at t0 sampling time whereas no notable change was reported in the samples collected in October and January (**Table 4.7**). Slag had no impact on extractable Mg concentration in acidic soil (**Table 4.8**).

Table 4.5: Changes in extractable P and K concentrations of subsequently collected alkaline soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable P and K Concentrations (mg kg ⁻¹)											
	P						K					
	t0		t1		t2		t0		t1		t2	
Control	5.6 ± 0.6	a	6.1 ± 0.8	a	3.9 ± 0.6	c	127 ± 3	a	82 ± 7	a	143 ± 4	a
G-0.5%	5.9 ± 1.3	a	8.2 ± 1.2	a	6.3 ± 1.0	ab	109 ± 2	a-c	72 ± 2	ab	125 ± 5	a
G-1.0%	5.2 ± 1.4	a	6.5 ± 1.8	a	5.0 ± 0.6	a-c	120 ± 10	ab	75 ± 7	ab	143 ± 5	a
G-2.0%	6.4 ± 0.4	a	7.5 ± 0.7	a	6.9 ± 0.3	a	87 ± 8	c	62 ± 3	ab	99 ± 20	b
NG-0.5%	5.1 ± 1.2	a	6.0 ± 0.9	a	4.1 ± 0.8	bc	94 ± 3	bc	56 ± 11	b	120 ± 4	ab
NG-1.0%	4.9 ± 0.9	a	7.0 ± 0.8	a	5.3 ± 1.4	a-c	88 ± 22	c	68 ± 3	ab	122 ± 4	a
NG-2.0%	5.1 ± 2.0	a	6.1 ± 0.8	a	5.0 ± 0.5	a-c	48 ± 1	d	61 ± 12	b	120 ± 4	ab

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.6: Changes in extractable P and K concentrations of subsequently collected acidic soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable P and K Concentrations (mg kg ⁻¹)											
	P						K					
	t0		t1		t2		t0		t1		t2	
Control	5.9±0.2	c	7.8±0.8	a	7.0±0.2	a	310±22	a	219±4	a	329±5	a
G-0.5%	6.9±2.9	bc	7.6±2.3	a	5.6±1.8	a	308±17	a	219±1	a	313±17	a
G-1.0%	9.5±0.2	ab	6.6±0.1	a	4.8±0.7	a	328±6	a	215±1	ab	272±8	a
G-2.0%	10.0±0.2	a	7.6±0.3	a	4.9±1.5	a	317±2	a	206±1	c	250±45	a
NG-0.5%	9.8±0.0	ab	6.9±0.7	a	5.0±0.2	a	313±4	a	219±4	a	261±62	a
NG-1.0%	9.5±0.2	ab	6.9±0.6	a	4.5±1.5	a	306±11	a	215±1	ab	266±47	a
NG-2.0%	10.1±0.2	a	8.5±0.1	a	4.5±0.2	a	301±9	a	210±2	bc	320±3	a

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.7: Changes in extractable Ca and Mg concentrations of subsequently collected alkaline soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable Ca and Mg Concentrations (mg kg ⁻¹)											
	Ca						Mg					
	t0		t1		t2		t0		t1		t2	
Control	4542 ± 122	a	5913 ± 455	a	5875 ± 580	a	184 ± 6	a	190 ± 14	a	205 ± 6	a
G-0.5%	3881 ± 111	ab	4884 ± 354	a	5223 ± 334	ab	166 ± 4	ab	176 ± 7	a	193 ± 9	a
G-1.0%	4093 ± 348	ab	5739 ± 853	a	5957 ± 397	a	168 ± 13	ab	179 ± 17	a	204 ± 5	a
G-2.0%	3024 ± 219	c	4635 ± 378	a	3935 ± 967	b	133 ± 11	b	158 ± 9	a	145 ± 32	b
NG-0.5%	3303 ± 137	bc	3877 ± 1340	a	4834 ± 197	ab	141 ± 5	b	146 ± 30	a	182 ± 5	ab
NG-1.0%	2608 ± 638	c	4579 ± 378	a	4891 ± 404	ab	129 ± 33	b	171 ± 7	a	187 ± 8	a
NG-2.0%	1398 ± 42	d	4226 ± 1201	a	5133 ± 127	ab	68 ± 2	c	154 ± 30	a	182 ± 5	ab

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.8: Changes in extractable Ca and Mg concentrations of subsequently collected acidic soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable Ca and Mg Concentrations (mg kg ⁻¹)											
	Ca						Mg					
	t0		t1		t2		t0		t1		t2	
Control	1728 ± 134	c	2254 ± 51	f	2228 ± 35	ab	286 ± 22	a	335 ± 6	a	351 ± 7	a
G-0.5%	1780 ± 114	bc	2638 ± 1	cd	2521 ± 130	ab	283 ± 16	a	344 ± 2	a	344 ± 20	a
G-1.0%	2008 ± 1	ab	2969 ± 32	b	2560 ± 109	ab	304 ± 5	a	346 ± 2	a	310 ± 13	a
G-2.0%	2185 ± 123	a	3330 ± 147	a	2802 ± 563	a	303 ± 4	a	336 ± 5	a	285 ± 54	a
NG-0.5%	1746 ± 4	c	2375 ± 52	ef	1893 ± 474	b	292 ± 1	a	338 ± 6	a	280 ± 68	a
NG-1.0%	1751 ± 62	c	2468 ± 41	de	2037 ± 370	ab	286 ± 9	a	338 ± 3	a	286 ± 50	a
NG-2.0%	1822 ± 45	bc	2701 ± 50	c	2815 ± 47	a	284 ± 8	a	342 ± 4	a	358 ± 7	a

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Ground slag amendment at highest dose drastically improved the Fe availability by 101%, 94%, and 78% over control in alkaline soil in all consecutive sampling times, respectively (**Table 4.9**). The extractable Fe level in acidic soil also tended to improve in response to slag application generally (**Table 4.10**). The highest dose of ground slag amendment significantly enhanced the Fe bioavailability by up to 36% compared to control in acidic soil collected at t0 sampling time. The extractable Zn concentration in alkaline soil was also responsive to steel slag amendment (**Table 4.9**). Ground slag amendment at highest dose had remarkable impact on Zn availability in all consecutive sampling times, achieving 88%, 121%, and 124% increases over control, respectively. Additionally, the highest dose of non-ground slag treatments was also effective in improving the Zn availability in alkaline soil significantly. In acidic soil, on the other hand, slag amendment notably boosted the extractable Zn level at t0 sampling time, irrespective of the slag particle size and dose (**Table 4.10**). In other sampling times, a general increase was also reported in response to ground slag application in acidic soil.

The availability of Cu was considerably affected by non-ground slag amendments in alkaline soil at all sampling times (**Table 4.11**). The lowest dose of non-ground slag treatment in alkaline soil, for instance, achieved 55% increase in extractable Cu level over control at t1 sampling time in October. Steel slag application slightly enhanced the bioavailability of Cu in acidic soil, regardless of the slag particle size and dose (**Table 4.12**). The soil B bioavailability in alkaline soil tended to enhance as a result of steel slag amendment generally (**Table 4.11**). The highest dose of ground slag amendments significantly elevated the extractable B concentration by 38%, 112%, and 109% compared to control at consecutive sampling times, respectively. The beneficial effect of steel slag on soil B availability was manifested more clearly in acidic soil (**Table 4.12**). At t0 sampling time in July, ground and non-ground slag amendment at highest dose attained 111% and 88% increases over control in acidic soil, respectively. Furthermore, increasing doses of ground and non-ground slag application gradually improved the acidic soil B availability at other sampling times as well. The highest dose of ground slag treatments in October and January (t1 and t2), for instance, ensured 329% and 282% increases when compared to control, respectively.

Table 4.9: Changes in extractable Fe and Zn concentrations of subsequently collected alkaline soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable Fe and Zn Concentrations (mg kg ⁻¹)											
	Fe						Zn					
	t0		t1		t2		t0		t1		t2	
Control	10.7±1.3	a	10.0±0.3	b	9.8±0.4	b	1.7±0.2	a	1.4±0.1	c	1.7±0.1	d
G-0.5%	17.3±2.8	a	13.7±1.5	b	11.7±0.6	b	2.8±0.8	a	2.4±0.2	ab	2.8±0.6	b
G-1.0%	19.6±8.2	a	13.0±2.6	b	12.4±0.2	b	3.2±1.6	a	2.3±0.4	ab	2.8±0.2	b
G-2.0%	21.5±4.6	a	19.4±0.9	a	17.4±0.6	a	3.2±0.9	a	3.1±0.2	a	3.8±0.2	a
NG-0.5%	13.4±0.8	a	11.8±0.4	b	9.5±0.3	b	2.0±0.3	a	1.9±0.1	bc	1.9±0.1	cd
NG-1.0%	16.1±1.8	a	11.5±0.9	b	10.9±0.9	b	2.6±0.3	a	2.1±0.3	bc	2.3±0.2	b-d
NG-2.0%	18.2±1.5	a	12.7±2.1	b	12.1±2.4	b	3.6±1.0	a	2.6±0.5	ab	2.6±0.3	bc

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.10: Changes in extractable Fe and Zn concentrations of subsequently collected acidic soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable Fe and Zn Concentrations (mg kg ⁻¹)											
	Fe						Zn					
	t0		t1		t2		t0		t1		t2	
Control	58.3 ± 0.5	c	64.5 ± 1.2	b	52.8 ± 1.0	ab	3.0 ± 0.0	d	3.0 ± 0.0	d	2.6 ± 0.0	bc
G-0.5%	68.0 ± 4.1	a-c	72.6 ± 4.4	a	54.4 ± 0.9	ab	3.8 ± 0.2	c	3.1 ± 0.1	b-d	2.7 ± 0.1	bc
G-1.0%	75.7 ± 1.4	ab	71.7 ± 5.0	ab	55.7 ± 2.9	a	4.7 ± 0.1	ab	3.2 ± 0.2	b-d	2.9 ± 0.2	b
G-2.0%	79.0 ± 5.2	a	70.9 ± 2.7	ab	48.5 ± 3.9	b	5.3 ± 0.3	a	3.7 ± 0.2	a	3.2 ± 0.1	a
NG-0.5%	63.0 ± 1.9	bc	69.7 ± 1.4	ab	55.3 ± 1.7	a	3.5 ± 0.0	cd	3.1 ± 0.0	cd	2.5 ± 0.1	c
NG-1.0%	70.8 ± 9.9	a-c	73.0 ± 0.4	a	55.6 ± 1.3	a	4.1 ± 0.2	bc	3.4 ± 0.0	a-c	2.6 ± 0.0	bc
NG-2.0%	70.4 ± 1.2	a-c	72.4 ± 1.5	a	54.3 ± 3.2	ab	4.5 ± 0.4	b	3.5 ± 0.0	ab	2.9 ± 0.2	b

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.11: Changes in extractable Cu and B concentrations of subsequently collected alkaline soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable Cu and B Concentrations (mg kg ⁻¹)											
	Cu						B					
	t0		t1		t2		t0		t1		t2	
Control	5.8 ± 1.0	a	4.7 ± 0.1	b	5.0 ± 0.3	b	0.21 ± 0.02	b-d	0.42 ± 0.01	d	0.33 ± 0.01	d
G-0.5%	7.1 ± 0.7	a	6.7 ± 0.8	a	6.5 ± 0.3	a	0.24 ± 0.02	a-c	0.58 ± 0.02	bc	0.43 ± 0.01	bc
G-1.0%	5.2 ± 2.1	a	4.4 ± 0.9	b	5.1 ± 0.1	b	0.26 ± 0.03	ab	0.64 ± 0.05	b	0.49 ± 0.05	b
G-2.0%	5.1 ± 0.8	a	5.9 ± 0.4	ab	7.0 ± 0.1	a	0.29 ± 0.02	a	0.89 ± 0.02	a	0.69 ± 0.01	a
NG-0.5%	7.4 ± 1.1	a	7.3 ± 0.5	a	6.9 ± 0.3	a	0.18 ± 0.02	d	0.49 ± 0.02	cd	0.38 ± 0.02	cd
NG-1.0%	7.8 ± 0.4	a	6.3 ± 0.3	a	6.7 ± 0.1	a	0.24 ± 0.02	a-d	0.57 ± 0.01	bc	0.46 ± 0.01	b
NG-2.0%	7.5 ± 0.3	a	6.8 ± 0.6	a	7.0 ± 0.1	a	0.19 ± 0.02	cd	0.56 ± 0.07	bc	0.48 ± 0.02	b

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.12: Changes in extractable Cu and B concentrations of subsequently collected acidic soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable Cu and B Concentrations (mg kg ⁻¹)											
	Cu						B					
	t0		t1		t2		t0		t1		t2	
Control	1.0±0.0	c	1.0±0.0	c	0.9±0.0	d	0.09±0.00	c	0.17±0.01	e	0.17±0.01	d
G-0.5%	1.1±0.0	bc	1.2±0.0	bc	1.1±0.0	c	0.12±0.01	bc	0.33±0.02	c	0.28±0.04	c
G-1.0%	1.2±0.0	ab	1.2±0.1	b	1.2±0.0	b	0.17±0.01	ab	0.47±0.04	b	0.42±0.03	b
G-2.0%	1.2±0.0	a	1.4±0.1	a	1.3±0.0	a	0.19±0.02	a	0.73±0.04	a	0.65±0.07	a
NG-0.5%	1.0±0.0	c	1.0±0.0	c	0.9±0.0	d	0.12±0.01	bc	0.22±0.01	de	0.17±0.02	d
NG-1.0%	1.1±0.1	a-c	1.1±0.0	bc	1.0±0.0	cd	0.12±0.01	bc	0.30±0.03	cd	0.26±0.03	cd
NG-2.0%	1.1±0.1	bc	1.2±0.0	bc	1.0±0.0	c	0.17±0.04	ab	0.43±0.04	b	0.30±0.04	c

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

The extractable Ni concentration in alkaline soil tended to reduce in response to steel slag application in general (**Table 4.13**). The highest dose of ground slag amendment, for instance, caused 44% decrease over control in alkaline soil samples collected at t0 sampling time. In acidic soil, on the other hand, Ni bioavailability was generally non-responsive to steel slag application (**Table 4.14**). The highest dose of ground slag treatments in acidic soil, however, reduced the extractable Ni concentration by 30% and 36% compared to control at t1 and t2 sampling times, respectively. No considerable alteration was observed in extractable Na level upon ground slag amendment in alkaline soil (**Table 4.13**). Increasing non-ground slag doses, however, significantly reduced the extractable Na level in alkaline soil by 25%, 31%, and 58% over control at t0 sampling time, respectively. In acidic soil, on the other hand, the availability of Na was significantly affected by almost all slag applications (**Table 4.14**). The highest dose of non-ground slag amendments considerably improved the acidic soil Na availability, reaching at 65%, 57%, and 48% increase over control at all consecutive sampling times, respectively.

The bioavailability of Cd was totally non-responsive to steel slag treatment, regardless of the soil type (**Table 4.15; 4.16**). Ground slag application at highest dose in July (t0) and October (t1) ensured notable decrease in extractable Pb level by 33% and 20% compared to control in alkaline soil (**Table 4.15**). Steel slag amendment was also effective in reducing the available Pb level in acidic soil, achieving 19% and 14% decrease over control in October (t1) and January (t2), respectively (**Table 4.16**).

Table 4.13: Changes in extractable Ni and Na concentrations of subsequently collected alkaline soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable Ni and Na Concentrations (mg kg ⁻¹)											
	Ni						Na					
	t0		t1		t2		t0		t1		t2	
Control	0.41 ± 0.03	a	0.29 ± 0.01	a	0.25 ± 0.01	a	118 ± 3	a	141 ± 8	a	138 ± 12	a
G-0.5%	0.30 ± 0.02	ab	0.24 ± 0.03	ab	0.19 ± 0.01	b	112 ± 3	ab	134 ± 4	a	136 ± 2	a
G-1.0%	0.36 ± 0.11	ab	0.27 ± 0.04	ab	0.25 ± 0.01	a	123 ± 7	a	153 ± 17	a	152 ± 8	a
G-2.0%	0.23 ± 0.05	b	0.21 ± 0.01	b	0.20 ± 0.00	b	109 ± 8	ab	150 ± 7	a	120 ± 28	a
NG-0.5%	0.29 ± 0.04	ab	0.24 ± 0.01	ab	0.18 ± 0.00	b	88 ± 2	bc	119 ± 30	a	128 ± 4	a
NG-1.0%	0.32 ± 0.01	ab	0.22 ± 0.01	b	0.20 ± 0.01	b	82 ± 20	c	132 ± 5	a	133 ± 2	a
NG-2.0%	0.30 ± 0.01	ab	0.23 ± 0.02	ab	0.19 ± 0.01	b	50 ± 3	d	136 ± 31	a	146 ± 3	a

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.14: Changes in extractable Ni and Na concentrations of subsequently collected acidic soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable Ni and Na Concentrations (mg kg ⁻¹)											
	Ni						Na					
	t0		t1		t2		t0		t1		t2	
Control	0.25 ± 0.01	a	0.30 ± 0.00	ab	0.25 ± 0.00	a	85 ± 7	c	139 ± 3	e	130 ± 5	b
G-0.5%	0.26 ± 0.01	a	0.28 ± 0.02	b	0.22 ± 0.00	b	94 ± 7	c	164 ± 3	d	136 ± 6	b
G-1.0%	0.27 ± 0.01	a	0.23 ± 0.02	c	0.19 ± 0.01	c	106 ± 0	bc	170 ± 6	d	128 ± 4	b
G-2.0%	0.25 ± 0.01	a	0.21 ± 0.01	c	0.16 ± 0.01	c	120 ± 15	ab	181 ± 2	c	138 ± 36	ab
NG-0.5%	0.25 ± 0.00	a	0.31 ± 0.01	a	0.25 ± 0.01	a	132 ± 9	a	183 ± 2	c	138 ± 29	ab
NG-1.0%	0.27 ± 0.02	a	0.31 ± 0.01	a	0.24 ± 0.01	a	133 ± 4	a	203 ± 2	b	145 ± 25	ab
NG-2.0%	0.26 ± 0.00	a	0.29 ± 0.00	ab	0.22 ± 0.01	b	140 ± 5	a	218 ± 6	a	193 ± 4	a

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test (p≤0.05).

Table 4.15: Changes in extractable Cd and Pb concentrations of subsequently collected alkaline soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable Cd and Pb Concentrations (mg kg ⁻¹)					
	Cd			Pb		
	t0	t1	t2	t0	t1	t2
Control	0.016 ± 0.001 a	0.014 ± 0.000 a	0.017 ± 0.001 ab	1.22 ± 0.08 a	1.34 ± 0.03 a	1.46 ± 0.05 a
G-0.5%	0.014 ± 0.001 a	0.014 ± 0.002 a	0.016 ± 0.001 bc	1.05 ± 0.03 ab	1.28 ± 0.15 a	1.33 ± 0.07 bc
G-1.0%	0.015 ± 0.005 a	0.014 ± 0.003 a	0.018 ± 0.001 a	1.08 ± 0.31 ab	1.19 ± 0.16 a	1.44 ± 0.02 ab
G-2.0%	0.012 ± 0.003 a	0.013 ± 0.001 a	0.018 ± 0.001 ab	0.82 ± 0.16 b	1.07 ± 0.07 a	1.30 ± 0.05 c
NG-0.5%	0.013 ± 0.002 a	0.014 ± 0.001 a	0.015 ± 0.000 c	1.02 ± 0.13 ab	1.31 ± 0.05 a	1.27 ± 0.02 c
NG-1.0%	0.015 ± 0.000 a	0.014 ± 0.001 a	0.016 ± 0.001 bc	1.14 ± 0.02 ab	1.21 ± 0.04 a	1.33 ± 0.03 bc
NG-2.0%	0.015 ± 0.001 a	0.014 ± 0.002 a	0.016 ± 0.000 bc	1.10 ± 0.06 ab	1.20 ± 0.09 a	1.28 ± 0.02 c

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.16: Changes in extractable Cd and Pb concentrations of subsequently collected acidic soil samples treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses throughout six months

Slag Treatment	Extractable Cd and Pb Concentrations (mg kg ⁻¹)					
	Cd			Pb		
	t0	t1	t2	t0	t1	t2
Control	0.031 ± 0.000 a	0.033 ± 0.001 a	0.028 ± 0.000 a	0.78 ± 0.00 a	0.84 ± 0.02 a	0.64 ± 0.01 a
G-0.5%	0.032 ± 0.001 a	0.032 ± 0.002 a	0.027 ± 0.001 ab	0.79 ± 0.03 a	0.81 ± 0.04 ab	0.63 ± 0.01 a
G-1.0%	0.033 ± 0.000 a	0.031 ± 0.002 a	0.028 ± 0.001 ab	0.84 ± 0.01 a	0.74 ± 0.05 bc	0.62 ± 0.02 ab
G-2.0%	0.032 ± 0.002 a	0.031 ± 0.002 a	0.027 ± 0.001 ab	0.81 ± 0.03 a	0.68 ± 0.03 c	0.55 ± 0.03 b
NG-0.5%	0.030 ± 0.002 a	0.033 ± 0.000 a	0.026 ± 0.001 ab	0.78 ± 0.02 a	0.83 ± 0.01 a	0.65 ± 0.04 a
NG-1.0%	0.031 ± 0.001 a	0.033 ± 0.001 a	0.025 ± 0.000 b	0.80 ± 0.02 a	0.83 ± 0.00 ab	0.64 ± 0.01 a
NG-2.0%	0.031 ± 0.001 a	0.031 ± 0.001 a	0.026 ± 0.001 ab	0.79 ± 0.04 a	0.79 ± 0.02 ab	0.62 ± 0.04 ab

Values are means and standard deviations of three independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

4.3. The Effect of Different Slag Doses on the Growth, Yield, and Mineral Composition of Wheat

The wheat elongation from the first experiment showed that steel slag amendment did not have significant effect on the general appearance of the plants in alkaline soil (**Figure 4.1**). In acidic soil, on the other hand, the considerable improvement was observed upon ground slag amendment under either type of fertilization (**Figure 4.2**).

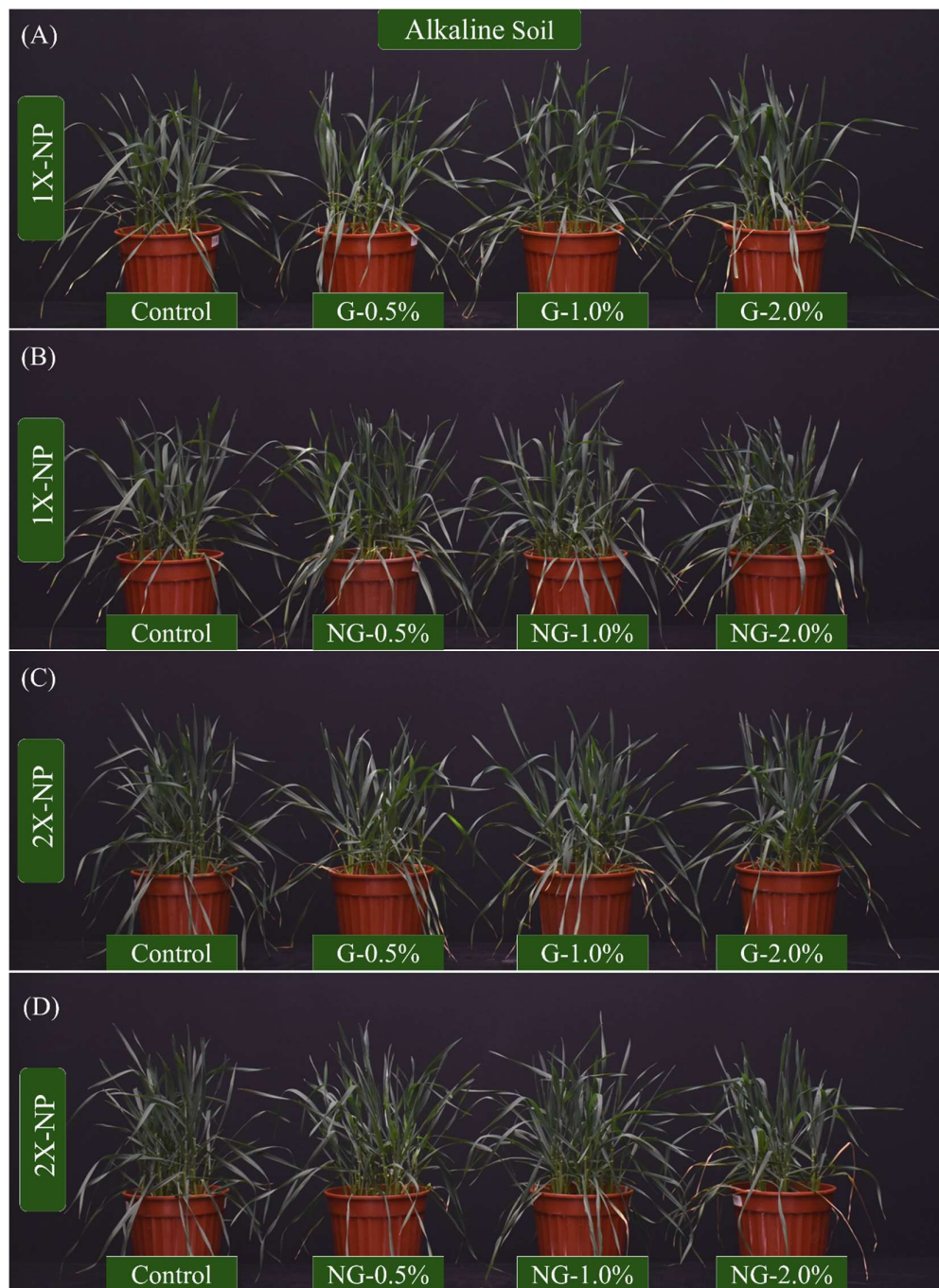


Figure 4.1: General appearance of 39 day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (G; 0-2 mm) or non-ground (NG; 0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP (A-B) or 2X-NP (C-D) fertilization regimes

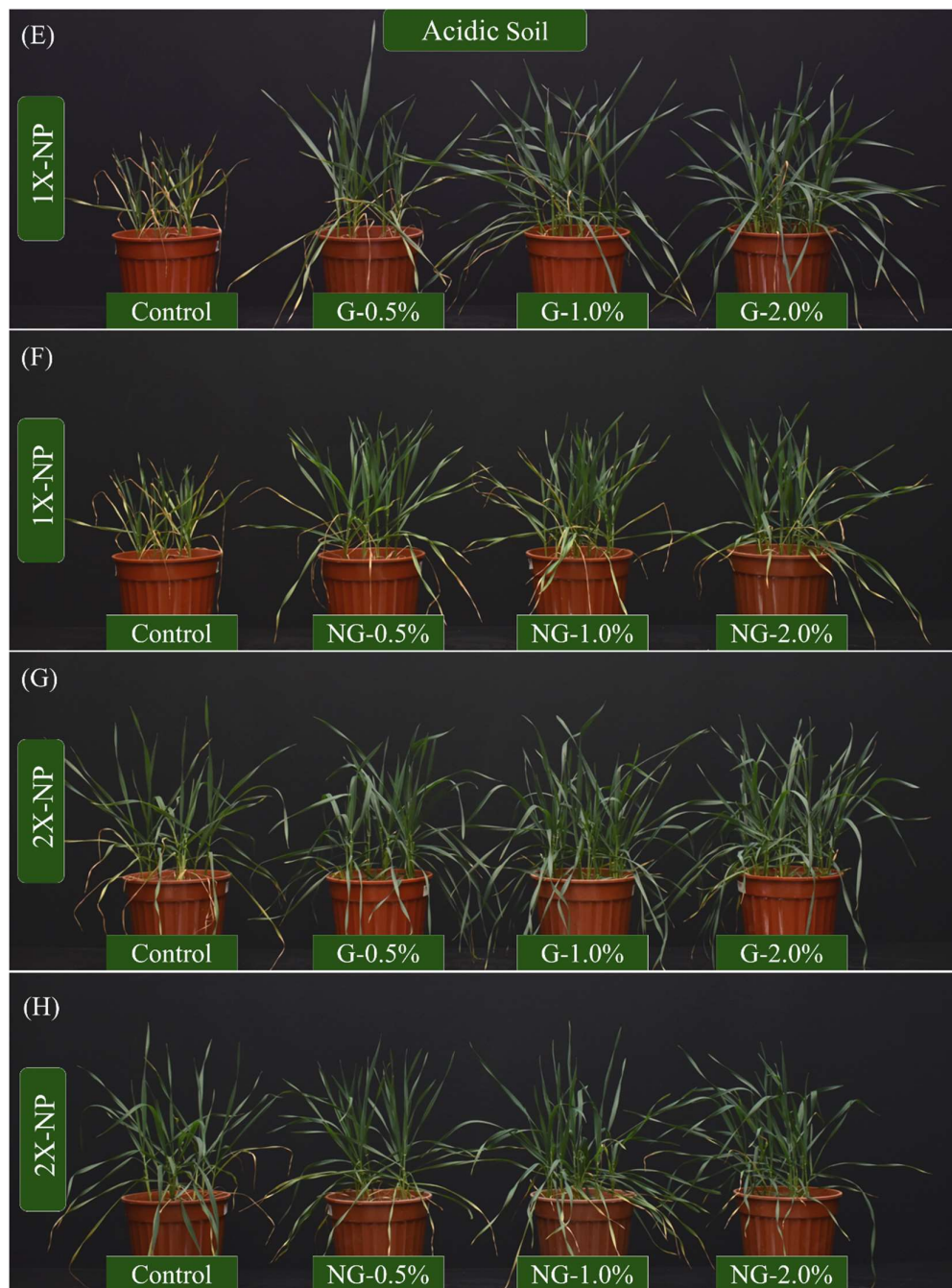


Figure 4.2: General appearance of 39 day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (G; 0-2 mm) or non-ground (NG; 0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP (E-F) or 2X-NP (G-H) fertilization regimes

A similar pattern was observed in the chlorophyll content data. While there was no notable impact in chlorophyll content and NBI values in alkaline soil, increasing ground slag treatments in acidic soil significantly improved the chlorophyll content by 27%, 31%, and 41% under 1X-NP condition, respectively (**Table 4.17**). Non-ground slag doses were also effective in enhancing the chlorophyll content by up to 36% over control. NBI values positively responded to slag amendment in acidic soil, showing gradual increase in response to increasing slag doses under 1X-NP fertilization, regardless of the slag particle size. Ground slag amendments in acidic soil also elevated NBI values by up to 32% compared to control under 2X-NP fertilization (**Table 4.17**).

Table 4.17: Chlorophyll content and nitrogen balance index (NBI) values obtained from the leaves of 39 day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline or acidic soils treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Fertilization	Slag Treatment	Chlorophyll Content ($\mu\text{g cm}^{-2}$)				NBI			
		Alkaline Soil		Acidic Soil		Alkaline Soil		Acidic Soil	
1X-NP	Control	40.9 $\pm$ 1.5	a-c	29.8 $\pm$ 3.0	d	37.3 $\pm$ 2.5	a	20.3 $\pm$ 3.4	g
	G-0.5%	39.7 $\pm$ 1.6	a-c	37.9 $\pm$ 2.5	bc	38.3 $\pm$ 4.6	a	27.2 $\pm$ 1.9	ef
	G-1.0%	39.7 $\pm$ 1.3	a-c	39.1 $\pm$ 1.8	a-c	37.0 $\pm$ 3.1	a	29.4 $\pm$ 3.6	d-f
	G-2.0%	38.6 $\pm$ 2.4	c	41.9 $\pm$ 0.9	ab	35.0 $\pm$ 1.0	a	35.9 $\pm$ 2.9	b-d
	NG-0.5%	42.8 $\pm$ 1.5	ab	34.0 $\pm$ 2.5	cd	40.7 $\pm$ 1.9	a	23.6 $\pm$ 0.9	fg
	NG-1.0%	41.3 $\pm$ 1.4	a-c	38.3 $\pm$ 3.6	a-c	39.8 $\pm$ 4.0	a	27.2 $\pm$ 4.4	ef
	NG-2.0%	41.5 $\pm$ 2.9	a-c	40.6 $\pm$ 2.3	ab	37.8 $\pm$ 1.7	a	28.2 $\pm$ 2.1	ef
2X-NP	Control	43.4 $\pm$ 1.9	a	38.8 $\pm$ 2.7	a-c	41.9 $\pm$ 3.2	a	33.4 $\pm$ 1.9	c-e
	G-0.5%	41.1 $\pm$ 2.1	a-c	43.1 $\pm$ 2.1	a	37.2 $\pm$ 4.0	a	41.6 $\pm$ 3.2	ab
	G-1.0%	41.3 $\pm$ 2.6	a-c	43.1 $\pm$ 1.9	a	37.5 $\pm$ 6.0	a	42.5 $\pm$ 2.7	ab
	G-2.0%	39.1 $\pm$ 2.5	bc	43.0 $\pm$ 2.3	ab	34.4 $\pm$ 1.5	a	44.2 $\pm$ 1.7	a
	NG-0.5%	42.8 $\pm$ 2.2	ab	38.9 $\pm$ 1.9	a-c	38.3 $\pm$ 0.9	a	31.2 $\pm$ 1.6	c-e
	NG-1.0%	42.1 $\pm$ 1.6	a-c	41.1 $\pm$ 1.7	ab	40.1 $\pm$ 2.3	a	33.2 $\pm$ 1.0	c-e
	NG-2.0%	42.2 $\pm$ 2.1	a-c	43.1 $\pm$ 1.9	a	36.5 $\pm$ 5.6	a	36.4 $\pm$ 3.4	bc

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

In alkaline soil, ground slag treatment had no significant effect on shoot growth whereas non-ground slag treatment considerably improved the dry biomass approximately 50% under 1X-NP condition, regardless of the slag dose (**Figure 4.3A**). Irrespective of the fertilization type, shoot growth was significantly enhanced by both ground and non-ground slag treatments in acidic soil. The highest dose of ground slag ensured a 300% increase under 1X-NP and a 132% increase under 2X-NP fertilization regimes over control (**Figure 4.3B**).

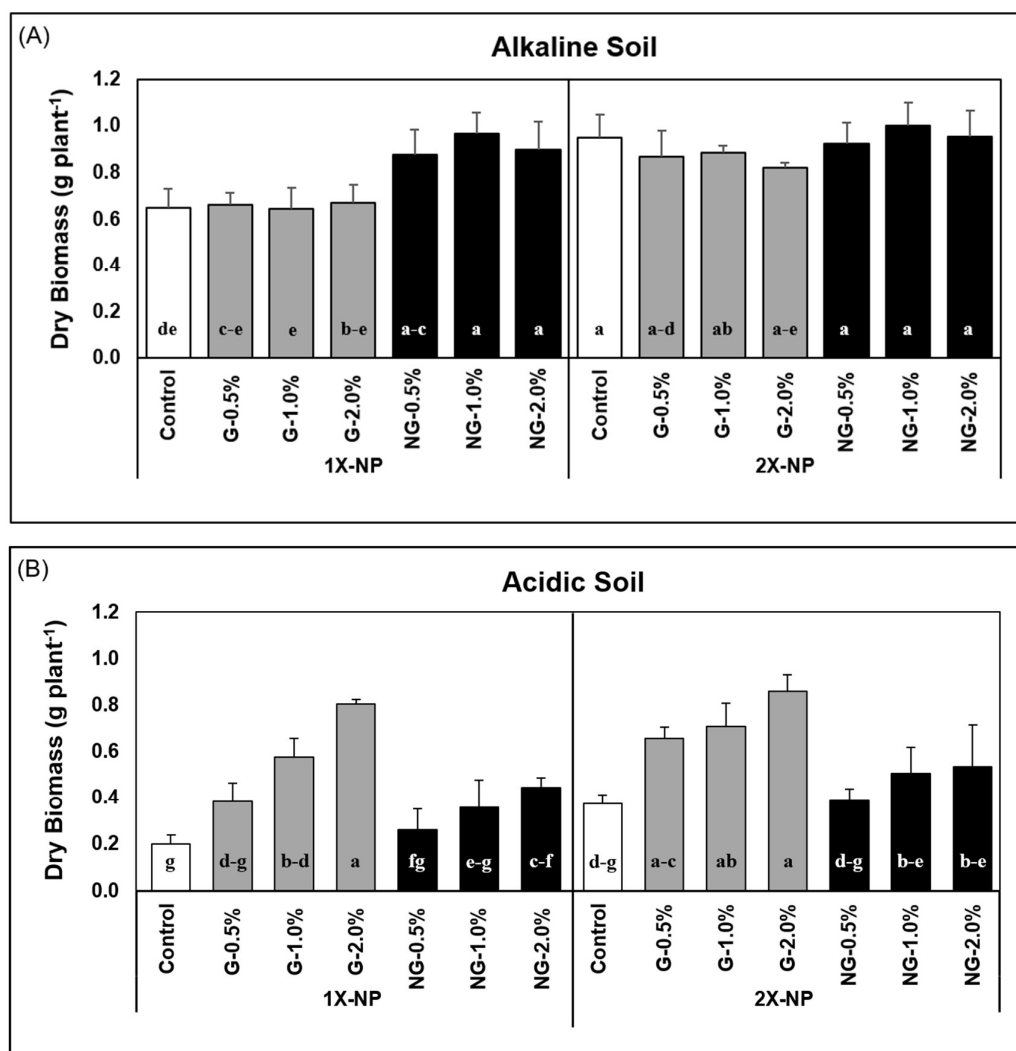


Figure 4.3: Shoot dry weight results obtained from the leaves of 39-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline (A) or acidic (B) soils treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes. Columns represent the mean and standard deviations of four independent

replicates. Different letters within columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

After obtaining the shoot growth data, mineral composition of leaf samples was determined (**Table 4.18; 4.19; 4.20; 4.21; 4.22; 4.23**). Slag application into alkaline soil did not significantly change the leaf P concentration whereas it caused 60% and 80% increases over control in acidic soil under 1X-NP fertilization in F-1.0% and F-2.0% groups, respectively (**Table 4.18; 4.19**). Non-ground doses, on the other hand, increased the leaf P concentration by up to 60% in acidic soil under 1X-NP condition. Under 2X-NP condition, medium and high ground slag amendment elevated the leaf P concentration by over 53% compared to control. Slag treatment considerably improved the leaf K concentration in acidic soil whereas there was no significant change observed in alkaline soil (**Table 4.18; 4.19**). Under 1X-NP fertilization regime, EAF slag amendment elevated shoot K level by up to 22% over control. The leaf Ca concentration was not responsive to slag amendment in both soil types, regardless of the particle size (**Table 4.18; 4.19**). Steel slag did not significantly alter the leaf Mg concentration in either type of soil even though slight increases were achieved. The leaf S concentration did not respond to slag application in acidic soil however high dose of ground slag amendment decreased the S level by 17% in alkaline soil (**Table 4.18; 4.19**).

Steel slag amendment did not significantly alter the leaf Fe concentration in both soil types under either type of fertilization although 45% decrease was observed in the highest dose of ground slag application in acidic soil (**Table 4.20; 4.21**). The highest dose of ground slag application into alkaline soil ensured increases in leaf Zn concentration by 59% and 28% over control under low and high fertilization, respectively (**Table 4.20**). Non-ground doses also improved shoot Zn level in a dose-dependent manner in alkaline soil. In acidic soil, on the other hand, leaf Zn concentration was not responsive to any type of slag treatment. There was no significant change observed in leaf Mn concentration as a result of ground slag amendment in acidic soil (**Table 4.21**). The medium and high doses of non-ground slag application, however, elevated shoot Mn level by over 28% compared to control. In alkaline soil, on the other hand, all doses of non-ground slag application into alkaline soil remarkably improved the leaf Mn levels by up to 200% under 1X-NP condition (**Table 4.20**). This effect was not observed under 2X-NP condition in terms

of leaf Mn concentration. Electric-arc-furnace slag treatment caused no significant change in leaf Cu levels in both soil types under both fertilization regimes (**Table 4.20; 4.21**). The leaf B concentration, on the other hand, drastically enhanced in response to slag amendment in both soil types (**Table 4.20; 4.21**). The highest dose of ground slag amendment in alkaline soil elevated the leaf B concentration by approximately 250% (under 1X-NP) and 200% (2X-NP). Furthermore, increasing ground slag treatments in acidic soil dramatically boosted the leaf B concentration by approximately 9-fold, 16-fold, and 21-fold over control under lower fertilization condition, respectively, and 3.5-fold, 5.5-fold and 7.6-fold over control under higher fertilization condition, respectively. Non-ground slag amendments in acidic soil also achieved considerable increase in terms of leaf B concentration under both fertilization types in a dose-dependent manner. The leaf Mo level was also responsive to all types of slag treatment in alkaline soil, reaching 144% and 200% increases in response to the highest dose of ground slag application under lower and higher fertilization regimes, respectively (**Table 4.20**). Moreover, slag application into acidic soil ensured considerable enhancement in leaf Mo concentration (**Table 4.21**). While the leaf Mo level in control group was not detectable, the highest dose of ground slag application into acidic soil remarkably increased the Mo concentration under both fertilization types. The leaf Ni level did not alter significantly in both types of soil under both fertilization regimes upon slag amendment (**Table 4.22; 4.23**).

Table 4.18: Macroelement concentrations of the leaves of 39-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Macroelement Concentrations (g kg ⁻¹)						
Fertilization	Slag Treatment	P	K	Ca	Mg	S
1X-NP	Control	1.9 ± 0.1 c	39.7 ± 0.8 a	7.9 ± 0.9 cd	1.92 ± 0.03 a	3.0 ± 0.1 ab
	G-0.5%	1.9 ± 0.1 a-c	41.3 ± 0.7 a	6.6 ± 0.3 d	1.80 ± 0.08 a	3.0 ± 0.2 ab
	G-1.0%	1.9 ± 0.1 bc	42.1 ± 1.3 a	6.6 ± 0.3 d	1.87 ± 0.08 a	3.0 ± 0.2 ab
	G-2.0%	2.0 ± 0.2 a-c	43.5 ± 2.0 a	6.7 ± 0.4 d	1.86 ± 0.06 a	3.1 ± 0.2 ab
	NG-0.5%	2.3 ± 0.1 a-c	42.8 ± 0.7 a	6.6 ± 0.4 d	1.98 ± 0.07 a	3.4 ± 0.2 ab
	NG-1.0%	2.5 ± 0.1 ab	43.8 ± 1.2 a	6.9 ± 0.3 d	1.96 ± 0.09 a	3.4 ± 0.1 ab
	NG-2.0%	2.5 ± 0.2 a	42.6 ± 1.8 a	6.9 ± 0.4 d	1.74 ± 0.11 a	3.1 ± 0.3 ab
2X-NP	Control	2.4 ± 0.5 a-c	42.2 ± 4.2 a	9.9 ± 0.5 ab	1.87 ± 0.17 a	3.5 ± 0.3 a
	G-0.5%	2.1 ± 0.2 a-c	40.8 ± 1.8 a	9.8 ± 0.3 ab	1.95 ± 0.05 a	3.2 ± 0.1 ab
	G-1.0%	2.2 ± 0.3 a-c	41.5 ± 2.7 a	9.0 ± 1.5 bc	1.97 ± 0.13 a	3.1 ± 0.2 ab
	G-2.0%	2.1 ± 0.3 a-c	40.3 ± 2.1 a	9.0 ± 0.8 bc	2.01 ± 0.22 a	2.9 ± 0.2 b
	NG-0.5%	2.3 ± 0.1 a-c	41.7 ± 1.8 a	8.9 ± 0.4 bc	1.95 ± 0.14 a	3.2 ± 0.1 ab
	NG-1.0%	2.5 ± 0.2 a	41.6 ± 1.3 a	9.4 ± 0.4 a-c	1.95 ± 0.11 a	3.5 ± 0.1 a
	NG-2.0%	2.4 ± 0.5 a-c	39.7 ± 1.9 a	10.6 ± 0.5 a	2.00 ± 0.19 a	3.3 ± 0.4 ab

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.19: Macroelement concentrations of the leaves of 39-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Macroelement Concentrations (g kg ⁻¹)								
Fertilization	Slag Treatment	P	K	Ca	Mg	S		
1X-NP	Control	1.0 ± 0.1 d	39.5 ± 1.7 d	5.1 ± 0.6 ab	1.45 ± 0.12 ab	2.5 ± 0.0 b		
	G-0.5%	1.3 ± 0.1 b-d	45.8 ± 0.4 a-c	4.1 ± 0.3 b	1.32 ± 0.05 b	2.5 ± 0.1 b		
	G-1.0%	1.6 ± 0.2 a-d	48.1 ± 1.1 a	4.3 ± 0.6 b	1.30 ± 0.07 b	2.5 ± 0.1 b		
	G-2.0%	1.8 ± 0.1 ab	47.2 ± 1.9 a-c	4.2 ± 0.4 b	1.32 ± 0.04 b	2.5 ± 0.1 b		
	NG-0.5%	1.6 ± 0.7 a-c	45.2 ± 3.4 a-c	6.1 ± 1.6 a	1.57 ± 0.23 a	2.6 ± 0.2 ab		
	NG-1.0%	1.2 ± 0.1 cd	43.5 ± 1.7 b-d	3.8 ± 0.7 b	1.34 ± 0.09 ab	2.8 ± 0.1 ab		
	NG-2.0%	1.4 ± 0.2 b-d	44.7 ± 2.0 a-c	4.0 ± 0.1 b	1.38 ± 0.07 ab	2.7 ± 0.2 ab		
2X-NP	Control	1.3 ± 0.1 b-d	43.3 ± 1.8 cd	5.0 ± 0.6 ab	1.33 ± 0.12 ab	2.6 ± 0.1 ab		
	G-0.5%	1.9 ± 0.1 ab	46.2 ± 1.1 a-c	4.8 ± 0.4 ab	1.27 ± 0.06 b	2.7 ± 0.1 ab		
	G-1.0%	2.0 ± 0.1 a	47.9 ± 2.3 ab	4.5 ± 0.4 b	1.26 ± 0.06 b	2.8 ± 0.1 ab		
	G-2.0%	2.1 ± 0.1 a	46.7 ± 1.1 a-c	4.6 ± 0.2 ab	1.29 ± 0.03 b	2.8 ± 0.0 ab		
	NG-0.5%	1.4 ± 0.1 b-d	43.9 ± 0.6 a-d	4.8 ± 0.3 ab	1.43 ± 0.09 ab	2.9 ± 0.1 a		
	NG-1.0%	1.4 ± 0.1 b-d	43.1 ± 0.7 cd	4.6 ± 0.3 ab	1.30 ± 0.03 b	2.8 ± 0.2 ab		
	NG-2.0%	1.6 ± 0.2 a-c	43.9 ± 2.2 a-c	4.7 ± 0.5 ab	1.25 ± 0.03 b	2.6 ± 0.1 ab		

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.20: Microelement concentrations of the leaves of 39-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Microelement Concentrations (mg kg ⁻¹)											
Fertilization	Slag Treatment	Fe		Zn		Mn		Cu		B	
1X-NP	Control	81 ± 21	a	22 ± 2	e	88 ± 3	b	9.7 ± 0.9	ab	8.7 ± 2.3	d
	G-0.5%	70 ± 18	a	27 ± 2	c-e	58 ± 9	b	8.3 ± 1.1	b	11.7 ± 4.0	cd
	G-1.0%	89 ± 8	a	31 ± 1	b-d	74 ± 3	b	9.5 ± 1.0	ab	18.8 ± 1.1	bc
	G-2.0%	84 ± 12	a	35 ± 2	a-c	85 ± 5	b	9.4 ± 0.3	ab	30.6 ± 3.7	a
	NG-0.5%	82 ± 12	a	34 ± 1	a-d	204 ± 84	a	10.7 ± 0.7	a	9.3 ± 1.9	d
	NG-1.0%	84 ± 18	a	39 ± 2	ab	266 ± 27	a	10.9 ± 0.6	a	10.3 ± 1.4	d
	NG-2.0%	83 ± 12	a	41 ± 2	a	265 ± 23	a	10.9 ± 0.6	a	12.3 ± 5.0	cd
2X-NP	Control	81 ± 20	a	25 ± 6	de	58 ± 8	b	9.9 ± 1.6	ab	7.8 ± 0.4	d
	G-0.5%	79 ± 5	a	26 ± 2	de	71 ± 4	b	10.3 ± 0.4	ab	12.1 ± 1.7	cd
	G-1.0%	87 ± 9	a	30 ± 5	b-e	77 ± 6	b	10.7 ± 0.6	a	13.9 ± 2.6	cd
	G-2.0%	79 ± 4	a	32 ± 5	a-d	77 ± 9	b	10.0 ± 1.2	ab	23.1 ± 6.6	ab
	NG-0.5%	72 ± 4	a	25 ± 3	de	62 ± 9	b	9.5 ± 0.6	ab	7.3 ± 2.4	d
	NG-1.0%	80 ± 27	a	26 ± 5	de	55 ± 12	b	9.2 ± 1.5	ab	7.5 ± 2.4	d
	NG-2.0%	86 ± 14	a	27 ± 6	c-e	78 ± 11	b	10.5 ± 1.0	ab	12.1 ± 2.6	cd

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.21: Microelement concentrations of the leaves of 39-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Microelement Concentrations (mg kg ⁻¹)													
Fertilization	Slag Treatment	Fe		Zn		Mn		Cu		B		Mo	Ni
1X-NP	Control	152 ± 38	ab	70 ± 13	a-c	209 ± 15	d	7.5 ± 0.4	ab	1.1 ± 0.6	g	<i>n.d</i>	1.6 ± 0.4
	G-0.5%	169 ± 80	ab	72 ± 11	a-c	220 ± 18	cd	7.7 ± 0.4	ab	10.4 ± 1.8	de	<i>n.d</i>	2.1 ± 1.0
	G-1.0%	110 ± 33	ab	64 ± 6	a-c	245 ± 9	b-d	7.3 ± 0.4	ab	17.7 ± 1.7	bc	<i>n.d</i>	2.5 ± 1.4
	G-2.0%	83 ± 10	b	59 ± 13	bc	199 ± 16	d	7.7 ± 0.4	ab	22.9 ± 1.6	a	0.4 ± 0.1	1.9 ± 1.3
	NG-0.5%	108 ± 38	ab	59 ± 6	bc	206 ± 10	d	7.5 ± 1.4	ab	7.0 ± 2.0	ef	<i>n.d</i>	2.2 ± 0.7
	NG-1.0%	232 ± 60	a	88 ± 11	a	269 ± 15	ab	8.2 ± 0.7	ab	10.5 ± 1.5	de	<i>n.d</i>	1.7 ± 1.0
	NG-2.0%	229 ± 110	a	77 ± 20	ab	268 ± 42	ab	7.9 ± 0.9	ab	21.3 ± 3.7	ab	<i>n.d</i>	1.8 ± 1.3
2X-NP	Control	75 ± 6	b	58 ± 3	bc	291 ± 12	ab	7.5 ± 0.3	ab	2.2 ± 0.5	g	<i>n.d</i>	1.8 ± 0.7
	G-0.5%	83 ± 7	b	57 ± 2	bc	278 ± 23	ab	8.3 ± 0.6	ab	7.7 ± 0.9	ef	<i>n.d</i>	1.6 ± 0.6
	G-1.0%	82 ± 19	b	57 ± 5	bc	270 ± 11	ab	8.2 ± 0.8	ab	12.2 ± 1.3	d	<i>n.d</i>	1.8 ± 0.7
	G-2.0%	78 ± 5	b	52 ± 2	c	262 ± 11	a-c	8.9 ± 0.9	a	16.7 ± 1.4	c	0.3 ± 0.1	1.6 ± 0.8
	NG-0.5%	128 ± 99	ab	64 ± 13	a-c	271 ± 32	ab	7.4 ± 0.7	ab	4.7 ± 0.6	fg	<i>n.d</i>	1.3 ± 0.6
	NG-1.0%	88 ± 9	b	59 ± 3	bc	286 ± 9	ab	7.0 ± 0.3	b	7.8 ± 0.4	ef	<i>n.d</i>	1.6 ± 0.7
	NG-2.0%	101 ± 36	ab	62 ± 10	bc	300 ± 13	a	7.1 ± 0.3	ab	8.8 ± 0.7	de	<i>n.d</i>	1.9 ± 0.8

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.22: Potentially toxic non-essential element concentrations of the leaves of 39-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Potentially Toxic Non-Essential Element Concentrations (mg kg ⁻¹)					
Fertilization	Slag Treatment	Cr	Cd	V	Pb
1X-NP	Control	6.6 ± 3.4 a	0.06 ± 0.03 b	0.10 ± 0.02 a	n.d
	G-0.5%	5.1 ± 2.5 a	0.03 ± 0.01 b	0.10 ± 0.02 a	n.d
	G-1.0%	6.9 ± 2.3 a	0.04 ± 0.01 b	0.13 ± 0.03 a	n.d
	G-2.0%	5.4 ± 0.3 a	0.02 ± 0.02 b	0.13 ± 0.03 a	n.d
	NG-0.5%	5.2 ± 0.8 a	0.19 ± 0.08 a	0.13 ± 0.04 a	n.d
	NG-1.0%	5.7 ± 3.0 a	0.21 ± 0.02 a	0.09 ± 0.01 a	n.d
	NG-2.0%	4.9 ± 1.2 a	0.19 ± 0.00 a	0.11 ± 0.00 a	n.d
2X-NP	Control	6.3 ± 2.4 a	0.04 ± 0.03 b	0.14 ± 0.01 a	n.d
	G-0.5%	5.8 ± 0.5 a	0.06 ± 0.02 b	0.11 ± 0.03 a	n.d
	G-1.0%	7.8 ± 1.9 a	0.05 ± 0.02 b	0.12 ± 0.02 a	n.d
	G-2.0%	6.3 ± 0.8 a	0.04 ± 0.03 b	0.13 ± 0.02 a	n.d
	NG-0.5%	4.8 ± 1.1 a	0.04 ± 0.02 b	0.11 ± 0.03 a	n.d
	NG-1.0%	5.4 ± 2.0 a	0.04 ± 0.00 b	0.11 ± 0.02 a	n.d
	NG-2.0%	6.9 ± 1.8 a	0.05 ± 0.02 b	0.12 ± 0.02 a	n.d

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.23: Potentially toxic non-essential element concentrations of the leaves of 39-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Potentially Toxic Non-Essential Element Concentrations (mg kg ⁻¹)					
Fertilization	Slag Treatment	Cr	Cd	V	Pb
1X-NP	Control	5.0 ± 0.8 a	0.21 ± 0.04 bc	0.15 ± 0.03 a	<i>n.d</i>
	G-0.5%	6.7 ± 0.9 a	0.24 ± 0.01 ab	0.11 ± 0.01 a	<i>n.d</i>
	G-1.0%	7.0 ± 1.9 a	0.27 ± 0.03 a	0.12 ± 0.02 a	<i>n.d</i>
	G-2.0%	6.1 ± 1.8 a	0.17 ± 0.02 cd	0.13 ± 0.03 a	<i>n.d</i>
	NG-0.5%	6.3 ± 0.5 a	0.22 ± 0.02 a-c	0.12 ± 0.06 a	<i>n.d</i>
	NG-1.0%	5.4 ± 1.5 a	0.15 ± 0.01 d-f	0.10 ± 0.02 a	<i>n.d</i>
	NG-2.0%	5.1 ± 1.7 a	0.15 ± 0.03 de	0.11 ± 0.01 a	<i>n.d</i>
2X-NP	Control	5.4 ± 0.3 a	0.12 ± 0.01 e-g	0.12 ± 0.04 a	<i>n.d</i>
	G-0.5%	5.4 ± 1.8 a	0.10 ± 0.02 e-g	0.11 ± 0.03 a	<i>n.d</i>
	G-1.0%	6.1 ± 3.2 a	0.10 ± 0.01 e-g	0.11 ± 0.03 a	<i>n.d</i>
	G-2.0%	4.8 ± 1.2 a	0.10 ± 0.02 e-g	0.13 ± 0.02 a	<i>n.d</i>
	NG-0.5%	4.5 ± 0.6 a	0.09 ± 0.03 fg	0.13 ± 0.02 a	<i>n.d</i>
	NG-1.0%	5.7 ± 0.6 a	0.08 ± 0.02 g	0.10 ± 0.03 a	<i>n.d</i>
	NG-2.0%	6.0 ± 1.1 a	0.08 ± 0.00 g	0.12 ± 0.02 a	<i>n.d</i>

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

General appearance of 85-day-old plants were documented as shown in **Figure 4.4**. While there was no considerable change in general appearance of the plants grown on alkaline soil, EAF slag amendment was effective in improving spike size and shoot height in acidic soil, particularly upon ground slag treatments under lower fertilization.



Figure 4.4: General harvest time appearance of 89 day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline (A-B-C-D) or acidic (E-F-G-H) soils treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP (A-B-E-F) or 2X-NP (C-D-G-H) fertilization regimes

Grain yield was remarkably improved upon slag amendment in acidic soil under both types of fertilization (**Table 4.24**). Irrespective of the slag doses, the highest dose of ground slag amendment into acidic soil significantly enhanced the grain yield by 461% and 200% over control under 1X-NP and 2X-NP conditions, respectively. Furthermore, non-ground slag doses also achieved significant enhancement in grain yield, especially under lower fertilization. In alkaline soil, on the other hand, grain yield was not responsive to any types of slag amendment. Ground EAF slag amendment in acidic soil boosted the grain number dramatically, reaching 677% and 265% over control under lower and higher fertilization regimes, respectively (**Table 4.24**). The highest dose of non-ground slag amendment also affected the grain number, achieving up to 230% increase over control under 2X-NP condition. However, no significant change was achieved in alkaline soil in terms of grain number. Although slight increases were attained in alkaline and acidic soils in terms of 1000 grain weight, there was no significant change observed in response to steel slag amendment under either type of fertilization regime (**Table 4.24**).

Table 4.24: Grain yield, grain number and 1000 grain weight results obtained from the spikes of 85-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline or acidic soils treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Fertilization	Slag Treatment	Grain Yield (g plant ⁻¹)		Grain Number (plant ⁻¹)			1000 Grain Weight (g)	
		Alkaline Soil	Acidic Soil	Alkaline Soil	Acidic Soil		Alkaline Soil	Acidic Soil
1X-NP	Control	0.77 ± 0.17 ab	0.18 ± 0.08 f	104 ± 15 a	13 ± 4 e		29.6 ± 4.2 a	35.5 ± 1.7 a
	G-0.5%	0.93 ± 0.06 ab	0.64 ± 0.10 b-d	140 ± 10 a	72 ± 15 a-c		28.0 ± 3.6 a	36.0 ± 3.1 a
	G-1.0%	1.04 ± 0.07 ab	0.73 ± 0.09 a-c	131 ± 24 a	87 ± 8 ab		30.3 ± 4.2 a	36.0 ± 3.0 a
	G-2.0%	0.95 ± 0.11 ab	1.01 ± 0.24 a	136 ± 5 a	101 ± 10 a		31.1 ± 3.8 a	35.4 ± 1.2 a
	NG-0.5%	0.98 ± 0.06 ab	0.69 ± 0.24 a-d	125 ± 17 a	92 ± 15 a		31.8 ± 2.8 a	35.7 ± 2.9 a
	NG-1.0%	1.00 ± 0.05 ab	0.64 ± 0.07 b-c	122 ± 5 a	80 ± 15 a-c		32.8 ± 1.3 a	33.3 ± 3.7 a
	NG-2.0%	0.86 ± 0.12 ab	0.74 ± 0.07 a-c	106 ± 7 a	82 ± 9 ab		32.6 ± 3.0 a	36.3 ± 2.4 a
2X-NP	Control	0.95 ± 0.22 ab	0.26 ± 0.02 ef	128 ± 25 a	23 ± 10 de		29.4 ± 1.3 a	29.5 ± 5.4 a
	G-0.5%	0.80 ± 0.07 ab	0.66 ± 0.07 b-d	104 ± 11 a	82 ± 7 ab		28.8 ± 2.9 a	32.3 ± 1.6 a
	G-1.0%	0.88 ± 0.06 ab	0.67 ± 0.08 b-d	122 ± 10 a	84 ± 9 ab		29.4 ± 2.3 a	32.0 ± 2.1 a
	G-2.0%	0.98 ± 0.21 ab	0.78 ± 0.17 ab	131 ± 24 a	77 ± 11 a-c		29.9 ± 1.0 a	35.1 ± 2.0 a
	NG-0.5%	1.04 ± 0.12 ab	0.36 ± 0.13 d-f	139 ± 20 a	48 ± 21 c-e		30.1 ± 0.9 a	30.9 ± 3.3 a
	NG-1.0%	1.08 ± 0.17 a	0.41 ± 0.08 c-f	140 ± 11 a	54 ± 8 b-d		32.8 ± 2.2 a	32.3 ± 4.3 a
	NG-2.0%	0.71 ± 0.09 b	0.63 ± 0.11 b-d	116 ± 15 a	76 ± 21 a-c		30.0 ± 2.0 a	31.7 ± 1.7 a

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Element analysis of grain samples was carried out after grain yield determination (**Table 4.25; 4.26; 4.27; 4.28; 4.29; 4.30**). The low and medium dose of ground slag application into alkaline soil ensured up to 58% increase over control in grain P concentration under 1X-NP fertilization (**Table 4.25**). This significant effect was not observed in other slag treatments in either type of soil under both fertilization types. Same pattern was also observed in grain K concentration (**Table 4.25**). Only low and medium doses of ground slag amendment significantly improved the grain K level in alkaline soil whereas there was no considerable change in acidic soil (**Table 4.26**). The grain Ca concentration, on the other hand, enhanced significantly upon the lowest dose of slag amendment in alkaline soil under 1X-NP condition, achieving 42% increase compared to control (**Table 4.25**). No significant alteration in grain Ca concentration was observed in acidic soil (**Table 4.26**). The grain Mg and S concentrations were not responsive to steel slag amendment in both soil types under either type of fertilization regime (**Table 4.25; 4.26**).

All ground slag applications slightly enhanced the grain Fe concentration by up to 44% over control under 1X-NP condition (**Table 4.27**). Furthermore, non-ground slag doses achieved 53% increase compared to control under the same fertilization. In acidic soil, however, no significant change was observed (**Table 4.28**). The grain Zn concentration remarkably elevated as a result of ground slag treatment in all doses in alkaline soil under 1X-NP fertilization (**Table 4.27**). The highest increase was attained by the highest dose of ground slag application, which elevated the grain Zn level by 144% over control. However, Zn concentration of the grains grown on acidic soil did not respond to any type of slag treatment under both fertilization types (**Table 4.28**). The highest dose of non-ground steel slag amendment dramatically enhanced the grain Mn concentration by 110% compared to control in alkaline soil under 1X-NP condition (**Table 4.27**). This effect was not achieved in acidic soil even though slight changes were observed (**Table 4.28**). The grain Cu and B levels were not responsive to any type of slag application in both soils (**Table 4.27; 4.28**). The grain Mo concentration of control group was below the detectable limit in acidic soil (**Table 4.28**). The medium and high doses of ground slag and the highest dose of non-ground slag achieved the accumulation of Mo in grain tissues in acidic soil under either regime of fertilization. In alkaline soil, on the other hand, there was no significant alteration in grain Mo concentration in response to slag amendment (**Table 4.27**). The lowest dose

of non-ground slag application significantly decreased the grain Ni level by 59% over control in alkaline soil under 2X-NP fertilization (**Table 4.29**). In acidic soil, all ground doses of slag application considerably decreased the grain Ni concentration by up to 70% under 2X-NP fertilization (**Table 4.30**).

The grain Cd level was not responsive to any type of slag amendment in alkaline soil (**Table 4.29**). However, the highest dose of ground and non-ground slag application into acidic soil significantly decreased the grain Cd concentration compared to control under 1X-NP condition whereas this effect was not observed under 2X-NP fertilization in acidic soil (**Table 4.30**). The grain Cr and V levels, on the other hand, were totally non-responsive to steel slag treatment in both types of soil under either fertilization regimes (**Table 4.29; 4.30**). Steel slag treatment had no significant impact on the grain Pb concentration in both soil types under both regimes of fertilization and all Pb levels were below the detectable limit (<0.001 ppm) (**Table 4.29; 4.30**).

Table 4.25: Macroelement concentrations of the grains of 89-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Macroelement Concentrations (g kg ⁻¹)											
Fertilization	Slag Treatment	P		K		Ca	Mg		S		
1X-NP	Control	3.6 ± 1.0	bc	5.1 ± 0.3	b-d	0.52 ± 0.03	b-d	1.42 ± 0.20	a-c	2.22 ± 0.10	a
	G-0.5%	5.7 ± 0.3	a	6.6 ± 0.3	a	0.74 ± 0.09	a	1.65 ± 0.13	ab	2.41 ± 0.09	a
	G-1.0%	5.6 ± 0.2	a	6.6 ± 0.3	a	0.64 ± 0.06	a-c	1.67 ± 0.04	a	2.34 ± 0.13	a
	G-2.0%	5.1 ± 0.2	ab	5.9 ± 0.3	ab	0.59 ± 0.05	a-d	1.66 ± 0.17	a	2.35 ± 0.16	a
	NG-0.5%	3.6 ± 1.6	bc	5.0 ± 1.2	b-d	0.46 ± 0.11	d	1.42 ± 0.27	a-c	2.39 ± 0.11	a
	NG-1.0%	2.9 ± 0.2	c	4.4 ± 0.2	d	0.46 ± 0.05	cd	1.31 ± 0.06	c	2.43 ± 0.07	a
	NG-2.0%	2.9 ± 0.3	c	4.6 ± 0.2	cd	0.51 ± 0.03	cd	1.29 ± 0.13	c	2.44 ± 0.17	a
2X-NP	Control	4.4 ± 0.3	a-c	5.5 ± 0.3	a-d	0.71 ± 0.08	a	1.51 ± 0.05	a-c	2.18 ± 0.09	a
	G-0.5%	3.3 ± 0.7	c	4.8 ± 0.6	cd	0.60 ± 0.10	a-d	1.32 ± 0.12	c	2.19 ± 0.14	a
	G-1.0%	3.2 ± 0.5	c	4.8 ± 0.2	b-d	0.62 ± 0.07	a-d	1.32 ± 0.06	bc	2.25 ± 0.15	a
	G-2.0%	4.2 ± 0.9	a-c	5.5 ± 0.2	a-d	0.76 ± 0.06	a	1.40 ± 0.15	a-c	2.26 ± 0.07	a
	NG-0.5%	4.4 ± 0.6	a-c	5.5 ± 0.6	a-d	0.74 ± 0.11	a	1.53 ± 0.02	a-c	2.33 ± 0.05	a
	NG-1.0%	4.5 ± 0.4	a-c	5.6 ± 0.3	a-c	0.73 ± 0.06	a	1.50 ± 0.05	a-c	2.30 ± 0.12	a
	NG-2.0%	4.1 ± 0.8	a-c	5.3 ± 0.4	b-d	0.70 ± 0.06	ab	1.47 ± 0.10	a-c	2.35 ± 0.03	a

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.26: Macroelement concentrations of the grains of 89-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Macroelement Concentrations (g kg ⁻¹)						
Fertilization	Slag Treatment	P	K	Ca	Mg	S
1X-NP	Control	5.7 ± 0.3 a	6.2 ± 1.0 a	0.49 ± 0.02 ab	1.86 ± 0.17 a	2.67 ± 0.25 a
	G-0.5%	5.4 ± 0.2 a	6.1 ± 0.9 a	0.53 ± 0.13 ab	1.84 ± 0.07 a	2.75 ± 0.14 a
	G-1.0%	5.3 ± 0.3 a	6.1 ± 0.5 a	0.53 ± 0.05 ab	1.80 ± 0.10 a	2.65 ± 0.10 a
	G-2.0%	5.2 ± 0.5 a	6.0 ± 0.6 a	0.54 ± 0.10 ab	1.73 ± 0.08 ab	2.48 ± 0.06 a
	NG-0.5%	5.5 ± 0.3 a	6.1 ± 0.4 a	0.61 ± 0.04 a	1.78 ± 0.09 a	2.62 ± 0.11 a
	NG-1.0%	4.8 ± 0.6 a	6.1 ± 0.7 a	0.53 ± 0.07 ab	1.64 ± 0.16 a-c	2.61 ± 0.13 a
	NG-2.0%	4.5 ± 0.7 ab	5.6 ± 0.2 ab	0.51 ± 0.04 ab	1.55 ± 0.13 a-d	2.59 ± 0.06 a
2X-NP	Control	3.1 ± 0.7 c	4.7 ± 0.2 bc	0.52 ± 0.08 ab	1.39 ± 0.18 cd	2.8 ± 0.3 a
	G-0.5%	2.7 ± 0.2 c	4.4 ± 0.2 bc	0.47 ± 0.04 ab	1.26 ± 0.05 d	2.5 ± 0.2 a
	G-1.0%	3.3 ± 0.5 bc	4.7 ± 0.2 bc	0.51 ± 0.05 ab	1.39 ± 0.13 cd	2.6 ± 0.2 a
	G-2.0%	3.5 ± 0.4 bc	4.6 ± 0.1 bc	0.45 ± 0.06 ab	1.44 ± 0.10 b-d	2.6 ± 0.2 a
	NG-0.5%	2.9 ± 0.6 c	4.4 ± 0.2 bc	0.43 ± 0.04 b	1.32 ± 0.16 d	2.9 ± 0.3 a
	NG-1.0%	3.0 ± 0.9 c	4.6 ± 0.3 bc	0.41 ± 0.05 b	1.37 ± 0.19 cd	2.9 ± 0.4 a
	NG-2.0%	2.6 ± 0.1 c	4.3 ± 0.2 c	0.44 ± 0.04 b	1.23 ± 0.02 d	2.6 ± 0.2 a

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.27: Microelement concentrations of the grains of 89-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Microelement Concentrations (mg kg ⁻¹)															
Fertilization	Slag Treatment	Fe		Zn		Mn		Cu		B	Mo	Ni			
1X-NP	Control	34 ± 4	b	34 ± 10	c	37 ± 2	c	6.6 ± 0.8	ab	0.42 ± 0.07	d-g	0.63 ± 0.06	c-e	0.41 ± 0.04	c-e
	G-0.5%	43 ± 5	ab	71 ± 5	ab	33 ± 2	c	7.3 ± 0.4	ab	0.39 ± 0.12	e-g	0.70 ± 0.06	c-e	0.32 ± 0.07	de
	G-1.0%	40 ± 9	ab	66 ± 16	ab	36 ± 8	c	7.0 ± 0.9	ab	0.25 ± 0.19	g	0.78 ± 0.10	b-e	0.36 ± 0.13	de
	G-2.0%	49 ± 12	ab	83 ± 30	a	47 ± 20	bc	6.9 ± 0.6	ab	0.23 ± 0.14	g	0.94 ± 0.25	a-d	0.36 ± 0.11	de
	NG-0.5%	47 ± 7	ab	51 ± 21	bc	61 ± 14	ab	7.1 ± 0.5	ab	0.30 ± 0.05	fg	0.97 ± 0.21	a-c	0.63 ± 0.17	a-c
	NG-1.0%	52 ± 2	a	46 ± 6	bc	71 ± 5	a	7.2 ± 0.3	ab	0.30 ± 0.13	fg	1.12 ± 0.13	ab	0.69 ± 0.13	ab
	NG-2.0%	51 ± 6	a	48 ± 4	bc	78 ± 9	a	7.7 ± 0.5	a	0.29 ± 0.07	fg	1.24 ± 0.22	a	0.79 ± 0.12	a
2X-NP	Control	46 ± 5	ab	49 ± 3	bc	39 ± 2	c	6.4 ± 0.2	b	0.94 ± 0.11	ab	0.52 ± 0.12	e	0.58 ± 0.13	a-d
	G-0.5%	39 ± 1	ab	40 ± 9	bc	34 ± 2	c	6.3 ± 0.3	b	0.81 ± 0.14	a-c	0.66 ± 0.11	c-e	0.47 ± 0.11	b-e
	G-1.0%	41 ± 4	ab	41 ± 4	bc	36 ± 1	c	6.6 ± 0.4	ab	0.76 ± 0.06	a-d	0.85 ± 0.14	b-e	0.44 ± 0.04	b-e
	G-2.0%	43 ± 3	ab	55 ± 8	a-c	36 ± 1	c	6.8 ± 0.2	ab	1.03 ± 0.39	a	0.91 ± 0.23	a-e	0.32 ± 0.11	de
	NG-0.5%	38 ± 1	ab	48 ± 3	bc	33 ± 2	c	6.1 ± 0.3	b	0.77 ± 0.20	a-e	0.57 ± 0.12	de	0.24 ± 0.05	e
	NG-1.0%	43 ± 3	ab	52 ± 6	bc	34 ± 1	c	6.4 ± 0.1	b	0.64 ± 0.06	b-f	0.69 ± 0.06	c-e	0.39 ± 0.07	c-e
	NG-2.0%	42 ± 9	ab	46 ± 11	bc	40 ± 2	c	6.6 ± 0.4	ab	0.48 ± 0.10	c-g	0.72 ± 0.04	c-e	0.40 ± 0.10	c-e

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.28: Microelement concentrations of the grains of 89-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Microelement Concentrations (mg kg ⁻¹)														
Fertilization	Slag Treatment	Fe		Zn		Mn		Cu		B	Mo	Ni		
1X-NP	Control	81 ± 14	a	139 ± 34	a	82 ± 12	ab	6.4 ± 1.8	a-c	0.23 ± 0.03	de	<i>n.d</i>	0.42 ± 0.13	b-d
	G-0.5%	86 ± 27	a	136 ± 23	a	91 ± 9	ab	7.2 ± 0.5	a	0.36 ± 0.08	a-d	<i>n.d</i>	0.68 ± 0.18	a-c
	G-1.0%	74 ± 11	a	127 ± 18	a	84 ± 11	ab	6.8 ± 0.4	ab	0.34 ± 0.05	b-e	0.13 ± 0.04	0.44 ± 0.09	a-d
	G-2.0%	53 ± 6	a	102 ± 15	a	69 ± 20	b	6.5 ± 0.8	a-c	0.21 ± 0.06	de	0.55 ± 0.19	0.30 ± 0.05	cd
	NG-0.5%	71 ± 13	a	117 ± 12	a	89 ± 8	ab	6.7 ± 0.3	ab	0.22 ± 0.02	de	<i>n.d</i>	0.42 ± 0.07	b-d
	NG-1.0%	87 ± 8	a	121 ± 17	a	97 ± 7	ab	6.5 ± 0.3	a-c	0.24 ± 0.05	de	<i>n.d</i>	0.59 ± 0.06	a-d
	NG-2.0%	84 ± 23	a	109 ± 8	a	91 ± 9	ab	6.5 ± 0.4	a-c	0.16 ± 0.07	e	0.18 ± 0.03	0.52 ± 0.15	a-d
2X-NP	Control	56 ± 11	a	112 ± 31	a	106 ± 11	a	4.5 ± 0.5	d	0.54 ± 0.12	a	<i>n.d</i>	0.74 ± 0.25	ab
	G-0.5%	51 ± 6	a	86 ± 7	a	84 ± 5	ab	4.4 ± 0.4	d	0.37 ± 0.03	a-d	0.05 ± 0.05	0.33 ± 0.05	cd
	G-1.0%	61 ± 8	a	102 ± 11	a	95 ± 13	ab	4.9 ± 0.4	cd	0.38 ± 0.15	a-d	0.22 ± 0.04	0.26 ± 0.01	d
	G-2.0%	65 ± 8	a	100 ± 17	a	100 ± 8	a	5.5 ± 0.3	b-d	0.50 ± 0.11	ab	0.69 ± 0.20	0.22 ± 0.05	d
	NG-0.5%	96 ± 32	a	118 ± 30	a	95 ± 15	ab	4.6 ± 0.6	d	0.48 ± 0.03	a-c	<i>n.d</i>	0.85 ± 0.25	a
	NG-1.0%	73 ± 31	a	121 ± 52	a	100 ± 18	a	4.1 ± 0.5	d	0.39 ± 0.08	a-d	<i>n.d</i>	0.67 ± 0.36	a-c
	NG-2.0%	68 ± 20	a	90 ± 9	a	89 ± 6	ab	4.6 ± 0.3	d	0.29 ± 0.04	c-e	0.12 ± 0.04	0.46 ± 0.10	a-d

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.29: Potentially toxic non-essential element concentrations of the grains of 89-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Potentially Toxic Non-Essential Element Concentrations (mg kg ⁻¹)					
Fertilization	Slag Treatment	Cr	Cd	V	Pb
1X-NP	Control	0.09 ± 0.05 a	0.02 ± 0.00 a	0.05 ± 0.01 a	n.d
	G-0.5%	0.10 ± 0.04 a	0.01 ± 0.00 a	0.04 ± 0.01 a	n.d
	G-1.0%	0.12 ± 0.03 a	0.02 ± 0.01 a	0.04 ± 0.00 a	n.d
	G-2.0%	0.10 ± 0.04 a	0.04 ± 0.04 a	0.05 ± 0.01 a	n.d
	NG-0.5%	0.07 ± 0.01 a	0.04 ± 0.01 a	0.04 ± 0.00 a	n.d
	NG-1.0%	0.09 ± 0.06 a	0.04 ± 0.01 a	0.05 ± 0.01 a	n.d
	NG-2.0%	0.11 ± 0.06 a	0.03 ± 0.01 a	0.05 ± 0.01 a	n.d
2X-NP	Control	0.08 ± 0.04 a	0.03 ± 0.00 a	0.05 ± 0.01 a	n.d
	G-0.5%	0.17 ± 0.10 a	0.02 ± 0.01 a	0.05 ± 0.01 a	n.d
	G-1.0%	0.09 ± 0.07 a	0.02 ± 0.01 a	0.05 ± 0.01 a	n.d
	G-2.0%	0.08 ± 0.01 a	0.02 ± 0.01 a	0.04 ± 0.01 a	n.d
	NG-0.5%	0.05 ± 0.03 a	0.04 ± 0.01 a	0.04 ± 0.01 a	n.d
	NG-1.0%	0.08 ± 0.03 a	0.03 ± 0.00 a	0.04 ± 0.01 a	n.d
	NG-2.0%	0.09 ± 0.04 a	0.03 ± 0.01 a	0.05 ± 0.01 a	n.d

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.30: Potentially toxic non-essential element concentrations of the grains of 89-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Potentially Toxic Non-Essential Element Concentrations (mg kg ⁻¹)					
Fertilization	Slag Treatment	Cr	Cd	V	Pb
1X-NP	Control	0.10 ± 0.04 a	0.20 ± 0.06 ab	0.05 ± 0.01 a	<i>n.d</i>
	G-0.5%	0.16 ± 0.13 a	0.18 ± 0.02 a-c	0.04 ± 0.01 a	<i>n.d</i>
	G-1.0%	0.07 ± 0.01 a	0.15 ± 0.01 b-d	0.04 ± 0.01 a	<i>n.d</i>
	G-2.0%	0.09 ± 0.01 a	0.09 ± 0.05 d-f	0.05 ± 0.01 a	<i>n.d</i>
	NG-0.5%	0.09 ± 0.04 a	0.22 ± 0.02 a	0.04 ± 0.01 a	<i>n.d</i>
	NG-1.0%	0.06 ± 0.02 a	0.13 ± 0.03 c-e	0.04 ± 0.01 a	<i>n.d</i>
	NG-2.0%	0.11 ± 0.05 a	0.11 ± 0.01 d-f	0.04 ± 0.01 a	<i>n.d</i>
2X-NP	Control	0.12 ± 0.07 a	0.06 ± 0.01 f	0.05 ± 0.01 a	<i>n.d</i>
	G-0.5%	0.24 ± 0.21 a	0.05 ± 0.00 f	0.04 ± 0.00 a	<i>n.d</i>
	G-1.0%	0.27 ± 0.30 a	0.07 ± 0.01 ef	0.05 ± 0.01 a	<i>n.d</i>
	G-2.0%	0.20 ± 0.12 a	0.07 ± 0.01 ef	0.04 ± 0.01 a	<i>n.d</i>
	NG-0.5%	0.10 ± 0.07 a	0.05 ± 0.01 f	0.05 ± 0.01 a	<i>n.d</i>
	NG-1.0%	0.17 ± 0.07 a	0.06 ± 0.01 f	0.04 ± 0.01 a	<i>n.d</i>
	NG-2.0%	0.13 ± 0.01 a	0.05 ± 0.00 f	0.04 ± 0.01 a	<i>n.d</i>

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

4.4. The Effect of the Selected Slag Dose on the Growth, Yield, and Mineral Composition of Wheat

According to results obtained from the first wheat experiment, the highest dose (2.0%) of slag treatment was selected for the next study. The elongation of the plants demonstrated remarkable increase in response to EAF slag amendment in acidic soil under either type of fertilization (**Figure 4.5**). The impact of steel slag application was more recognizable in acidic soil than alkaline soil in terms of shoot density and height.

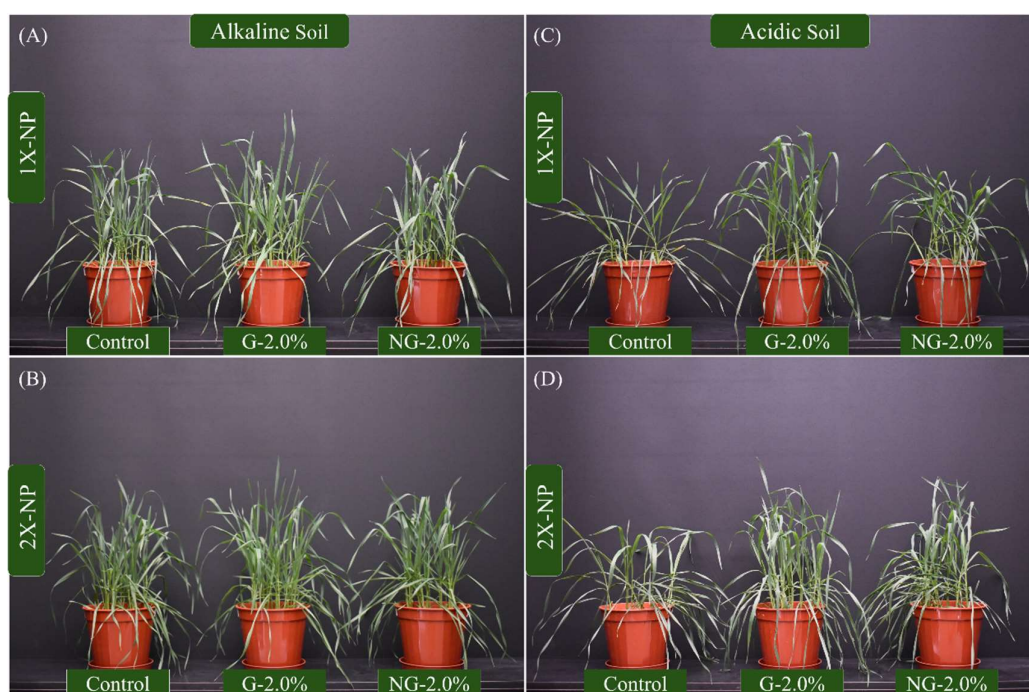


Figure 4.5: General appearance of 40 day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline (A-B) or acidic (C-D) soils treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP (A-C) or 2X-NP (B-D) fertilization regimes

Under 1X-NP condition, ground and non-ground slag treatment enhanced the chlorophyll content by 18% and 8% in acidic soil, respectively (**Table 4.31**). It also increased the leaf chlorophyll content by over 9% compared to control under 2X-NP

fertilization, regardless of the particle size. In alkaline soil, on the other hand, leaf chlorophyll content was non-responsive to steel slag treatment.

Table 4.31: Chlorophyll content results obtained from the leaves of 40-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline or acidic soils treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Fertilization	Slag Treatment	Chlorophyll Content ($\mu\text{g cm}^{-2}$)	
		Alkaline Soil	Acidic Soil
1X-NP	Control	42.1 $\pm$ 1.6 a	32.9 $\pm$ 2.8 c
	G-2.0%	41.1 $\pm$ 1.0 a	38.7 $\pm$ 0.6 ab
	NG-2.0%	42.2 $\pm$ 1.7 a	35.6 $\pm$ 2.7 bc
2X-NP	Control	42.5 $\pm$ 2.1 a	37.6 $\pm$ 1.2 ab
	G-2.0%	40.3 $\pm$ 1.0 a	41.3 $\pm$ 1.4 a
	NG-2.0%	43.1 $\pm$ 0.5 a	41.0 $\pm$ 0.9 a

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Although slight changes in shoot biomass were observed in alkaline soil, no significant increase or decrease was documented (**Figure 4.6A**). Ground steel slag application into acidic soil drastically improved the shoot dry biomass by 65% compared to control under 1X-NP condition (**Figure 4.6B**). Same application showed the beneficial effect more clearly under 2X-NP condition, achieving 78% increase in shoot dry biomass over control. Non-ground dose of slag, on the other hand, ensured 29% increase compared to control in acidic soil under 2X-NP fertilization.

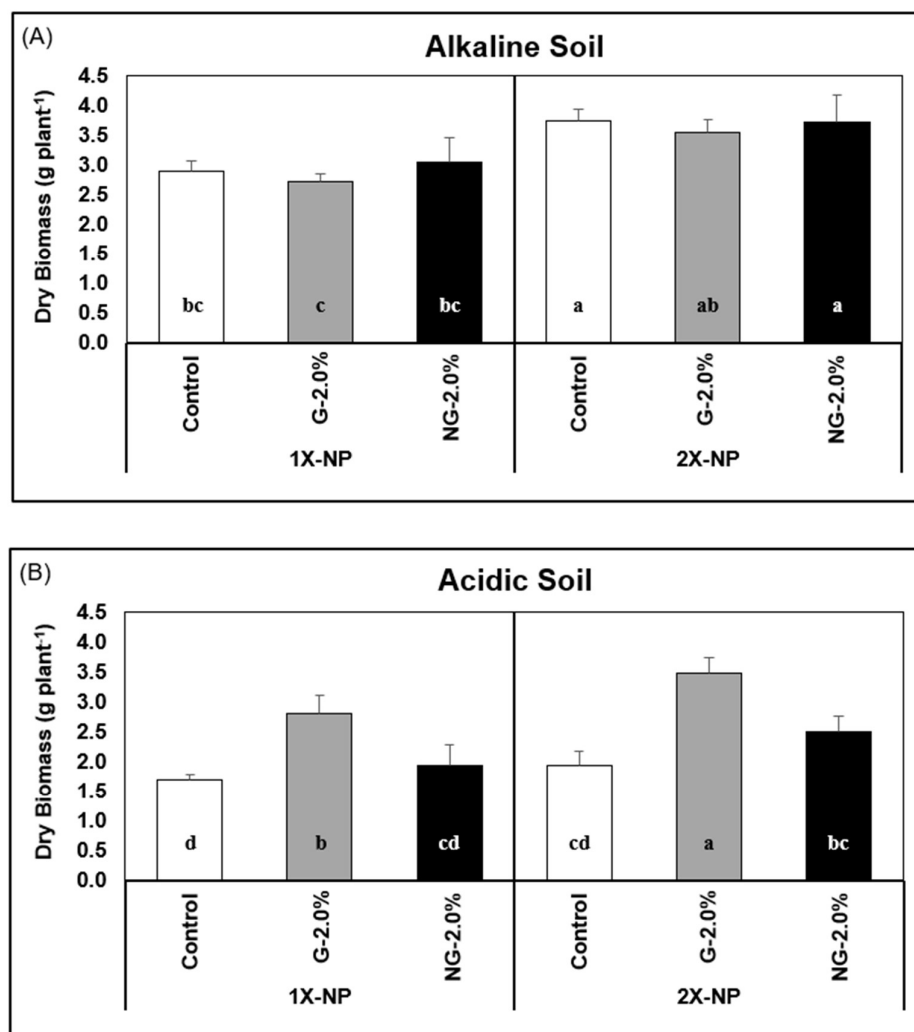


Figure 4.6: Dry biomass results obtained from the leaves of 40-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline (A) or acidic (B) soils treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes. Columns represent the mean and standard deviations of four independent replicates. Different letters within columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

After obtaining the shoot biomass data, element analysis of the leaves was carried out (Table 4.32; 4.33; 4.34; 4.35; 4.36; 4.37). According to results, leaf N concentration showed slight decreases in response to both ground and non-ground slag treatment in alkaline soil under both types of fertilization (Table 4.32). In acidic soil, on the other hand, significant decrease was observed under 2X-NP condition, irrespective of the

particle size (**Table 4.33**). Compared to control, the leaf P concentration was notably enhanced by 86% (under 1X-NP) and 39% (under 2X-NP) upon steel slag amendment in acidic soil, regardless of the particle size (**Table 4.33**). No significant change was documented in alkaline soil in terms of leaf P level (**Table 4.32**). While leaf K concentration was decreased in response to slag treatment in alkaline soil under 2X-NP fertilization, it significantly improved by both ground and non-ground slag application in acidic soil under 1X-NP fertilization (**Table 4.32; 4.33**). The leaf Ca level did not change significantly upon steel slag application in both types of soil (**Table 4.32; 4.33**). The Mg concentration of the leaves grown on non-ground slag-treated alkaline soil decreased by 7% over control whereas there was no significant alteration documented in acidic soil (**Table 4.32; 4.33**). Both ground and non-ground slag treatment in alkaline soil notably decreased the leaf S level by 18% compared to control under 2X-NP condition (**Table 4.32**).

There was no significant change observed in the leaf Fe concentration upon slag amendment in both types of soil (**Table 4.34; 4.35**). The leaf Zn level, on the other hand, showed considerable increase by up to 41% in response to both ground and non-ground slag amendment in alkaline soil under 1X-NP condition (**Table 4.34**). Slag amendment slightly enhanced the leaf Zn level under 2X-NP fertilization regime as well whereas Zn level of leaves grown on acidic soil was non-responsive to steel slag amendment (**Table 4.34; 4.35**). The leaf Mn concentration was significantly boosted by over 17% compared to control in response to both ground and non-ground slag application in alkaline soil under 1X-NP fertilization regime whereas it reduced by 23% over control under 2X-NP condition (**Table 4.34**). No significant increase or decrease was observed in leaf Mn level in acidic soil (**Table 4.35**). The leaf Cu level boosted by over 22% when compared to control acidic soil under 1X-NP fertilization (**Table 4.35**). In alkaline soil, however, there was no considerable change under both regimes of fertilization (**Table 4.34**). The leaf B level responded to steel slag amendment significantly in both soil types (**Table 4.34; 4.35**). Ground slag application into alkaline soil dramatically increased the leaf B level by 270% and 132% under low and high fertilization regimes, respectively. Non-ground slag treatment also drastically enhanced the leaf B concentration by 203% over control in alkaline soil under 1X-NP condition. In acidic soil, on the other hand, 264% and 256% increases in the leaf B

level were documented in response to ground slag amendment under 1X-NP and 2X-NP conditions, respectively. Non-ground slag doses also improved the B level significantly, achieving 59% and 84% enhancements under low and high fertilization types, respectively. The leaf Mo concentration was enhanced in response to slag amendment in alkaline soil, irrespective of the particle size (**Table 4.34**). Ground slag application into alkaline soil ensured 171% (under 1X-NP) and 150% (under 2X-NP) increases over control. In acidic soil, ground slag amendment provided the Mo accumulation in leaves (**Table 4.35**). There was no detectable Mo level in control and non-ground slag treatment groups. The leaf Ni concentration did not respond to slag application in both soil types under both regimes of fertilization (**Table 4.36; 4.37**).

The ground and non-ground slag treatments in alkaline soil reduced the leaf Cd level under both types of fertilization, ensuring a 31% decrease over control under 2X-NP condition (**Table 4.37**). It was also effective in reducing the leaf Cd concentration in acidic soil, achieving 60% decrease compared to control under 1X-NP fertilization. The leaf Cr and Pb concentration, on the other hand, did not respond to any type of slag treatment significantly in both types of soil (**Table 4.36; 4.37**). Steel slag treatment had no impact on the leaf V level (**Table 4.36; 4.37**). The leaf V level was undetectable (<0.001 ppm) in all groups.

Table 4.32: Macrolement concentrations of the leaves of 40-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Macrolement Concentrations (g kg ⁻¹)								
Fertilization	Slag Treatment	N	P	K	Ca	Mg	S	
1X-NP	Control	4.3 ± 0.1 bc	2.7 ± 0.2 b	44.5 ± 0.8 a	6.6 ± 0.2 b	2.04 ± 0.09 c	3.7 ± 0.2 b	
	G-2.0%	4.1 ± 0.0 c	2.7 ± 0.1 b	46.2 ± 0.6 a	6.1 ± 0.1 b	2.04 ± 0.06 c	3.4 ± 0.1 b	
	NG-2.0%	4.1 ± 0.2 c	2.5 ± 0.1 b	45.3 ± 0.8 a	6.1 ± 0.4 b	2.06 ± 0.07 c	3.6 ± 0.1 b	
2X-NP	Control	4.6 ± 0.2 a	3.2 ± 0.1 a	45.7 ± 0.5 a	7.9 ± 0.2 a	2.30 ± 0.06 a	4.4 ± 0.1 a	
	G-2.0%	4.3 ± 0.1 bc	2.8 ± 0.2 ab	44.1 ± 1.4 ab	8.2 ± 0.7 a	2.22 ± 0.08 ab	3.7 ± 0.2 b	
	NG-2.0%	4.4 ± 0.1 ab	3.1 ± 0.3 a	42.0 ± 1.4 b	7.6 ± 0.6 a	2.13 ± 0.04 bc	3.6 ± 0.1 b	

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.33: Macroelement concentrations of the leaves of 40-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Macroelement Concentrations (g kg ⁻¹)													
Fertilization	Slag Treatment	N		P		K		Ca		Mg		S	
1X-NP	Control	4.5 ± 0.1	b-d	1.4 ± 0.1	c	53.5 ± 1.8	b	3.0 ± 0.2	bc	1.19 ± 0.04	ab	3.0 ± 0.1	ab
	G-2.0%	4.4 ± 0.1	d	2.6 ± 0.1	a	57.7 ± 2.3	a	3.4 ± 0.3	b	1.31 ± 0.10	a	2.9 ± 0.1	b
	NG-2.0%	4.8 ± 0.2	ab	2.6 ± 0.2	a	58.1 ± 0.8	a	3.0 ± 0.0	c	1.12 ± 0.01	b	3.2 ± 0.1	a
2X-NP	Control	5.1 ± 0.1	a	1.8 ± 0.1	b	51.0 ± 1.4	b	4.4 ± 0.2	a	1.31 ± 0.07	a	3.0 ± 0.1	ab
	G-2.0%	4.4 ± 0.2	cd	2.5 ± 0.2	a	53.7 ± 1.3	b	4.0 ± 0.2	a	1.24 ± 0.03	a	3.1 ± 0.1	ab
	NG-2.0%	4.7 ± 0.2	bc	2.5 ± 0.2	a	51.7 ± 1.4	b	4.0 ± 0.3	a	1.21 ± 0.04	ab	3.2 ± 0.1	ab

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test (p≤0.05).

Table 4.34: Microelement concentrations of the leaves of 40-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Microelement Concentrations (mg kg ⁻¹)															
Fertilization	Slag Treatment	Fe		Zn		Mn		Cu		B		Mo		Ni	
1X-NP	Control	107 ± 9	a	32 ± 2	c	97 ± 4	b	10.7 ± 0.9	ab	3.3 ± 0.2	c	0.7 ± 0.1	c	1.6 ± 0.2	a
	G-2.0%	116 ± 18	a	45 ± 4	a	115 ± 6	a	10.5 ± 0.2	b	12.2 ± 1.8	ab	1.9 ± 0.3	a	2.1 ± 0.9	a
	NG-2.0%	111 ± 22	a	43 ± 2	a	114 ± 4	a	10.8 ± 0.2	ab	10.0 ± 1.2	b	1.2 ± 0.1	bc	1.8 ± 0.6	a
2X-NP	Control	106 ± 7	a	32 ± 1	c	108 ± 4	ab	11.7 ± 0.3	a	5.6 ± 0.3	c	0.6 ± 0.1	c	1.9 ± 0.4	a
	G-2.0%	107 ± 19	a	37 ± 1	b	108 ± 7	ab	11.1 ± 0.3	ab	13.0 ± 1.7	a	1.5 ± 0.5	ab	2.1 ± 0.7	a
	NG-2.0%	100 ± 3	a	34 ± 0	bc	83 ± 5	c	10.4 ± 0.2	b	5.5 ± 1.1	c	0.9 ± 0.4	c	1.7 ± 0.3	a

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.35: Microelement concentrations of the leaves of 40-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Microelement Concentrations (mg kg ⁻¹)														
Fertilization	Slag Treatment	Fe		Zn		Mn		Cu		B		Mo	Ni	
1X-NP	Control	116 ± 24	a	55 ± 4	a	202 ± 6	a	7.4 ± 0.4	b	3.9 ± 0.3	d	<i>n.d</i>	2.8 ± 2.2	a
	G-2.0%	121 ± 19	a	54 ± 8	a	228 ± 50	a	9.3 ± 0.3	a	14.2 ± 0.3	a	0.51 ± 0.05	1.9 ± 0.1	a
	NG-2.0%	133 ± 11	a	58 ± 1	a	240 ± 16	a	9.0 ± 0.1	a	6.2 ± 0.6	c	<i>n.d</i>	1.7 ± 0.2	a
2X-NP	Control	139 ± 60	a	59 ± 9	a	238 ± 19	a	8.5 ± 0.6	a	4.5 ± 0.6	cd	<i>n.d</i>	1.6 ± 0.3	a
	G-2.0%	104 ± 23	a	53 ± 3	a	238 ± 12	a	8.8 ± 0.2	a	16.0 ± 1.2	a	0.26 ± 0.05	1.0 ± 0.2	a
	NG-2.0%	118 ± 5	a	64 ± 12	a	242 ± 19	a	9.2 ± 0.3	a	8.3 ± 1.4	b	<i>n.d</i>	2.0 ± 1.2	a

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test (p≤0.05).

Table 4.36: Potentially toxic non-essential element concentrations of the leaves of 40-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Potentially Toxic Non-Essential Element Concentrations (mg kg ⁻¹)					
Fertilization	Slag Treatment	Cr	Cd	V	Pb
1X-NP	Control	5.8 ± 1.3 a	0.16 ± 0.02 a	<i>n.d.</i>	1.85 ± 0.81 a
	G-2.0%	7.8 ± 3.4 a	0.12 ± 0.03 ab	<i>n.d.</i>	1.71 ± 0.41 a
	NG-2.0%	6.4 ± 2.1 a	0.14 ± 0.01 ab	<i>n.d.</i>	0.87 ± 0.28 a
2X-NP	Control	6.6 ± 1.7 a	0.16 ± 0.03 a	<i>n.d.</i>	1.73 ± 0.40 a
	G-2.0%	7.5 ± 2.8 a	0.11 ± 0.01 b	<i>n.d.</i>	1.71 ± 0.58 a
	NG-2.0%	6.2 ± 0.7 a	0.11 ± 0.01 b	<i>n.d.</i>	1.50 ± 0.08 a

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.37: Potentially toxic non-essential element concentrations of the leaves of 40-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Potentially Toxic Non-Essential Element Concentrations (mg kg ⁻¹)						
Fertilization	Slag Treatment	Cr	Cd	V	Pb	
1X-NP	Control	8.3 ± 3.0 a	0.25 ± 0.02 a	<i>n.d.</i>	1.00 ± 0.33 a	
	G-2.0%	7.2 ± 1.1 ab	0.17 ± 0.04 b	<i>n.d.</i>	0.77 ± 0.32 a	
	NG-2.0%	6.7 ± 1.0 ab	0.10 ± 0.01 c	<i>n.d.</i>	1.23 ± 0.25 a	
2X-NP	Control	5.7 ± 0.7 ab	0.17 ± 0.03 b	<i>n.d.</i>	1.34 ± 0.42 a	
	G-2.0%	4.1 ± 0.9 b	0.13 ± 0.02 bc	<i>n.d.</i>	1.13 ± 0.59 a	
	NG-2.0%	6.5 ± 2.1 ab	0.16 ± 0.04 bc	<i>n.d.</i>	1.19 ± 0.20 a	

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

General appearance of 123-day-old plants were documented as shown in **Figure 4.7**. There was no recognizable change observed in general appearance of the plants grown on alkaline soil whereas EAF slag amendment was showed to improve shoot density in acidic soil, particularly upon ground slag treatment.

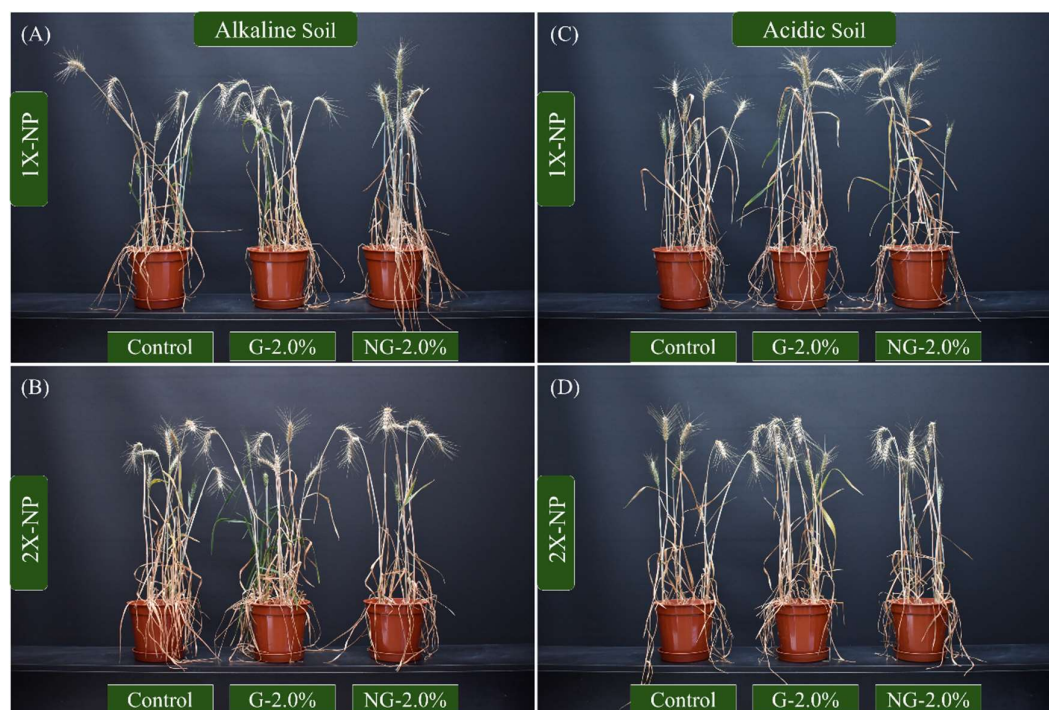


Figure 4.7: General harvest time appearance of 123 day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline (A-B) or acidic (C-D) soils treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP (A-C) or 2X-NP (B-D) fertilization regimes

Grain yield was non-responsive to slag amendment in alkaline soil whereas it considerably improved through ground slag application into acidic soil (**Table 4.38**). Under 1X-NP condition, 22% increase was achieved in response to ground slag amendment while it reached 58% increase over control under 2X-NP fertilization regime. Slag amendment had no significant effect on grain number in alkaline soil whereas it ensured significant enhancement by over 61% over control in acidic soil under 2X-NP condition (**Table 4.38**). Although several increases or decreases were observed in 1000 grain weight, no significant change was documented in both soils.

Table 4.38: Grain yield, grain number and 1000 grain weight results obtained from the spikes of 123-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline or acidic soils treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Fertilization	Slag Treatment	Grain Yield (g plant ⁻¹)		Grain Number (plant ⁻¹)		1000 Grain Weight (g)	
		Alkaline Soil	Acidic Soil	Alkaline Soil	Acidic Soil	Alkaline Soil	Acidic Soil
1X-NP	Control	1.90 ± 0.40 a	1.67 ± 0.39 b	185 ± 52 a	160 ± 49 b	41.8 ± 4.7 a	39.6 ± 1.7 a
	G-2.0%	1.84 ± 0.13 a	2.04 ± 0.32 ab	186 ± 29 a	187 ± 27 ab	40.1 ± 4.1 a	43.9 ± 4.8 a
	NG-2.0%	1.96 ± 0.64 a	1.81 ± 0.37 b	196 ± 59 a	146 ± 24 b	39.6 ± 1.5 a	42.8 ± 5.6 a
2X-NP	Control	2.23 ± 0.45 a	1.65 ± 0.40 b	205 ± 40 a	156 ± 37 b	40.5 ± 4.3 a	42.3 ± 2.6 a
	G-2.0%	2.07 ± 0.35 a	2.61 ± 0.34 a	197 ± 19 a	252 ± 21 a	41.9 ± 3.2 a	41.5 ± 3.5 a
	NG-2.0%	2.42 ± 0.13 a	1.88 ± 0.18 ab	231 ± 17 a	201 ± 21 ab	42.0 ± 1.1 a	37.4 ± 2.4 a

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

After the grain yield determination results, the grains were subjected to element analysis (**Table 4.39; 4.40; 4.41; 4.42; 4.43; 4.44**). The grain N, P, and K levels did not respond to slag treatment significantly in both soils (**Table 4.39; 4.40**). Although the grain Ca concentration showed slight changes in response to slag amendment, no significant difference was reported (**Table 4.39; 4.40**). The grain Mg concentration, on the other hand, notably increased by over 11% compared to control in response to slag amendment in acidic soil under 2X-NP condition, regardless of the particle size (**Table 4.40**). Non-ground slag amendment in alkaline soil significantly elevated the grain S concentration under 1X-NP whereas it reduced the S concentration under 2X-NP condition (**Table 4.39**). In acidic soil, ground slag treatment reduced the grain S concentration considerably, causing a 8% decrease over control under 2X-NP fertilization (**Table 4.40**).

Non-ground slag application into alkaline soil caused a 23% decrease in the grain Fe level compared to control under 2X-NP fertilization regime whereas it had no impact on the same parameter in acidic soil (**Table 4.41; 4.42**). The grain Zn level, on the other hand, remarkably boosted in response to both ground and non-ground slag application into alkaline soil under 1X-NP condition, ensuring a 28% increase over control (**Table 4.41**). In acidic soil, however, slag application decreased the grain Fe concentration under 1X-NP condition, irrespective of the particle size (**Table 4.42**). The grain Mn concentration reduced significantly in response to non-ground slag treatment in alkaline soil under 2X-NP fertilization regime (**Table 4.41**). Non-ground slag amendment in alkaline soil decreased the grain Cu concentration notably by 12% over control under 2X-NP condition. However, the same treatment elevated the same parameter by 14% compared to control under 1X-NP fertilization. The grain B level was non-responsive to steel slag application in alkaline soil (**Table 4.41**). Ground slag amendment slightly boosted the same parameter in acidic soil under 1X-NP fertilization (**Table 4.42**). It also ensured significant enhancement in the grain Mo level in alkaline soil by 45% (under 1X-NP) and 37% (under 2X-NP) over control (**Table 4.41**). Ground slag amendment provided the Mo accumulation in grain tissues grown on acidic soil (**Table 4.42**). The grain Mo concentration was undetectable in control and non-ground treatment groups.

Steel slag had no notable impact on the grain Ni, Cr, V, and Pb level (**Table 4.43; 4.44**). The concentrations of those potentially toxic elements were undetectable

(<0.001 ppm) in all groups. Slag amendment affected the grain Cd level in alkaline soil, achieving 43% decrease over control under 2X-NP condition, regardless of the particle size (**Table 4.43**). In acidic soil, on the other hand, ground and non-ground slag treatment drastically reduced the same parameter by 70% and 55% over control under 1X-NP fertilization, respectively (**Table 4.44**).

Table 4.39: Macroelement concentrations of the grains of 123-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Macroelement Concentrations (g kg ⁻¹)							
Fertilization	Slag Treatment	N	P	K	Ca	Mg	S
1X-NP	Control	3.22 ± 0.47 a	4.94 ± 0.15 a	5.41 ± 0.29 a	0.55 ± 0.04 ab	1.75 ± 0.07 ab	2.03 ± 0.06 bc
	G-2.0%	3.44 ± 0.12 a	4.77 ± 0.33 a	5.36 ± 0.54 a	0.54 ± 0.03 b	1.77 ± 0.10 ab	1.94 ± 0.08 c
	NG-2.0%	3.44 ± 0.37 a	5.22 ± 0.35 a	5.67 ± 0.48 a	0.53 ± 0.06 b	1.86 ± 0.07 a	2.22 ± 0.08 a
2X-NP	Control	3.34 ± 0.16 a	5.44 ± 0.50 a	5.43 ± 0.68 a	0.62 ± 0.06 ab	1.87 ± 0.11 a	2.32 ± 0.11 a
	G-2.0%	3.19 ± 0.14 a	4.88 ± 0.10 a	5.18 ± 0.32 a	0.65 ± 0.06 a	1.75 ± 0.03 ab	2.18 ± 0.06 ab
	NG-2.0%	3.43 ± 0.21 a	4.74 ± 0.50 a	5.40 ± 0.40 a	0.62 ± 0.02 ab	1.67 ± 0.09 b	2.01 ± 0.04 bc

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.40: Macroelement concentrations of the grains of 123-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Macroelement Concentrations (g kg ⁻¹)							
Fertilization	Slag Treatment	N	P	K	Ca	Mg	S
1X-NP	Control	3.46 ± 0.18 a	4.75 ± 0.07 a	4.73 ± 0.25 a	0.33 ± 0.08 b	1.78 ± 0.02 ab	2.10 ± 0.06 ab
	G-2.0%	3.21 ± 0.03 a	4.88 ± 0.32 a	5.22 ± 0.63 a	0.34 ± 0.03 b	1.87 ± 0.14 a	1.96 ± 0.04 b
	NG-2.0%	3.40 ± 0.17 a	4.66 ± 0.11 a	4.83 ± 0.16 a	0.35 ± 0.03 b	1.78 ± 0.03 ab	1.99 ± 0.10 b
2X-NP	Control	3.39 ± 0.14 a	4.73 ± 0.27 a	5.04 ± 0.12 a	0.54 ± 0.12 a	1.65 ± 0.07 b	2.16 ± 0.08 a
	G-2.0%	3.32 ± 0.21 a	4.81 ± 0.24 a	5.17 ± 0.21 a	0.46 ± 0.05 ab	1.84 ± 0.06 a	1.99 ± 0.04 b
	NG-2.0%	3.46 ± 0.14 a	4.97 ± 0.13 a	5.44 ± 0.51 a	0.49 ± 0.10 ab	1.86 ± 0.03 a	2.01 ± 0.08 ab

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.41: Microelement concentrations of the grains of 123-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Microelement Concentrations (mg kg ⁻¹)									
Fertilization	Slag Treatment	Fe	Zn	Mn	Cu	B	Mo	Ni	
1X-NP	Control	44.6 ± 3.3 bc	47 ± 4 c	42 ± 2 ab	7.2 ± 0.4 bc	0.34 ± 0.11 ab	0.49 ± 0.06 c	n.d	
	G-2.0%	45.3 ± 3.6 bc	60 ± 6 ab	38 ± 0 b	7.5 ± 0.3 a-c	0.56 ± 0.16 a	0.71 ± 0.10 ab	n.d	
	NG-2.0%	47.0 ± 5.9 bc	62 ± 6 a	41 ± 3 ab	8.2 ± 0.6 a	0.27 ± 0.07 b	0.62 ± 0.07 a-c	n.d	
2X-NP	Control	56.3 ± 1.0 a	42 ± 4 c	46 ± 3 a	7.7 ± 0.3 ab	0.50 ± 0.08 ab	0.54 ± 0.12 bc	n.d	
	G-2.0%	51.2 ± 1.7 ab	50 ± 3 bc	42 ± 2 ab	7.5 ± 0.2 a-c	0.49 ± 0.09 ab	0.74 ± 0.10 a	n.d	
	NG-2.0%	43.1 ± 2.0 c	41 ± 5 c	37 ± 4 b	6.8 ± 0.2 c	0.40 ± 0.15 ab	0.56 ± 0.03 a-c	n.d	

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.42: Microelement concentrations of the grains of 123-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Microelement Concentrations (mg kg ⁻¹)										
Fertilization	Slag Treatment	Fe	Zn	Mn	Cu	B	Mo	Ni		
1X-NP	Control	69.4 ± 3.7 a	102 ± 5 a	91 ± 3 ab	7.5 ± 0.2 a	0.57 ± 0.04 c	<i>n.d</i>	<i>n.d</i>		
	G-2.0%	64.3 ± 6.2 a	77 ± 4 b	69 ± 23 b	7.1 ± 0.3 ab	0.71 ± 0.07 ab	0.36 ± 0.04	<i>n.d</i>		
	NG-2.0%	68.7 ± 4.0 a	88 ± 5 ab	112 ± 3 a	7.5 ± 0.5 a	0.66 ± 0.03 bc	<i>n.d</i>	<i>n.d</i>		
2X-NP	Control	65.6 ± 6.2 a	88 ± 11 ab	110 ± 10 a	6.2 ± 0.6 c	0.74 ± 0.10 ab	<i>n.d</i>	<i>n.d</i>		
	G-2.0%	70.6 ± 3.9 a	78 ± 7 b	90 ± 4 ab	6.4 ± 0.2 bc	0.83 ± 0.06 a	0.29 ± 0.06	<i>n.d</i>		
	NG-2.0%	73.1 ± 5.1 a	89 ± 12 ab	97 ± 8 a	6.4 ± 0.5 bc	0.81 ± 0.02 a	<i>n.d</i>	<i>n.d</i>		

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.43: Potentially toxic non-essential element concentrations of the grains of 123-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Potentially Toxic Non-Essential Element Concentrations (mg kg ⁻¹)					
Fertilization	Slag Treatment	Cr	Cd	V	Pb
1X-NP	Control	<i>n.d</i>	0.03 ± 0.01 ^b	<i>n.d</i>	<i>n.d</i>
	G-2.0%	<i>n.d</i>	0.02 ± 0.01 ^b	<i>n.d</i>	<i>n.d</i>
	NG-2.0%	<i>n.d</i>	0.03 ± 0.01 ^b	<i>n.d</i>	<i>n.d</i>
2X-NP	Control	<i>n.d</i>	0.07 ± 0.01 ^a	<i>n.d</i>	<i>n.d</i>
	G-2.0%	<i>n.d</i>	0.04 ± 0.00 ^b	<i>n.d</i>	<i>n.d</i>
	NG-2.0%	<i>n.d</i>	0.04 ± 0.01 ^b	<i>n.d</i>	<i>n.d</i>

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.44: Potentially toxic non-essential element concentrations of the grains of 123-day-old bread wheat (*Triticum aestivum* cv. Nusrat) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with the selected dose (2.0%) under 1X-NP or 2X-NP fertilization regimes

Potentially Toxic Non-Essential Element Concentrations (mg kg ⁻¹)					
Fertilization	Slag Treatment	Cr	Cd	V	Pb
1X-NP	Control	<i>n.d</i>	0.20 ± 0.01 ^a	<i>n.d</i>	<i>n.d</i>
	G-2.0%	<i>n.d</i>	0.06 ± 0.01 ^c	<i>n.d</i>	<i>n.d</i>
	NG-2.0%	<i>n.d</i>	0.09 ± 0.01 ^{bc}	<i>n.d</i>	<i>n.d</i>
2X-NP	Control	<i>n.d</i>	0.13 ± 0.02 ^b	<i>n.d</i>	<i>n.d</i>
	G-2.0%	<i>n.d</i>	0.09 ± 0.01 ^{bc}	<i>n.d</i>	<i>n.d</i>
	NG-2.0%	<i>n.d</i>	0.13 ± 0.04 ^b	<i>n.d</i>	<i>n.d</i>

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

4.5. The Effect of Different Slag Doses on the Growth, Yield, and Mineral Composition of Lettuce

The impact of steel slag amendment on lettuce (*Lactuca sativa* cv. Papyon) was investigated. General appearance of lettuce grown on control or slag-treated alkaline and acidic soils was shown in **Figure 4.8**. No considerable change in lettuce density was observed as a result of slag amendment in alkaline soil. All treatment groups under both fertilization regimes were similar in terms of general growth. In acidic soil, however, lettuce growth was observed to improve upon increasing EAF slag doses, particularly under 1X-NP fertilization.

Lettuce growth was documented by obtaining the dry biomass data (**Table 4.45**). According to the results, steel slag amendment showed no significant impact on lettuce dry biomass. Increasing doses of ground slag application into alkaline soil slightly reduced the dry biomass by 10%, 21%, and 28% over control under 1X-NP fertilization, respectively. The lowest dose of ground slag amendment under 2X-NP condition, on the other hand, increased the dry biomass by up to 13% compared to control. Other slag doses reduced the dry biomass values under 2X-NP condition, regardless of the particle size. In acidic soil, however, drastic increases were observed over control under both types of fertilization. Increasing doses of ground slag application into acidic soil enhanced the dry biomass by approximately 2-fold, 3-fold, and 5-fold compared to control under 1X-NP condition, respectively. In addition, the highest dose of non-ground slag also significantly improved the dry biomass 187% over control under the same fertilization. Steel slag amendment was remarkably effective under 2X-NP condition as well. The medium and the highest doses of ground slag significantly boosted the dry biomass by 125% and 160% over control under 2X-NP fertilization regime. Non-ground slag doses also achieved slight increases in dry biomass, reaching 30% increase over control under 2X-NP fertilization, irrespective of the dose.

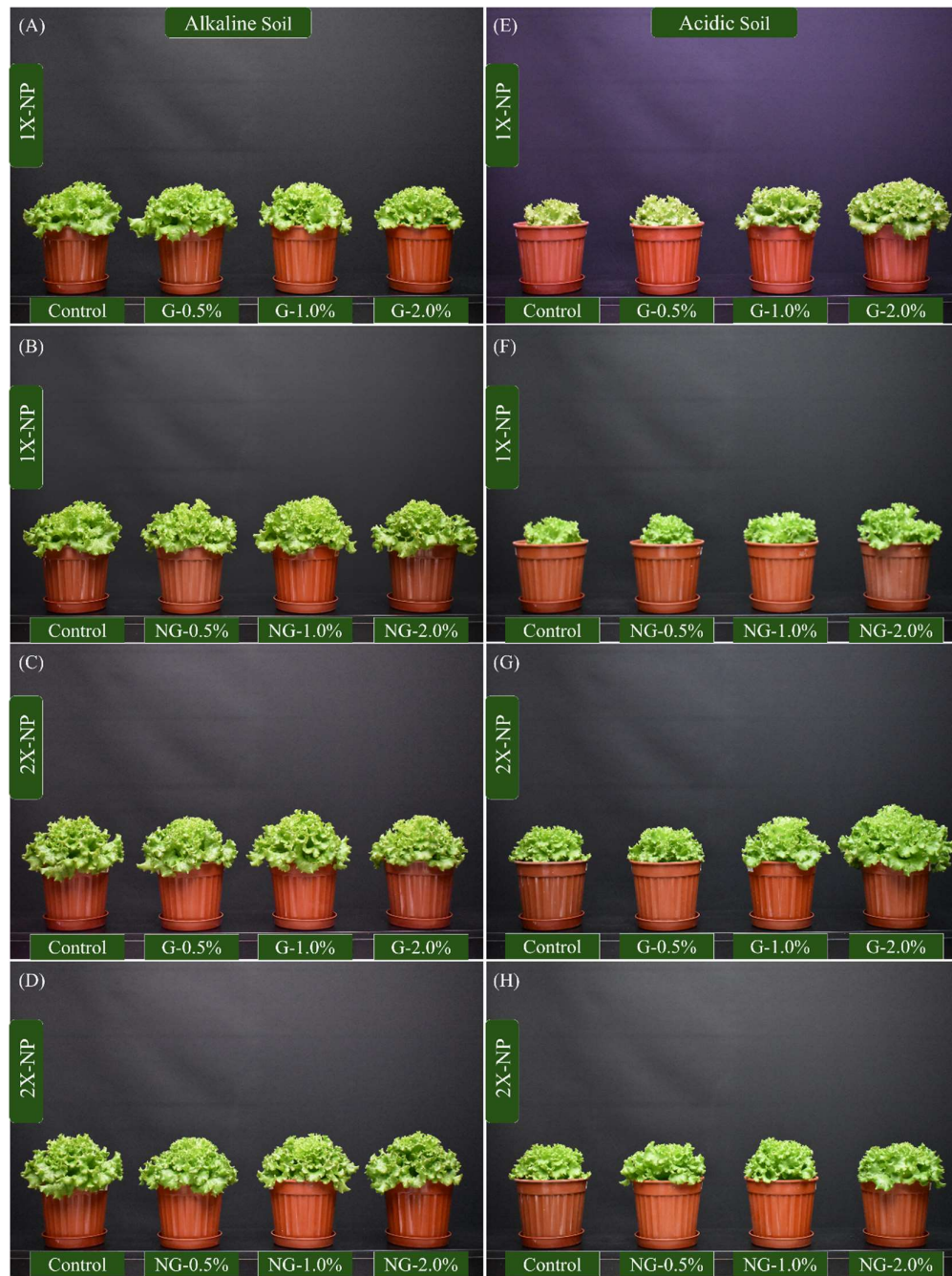


Figure 4.8: General harvest time appearance of 59 day-old lettuce (*Lactuca sativa* cv. Papyon) grown on alkaline (A-B-C-D) or acidic (E-F-G-H) soils treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP (A-B-E-F) or 2X-NP (C-D-G-H) fertilization regimes

Table 4.45: Dry biomass results obtained from 59-day-old lettuce (*Lactuca sativa* cv. Papyon) grown on alkaline or acidic soils treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Fertilization	Slag Treatment	Dry Biomass (g plant ⁻¹)			
		Alkaline Soil		Acidic Soil	
1X-NP	Control	3.9 ± 0.7	a-c	0.8 ± 0.3	d
	G-0.5%	3.5 ± 0.3	bc	1.8 ± 0.2	b-d
	G-1.0%	3.1 ± 0.7	bc	2.3 ± 0.8	bc
	G-2.0%	2.8 ± 0.2	c	4.4 ± 0.3	a
	NG-0.5%	4.0 ± 0.6	a-c	1.1 ± 0.2	cd
	NG-1.0%	3.9 ± 0.6	a-c	1.7 ± 0.1	b-d
	NG-2.0%	4.1 ± 0.8	a-c	2.3 ± 0.5	bc
2X-NP	Control	4.6 ± 0.3	ab	2.0 ± 0.6	b-d
	G-0.5%	5.2 ± 0.5	a	2.5 ± 0.2	b
	G-1.0%	4.2 ± 0.9	a-c	4.5 ± 0.9	a
	G-2.0%	3.5 ± 0.6	bc	5.2 ± 0.6	a
	NG-0.5%	4.5 ± 0.6	ab	2.6 ± 0.6	b
	NG-1.0%	3.8 ± 0.7	a-c	2.4 ± 0.5	bc
	NG-2.0%	4.3 ± 0.5	a-c	2.6 ± 0.8	b

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

After obtaining the dry biomass results, mineral composition of lettuce was determined (**Table 4.46; 4.47; 4.48; 4.49; 4.50; 4.51**). The lettuce P concentration did not respond significantly to steel slag application in alkaline soil (**Table 4.46**). In acidic soil, however, slag treatment reduced the P concentration under 1X-NP condition (**Table 4.47**). The medium dose of ground slag and the lowest dose of non-ground slag significantly decreased the P level by up to 24% over control under the same conditions. Slag application into alkaline soil generally enhanced the lettuce K concentration under both fertilization types (**Table 4.46**). The highest dose of ground

slag amendment caused significant increase in K concentration by over 21% compared to control in alkaline soil under 1X-NP condition. It also ensured slight increases in K concentration in the same soil type under 2X-NP condition whereas there was no significant change determined in acidic soil under both fertilization regimes (**Table 4.47**). The lettuce Ca level was non-responsive to steel slag amendment in alkaline soil (**Table 4.46**). In acidic soil, however, the medium and the highest dose of ground slag treatment significantly improved the Ca concentration by 75% and 50% under 2X-NP condition, respectively (**Table 4.47**). Steel slag application had no remarkable effect on the lettuce Mg concentration in both types of soil (**Table 4.46; 4.47**). Nevertheless, the medium dose of ground slag slightly boosted the Mg level in acidic soil by 28% over control under 2X-NP fertilization regime. The lettuce S concentration, on the other hand, did not respond to any type of slag amendment in either type of soil under both fertilization regimes (**Table 4.46; 4.47**).

The lettuce Fe level was non-responsive to steel slag amendment in both alkaline and acidic soils under either type of fertilization (**Table 4.48; 4.49**). Increasing doses of slag amendment in alkaline soil enhanced the lettuce Zn concentration under 1X-NP condition (**Table 4.48**). The medium and the highest dose of ground slag application, for instance, caused notable increases by 56% and 84% over control in alkaline soil under 1X-NP fertilization regime, respectively. Under 2X-NP condition, on the other hand, the highest dose of ground slag amendment significantly improved the Zn concentration by up to 54% compared to control. In acidic soil, the medium dose of ground slag treatment elevated the lettuce Zn level by 67% over control under 2X-NP fertilization (**Table 4.49**). The lettuce Mn concentration did not respond to slag application significantly in both soils under either type of fertilization regimes (**Table 4.48; 4.49**). In alkaline soil, the medium and the highest dose of ground slag treatment ensured considerable increases in the Cu level by 29% and 25% over control under 2X-NP condition, respectively (**Table 4.48**). However, slag amendment caused no significant alteration in the Cu level in acidic soil under either fertilization regimes (**Table 4.49**). The lettuce B level was non-responsive to steel slag treatment in alkaline soil whereas the medium dose of ground slag amendment significantly elevated the B concentration by 19% compared to control in acidic soil under 1X-NP condition (**Table 4.48; 4.49**). The lettuce Mo level was non-responsive to steel slag application

in alkaline soil (**Table 4.48**). Its concentration was undetectable in all treatment groups including control in acidic soil (**Table 4.49**). Steel slag treatment caused no significant difference in the lettuce Ni level between control and treatment groups in both types of soil (**Table 4.50; 4.51**).

The lettuce Cd level, on the other hand, did not change significantly in response to steel slag application in both alkaline and acidic soil types (**Table 4.50; 4.51**). Steel slag amendment did not affect the lettuce Cr, V, or Pb levels notably (**Table 4.50; 4.51**). The concentrations of Cr, V, or Pb in lettuce were undetectable in all groups (<0.001 ppm).

Table 4.46: Macroelement concentrations of 59-day-old lettuce (*Lactuca sativa* cv. Papyon) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Macroelement Concentrations (g kg ⁻¹)								
Fertilization	Slag Treatment	P	K	Ca	Mg	S		
1X-NP	Control	4.1 ± 0.4 a	53.0 ± 4.6 b	17.7 ± 1.4 d	6.5 ± 0.6 a	4.0 ± 0.2 a-c		
	G-0.5%	4.3 ± 0.3 a	54.2 ± 3.4 ab	18.8 ± 0.5 b-d	6.5 ± 0.1 a	4.1 ± 0.2 a-c		
	G-1.0%	4.8 ± 0.4 a	57.7 ± 4.1 ab	19.4 ± 1.8 a-d	6.2 ± 0.7 a	4.3 ± 0.3 ab		
	G-2.0%	4.7 ± 0.2 a	64.5 ± 2.2 a	18.5 ± 0.4 b-d	5.8 ± 0.4 a	4.4 ± 0.1 a		
	NG-0.5%	4.4 ± 0.4 a	55.6 ± 2.9 ab	18.5 ± 1.7 b-d	6.3 ± 0.5 a	4.4 ± 0.1 a		
	NG-1.0%	4.6 ± 0.3 a	54.0 ± 3.4 ab	20.1 ± 0.8 a-d	6.4 ± 0.6 a	4.4 ± 0.2 a		
	NG-2.0%	4.5 ± 0.2 a	54.1 ± 6.0 ab	18.4 ± 1.5 cd	6.3 ± 0.6 a	4.0 ± 0.3 a-c		
2X-NP	Control	4.7 ± 0.7 a	55.1 ± 5.6 ab	22.6 ± 2.1 a	6.5 ± 0.5 a	4.1 ± 0.6 a-c		
	G-0.5%	4.4 ± 0.3 a	59.9 ± 6.9 ab	21.8 ± 0.9 ab	6.0 ± 0.5 a	4.0 ± 0.2 a-c		
	G-1.0%	4.8 ± 0.4 a	58.6 ± 3.2 ab	21.1 ± 0.6 a-c	5.8 ± 0.4 a	3.9 ± 0.1 a-c		
	G-2.0%	4.5 ± 0.4 a	60.8 ± 3.5 ab	19.6 ± 1.0 a-d	5.6 ± 0.4 a	4.0 ± 0.1 a-c		
	NG-0.5%	4.0 ± 0.4 a	56.2 ± 4.9 ab	20.1 ± 1.4 a-d	6.0 ± 0.6 a	3.7 ± 0.2 bc		
	NG-1.0%	4.2 ± 0.4 a	58.7 ± 4.5 ab	20.7 ± 1.9 a-d	5.8 ± 0.3 a	3.9 ± 0.3 a-c		
	NG-2.0%	4.4 ± 0.6 a	54.0 ± 3.7 ab	22.2 ± 1.1 a	6.0 ± 0.3 a	3.6 ± 0.2 c		

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.47: Macroelement concentrations of 59-day-old lettuce (*Lactuca sativa* cv. Papyon) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Macroelement Concentrations (g kg ⁻¹)								
Fertilization	Slag Treatment	P	K	Ca	Mg	S		
1X-NP	Control	4.1 ± 0.6 a	81.8 ± 1.6 ab	13.2 ± 0.7 bc	3.1 ± 0.3 a-c	3.6 ± 0.2 a		
	G-0.5%	3.5 ± 0.3 ab	85.3 ± 6.1 ab	13.0 ± 1.0 bc	3.0 ± 0.3 a-c	3.7 ± 0.2 a		
	G-1.0%	3.1 ± 0.1 b	86.5 ± 3.4 ab	11.6 ± 2.4 c	2.8 ± 0.3 bc	3.7 ± 0.3 a		
	G-2.0%	3.5 ± 0.3 ab	79.7 ± 6.4 b	13.8 ± 1.7 bc	3.7 ± 0.3 a-c	3.5 ± 0.2 a		
	NG-0.5%	3.1 ± 0.4 b	85.5 ± 4.7 ab	13.5 ± 1.7 bc	3.2 ± 0.5 a-c	3.4 ± 0.2 a		
	NG-1.0%	3.6 ± 0.1 ab	86.7 ± 1.7 ab	11.2 ± 0.5 bc	2.6 ± 0.1 c	3.9 ± 0.1 a		
	NG-2.0%	3.5 ± 0.2 ab	85.7 ± 3.5 ab	14.0 ± 3.9 bc	2.9 ± 0.5 a-c	3.8 ± 0.3 a		
2X-NP	Control	3.6 ± 0.5 ab	83.0 ± 4.2 ab	11.4 ± 1.3 c	3.2 ± 0.3 a-c	3.8 ± 0.3 a		
	G-0.5%	3.4 ± 0.3 ab	77.2 ± 3.4 b	14.1 ± 1.8 bc	3.1 ± 0.2 a-c	3.9 ± 0.3 a		
	G-1.0%	3.4 ± 0.3 ab	79.0 ± 4.2 b	19.9 ± 1.8 a	4.1 ± 0.7 a	3.7 ± 0.1 a		
	G-2.0%	3.7 ± 0.2 ab	85.9 ± 8.1 ab	17.1 ± 1.9 ab	3.9 ± 0.2 ab	3.8 ± 0.2 a		
	NG-0.5%	3.4 ± 0.3 ab	87.3 ± 3.7 ab	14.2 ± 1.0 bc	3.1 ± 0.1 a-c	3.9 ± 0.2 a		
	NG-1.0%	3.2 ± 0.3 b	91.9 ± 3.3 a	12.9 ± 1.4 bc	3.4 ± 0.1 a-c	4.0 ± 0.1 a		
	NG-2.0%	3.2 ± 0.1 b	88.7 ± 3.9 ab	12.4 ± 3.6 bc	3.5 ± 1.0 a-c	3.9 ± 0.2 a		

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.48: Microelement concentrations of 59-day-old lettuce (*Lactuca sativa* cv. Papyon) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Microelement Concentrations (mg kg ⁻¹)										
Fertilization	Slag Treatment	Fe	Zn	Mn	Cu	B	Mo	Ni		
1X-NP	Control	293 ± 120 a	32 ± 2 e	103 ± 12 a	14.2 ± 1.9 a-d	38.6 ± 3.3 a	0.33 ± 0.08 a-d	0.8 ± 0.5 a		
	G-0.5%	220 ± 52 a	36 ± 3 de	113 ± 4 a	15.0 ± 0.5 a-d	36.3 ± 0.7 a	0.42 ± 0.06 ab	1.1 ± 1.0 a		
	G-1.0%	210 ± 61 a	50 ± 4 a-c	116 ± 15 a	17.1 ± 1.3 a	35.8 ± 3.0 a	0.39 ± 0.03 a-c	0.8 ± 0.4 a		
	G-2.0%	253 ± 51 a	59 ± 9 a	116 ± 10 a	16.7 ± 1.0 a-d	35.9 ± 1.3 a	0.45 ± 0.04 a	0.7 ± 0.3 a		
	NG-0.5%	193 ± 59 a	39 ± 4 c-e	106 ± 6 a	15.3 ± 1.3 a-d	37.6 ± 1.7 a	0.34 ± 0.05 a-d	0.8 ± 0.3 a		
	NG-1.0%	242 ± 160 a	43 ± 3 b-e	114 ± 14 a	16.2 ± 0.8 a-c	37.5 ± 2.1 a	0.36 ± 0.02 a-c	1.5 ± 1.8 a		
	NG-2.0%	192 ± 28 a	47 ± 3 a-d	100 ± 12 a	16.4 ± 1.0 a-c	36.1 ± 3.9 a	0.43 ± 0.02 a	0.6 ± 0.1 a		
2X-NP	Control	186 ± 48 a	35 ± 9 e	118 ± 10 a	12.8 ± 2.1 d	36.2 ± 3.9 a	0.28 ± 0.09 b-d	0.9 ± 0.4 a		
	G-0.5%	228 ± 89 a	36 ± 3 de	111 ± 13 a	13.6 ± 0.9 b-d	37.0 ± 1.6 a	0.32 ± 0.05 a-d	0.7 ± 0.2 a		
	G-1.0%	239 ± 54 a	43 ± 3 b-e	119 ± 8 a	16.5 ± 0.7 a-c	36.3 ± 2.6 a	0.32 ± 0.05 a-d	1.0 ± 0.3 a		
	G-2.0%	239 ± 94 a	54 ± 3 ab	112 ± 19 a	16.0 ± 1.6 a-c	34.3 ± 2.3 a	0.34 ± 0.06 a-d	0.7 ± 0.3 a		
	NG-0.5%	213 ± 52 a	31 ± 5 e	109 ± 11 a	13.4 ± 1.3 cd	35.8 ± 2.6 a	0.21 ± 0.08 d	0.8 ± 0.1 a		
	NG-1.0%	264 ± 78 a	35 ± 4 e	115 ± 6 a	14.6 ± 1.0 a-d	36.4 ± 1.6 a	0.28 ± 0.02 b-d	0.9 ± 0.2 a		
	NG-2.0%	198 ± 30 a	32 ± 3 e	109 ± 11 a	14.0 ± 1.4 a-d	34.8 ± 0.8 a	0.28 ± 0.01 cd	0.8 ± 0.2 a		

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.49: Microelement concentrations of 59-day-old lettuce (*Lactuca sativa* cv. Papyon) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Microelement Concentrations (mg kg ⁻¹)									
Fertilization	Slag Treatment	Fe	Zn	Mn	Cu	B	Mo	Ni	
1X-NP	Control	289 ± 156 a	91 ± 11 ab	511 ± 35 a-d	13.1 ± 1.2 a	30.3 ± 1.7 b	<i>n.d</i>	1.0 ± 0.5 a	
	G-0.5%	193 ± 40 a	101 ± 17 ab	435 ± 118 b-d	12.2 ± 1.4 a	34.6 ± 0.5 ab	<i>n.d</i>	0.4 ± 0.0 a	
	G-1.0%	232 ± 64 a	103 ± 13 ab	352 ± 33 cd	12.2 ± 0.7 a	36.0 ± 2.1 a	<i>n.d</i>	0.3 ± 0.2 a	
	G-2.0%	189 ± 63 a	95 ± 3 b	140 ± 22 d	13.0 ± 0.8 a	33.4 ± 1.1 ab	<i>n.d</i>	0.4 ± 0.4 a	
	NG-0.5%	251 ± 102 a	101 ± 25 ab	656 ± 202 a-d	10.2 ± 2.0 a	31.7 ± 2.0 ab	<i>n.d</i>	1.7 ± 2.1 a	
	NG-1.0%	248 ± 52 a	85 ± 5 b	396 ± 34 cd	13.5 ± 0.9 a	34.3 ± 2.5 ab	<i>n.d</i>	0.6 ± 0.6 a	
	NG-2.0%	321 ± 160 a	113 ± 42 ab	585 ± 412 a-d	12.6 ± 1.7 a	34.8 ± 1.5 ab	<i>n.d</i>	0.6 ± 0.4 a	
2X-NP	Control	340 ± 141 a	94 ± 9 b	699 ± 92 a-c	11.6 ± 2.3 a	34.0 ± 1.9 ab	<i>n.d</i>	1.0 ± 0.6 a	
	G-0.5%	289 ± 45 a	121 ± 7 ab	1132 ± 274 a	11.7 ± 0.8 a	34.3 ± 2.5 ab	<i>n.d</i>	0.5 ± 0.1 a	
	G-1.0%	448 ± 135 a	157 ± 41 a	998 ± 381 ab	12.0 ± 0.1 a	36.1 ± 2.1 a	<i>n.d</i>	0.4 ± 0.2 a	
	G-2.0%	253 ± 86 a	88 ± 4 b	188 ± 37 cd	12.1 ± 0.7 a	35.4 ± 3.1 ab	<i>n.d</i>	0.2 ± 0.1 a	
	NG-0.5%	194 ± 73 a	94 ± 11 b	710 ± 166 a-c	11.1 ± 1.7 a	35.2 ± 2.1 ab	<i>n.d</i>	0.7 ± 0.2 a	
	NG-1.0%	314 ± 13 a	111 ± 10 ab	644 ± 166 a-d	11.5 ± 1.6 a	33.7 ± 1.4 ab	<i>n.d</i>	1.4 ± 0.7 a	
	NG-2.0%	269 ± 117 a	119 ± 39 ab	574 ± 312 a-d	11.4 ± 1.2 a	32.9 ± 0.7 ab	<i>n.d</i>	0.7 ± 0.2 a	

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.50: Potentially toxic non-essential element concentrations of 59-day-old lettuce (*Lactuca sativa* cv. Papyon) grown on alkaline soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Potentially Toxic Non-Essential Element Concentrations (mg kg ⁻¹)					
Fertilization	Slag Treatment	Cr	Cd	V	Pb
1X-NP	Control	<i>n.d</i>	0.26 ± 0.03 ^a	<i>n.d</i>	<i>n.d</i>
	G-0.5%	<i>n.d</i>	0.27 ± 0.05 ^a	<i>n.d</i>	<i>n.d</i>
	G-1.0%	<i>n.d</i>	0.26 ± 0.01 ^a	<i>n.d</i>	<i>n.d</i>
	G-2.0%	<i>n.d</i>	0.29 ± 0.04 ^a	<i>n.d</i>	<i>n.d</i>
	NG-0.5%	<i>n.d</i>	0.28 ± 0.04 ^a	<i>n.d</i>	<i>n.d</i>
	NG-1.0%	<i>n.d</i>	0.28 ± 0.04 ^a	<i>n.d</i>	<i>n.d</i>
	NG-2.0%	<i>n.d</i>	0.25 ± 0.05 ^a	<i>n.d</i>	<i>n.d</i>
2X-NP	Control	<i>n.d</i>	0.23 ± 0.03 ^a	<i>n.d</i>	<i>n.d</i>
	G-0.5%	<i>n.d</i>	0.24 ± 0.07 ^a	<i>n.d</i>	<i>n.d</i>
	G-1.0%	<i>n.d</i>	0.24 ± 0.09 ^a	<i>n.d</i>	<i>n.d</i>
	G-2.0%	<i>n.d</i>	0.26 ± 0.04 ^a	<i>n.d</i>	<i>n.d</i>
	NG-0.5%	<i>n.d</i>	0.24 ± 0.04 ^a	<i>n.d</i>	<i>n.d</i>
	NG-1.0%	<i>n.d</i>	0.27 ± 0.07 ^a	<i>n.d</i>	<i>n.d</i>
	NG-2.0%	<i>n.d</i>	0.25 ± 0.04 ^a	<i>n.d</i>	<i>n.d</i>

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

Table 4.51: Potentially toxic non-essential element concentrations of 59-day-old lettuce (*Lactuca sativa* cv. Papyon) grown on acidic soil treated with no slag (control) and ground (0-2 mm) or non-ground (0-4 mm) slag with low (0.5%), medium (1.0%), and high (2.0%) doses under 1X-NP or 2X-NP fertilization regimes

Potentially Toxic Non-Essential Element Concentrations (mg kg ⁻¹)						
Fertilization	Slag Treatment	Na	Cd	Cr	V	Pb
1X-NP	Control	3.0 ± 0.2 ab	1.32 ± 0.07 a-c	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	G-0.5%	2.6 ± 0.2 bc	1.26 ± 0.36 a-c	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	G-1.0%	2.5 ± 0.1 bc	1.01 ± 0.18 a-c	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	G-2.0%	2.3 ± 0.2 c	0.49 ± 0.03 c	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	NG-0.5%	3.0 ± 0.3 bc	1.52 ± 0.60 a-c	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	NG-1.0%	2.5 ± 0.2 bc	0.80 ± 0.06 bc	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	NG-2.0%	3.0 ± 0.1 a-c	1.37 ± 1.05 a-c	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
2X-NP	Control	3.7 ± 0.4 a	1.02 ± 0.21 a-c	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	G-0.5%	3.7 ± 0.3 a	2.14 ± 0.64 a	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	G-1.0%	3.0 ± 0.6 a-c	2.04 ± 0.41 ab	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	G-2.0%	2.5 ± 0.1 bc	0.56 ± 0.02 c	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	NG-0.5%	2.9 ± 0.2 bc	1.55 ± 0.49 a-c	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	NG-1.0%	2.7 ± 0.2 bc	1.49 ± 0.44 a-c	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>
	NG-2.0%	2.9 ± 0.1 bc	1.28 ± 0.77 a-c	<i>n.d</i>	<i>n.d</i>	<i>n.d</i>

Values are means and standard deviations of four independent replicates. Different letters along columns indicate significant differences between means according to Tukey's HSD test ($p \leq 0.05$).

5. DISCUSSION

5.1. Soil Experiment

The changes in the physicochemical properties and extractable element concentrations of soils used in the soil incubation experiment exhibited the role of EAF slag as fertilizer and soil amendment. Our results showed that EAF slag amendment was effective in elevating the soil pH over time in both alkaline and acidic environments across subsequent sampling periods, which could be explained by the highly alkaline nature of the material (**Table 4.1; 4.3**). It has been exhibited that the particle size did not cause a pH difference in our slag material (**Table 4.1**). However, the EC was higher in ground slag, which could be attributed to the increased surface area of finer particles that ensured the facilitated release of ions into solution [Li et al., 2024]. The extractable and total element concentrations of EAF slag were also expected to follow the same principle. The particle size was effective in the alteration of the extractable and total element concentrations in general (**Table 4.1; 4.2**).

The initial sampling immediately taken after the slag-soil incorporation revealed that all doses of EAF slag application raised the pH of alkaline soil to a certain extent (**Table 4.3**). This effect maintained through subsequent sampling times, which showed the sustained impact of the slag application in alkaline environments. Previous literature reported that steel slag treatment achieved the acidic soil neutralization through pH modification [Gu et al., 2011; He et al., 2017; Deus et al., 2020]. In parallel with these studies, EAF slag amendment caused a delayed yet considerable impact in terms of pH elevation in acidic soil (**Table 4.3**). While there was no notable alteration in soil pH at initial sampling, subsequent samples' pH was significantly boosted by the slag amendment, which suggested the effect of EAF slag in neutralizing the acidic soil types.

The effect of steel slag amendment on EC were variable across soil types and sampling times. The alkaline soil EC generally remained unaffected in response to EAF slag treatment through the sampling period (**Table 4.4**). Conversely, all EAF slag

amendments in acidic soil increased EC at t0 to some extent. At subsequent samples, however, the majority of EC values reduced over control, suggesting a potential stabilization effect of slag particles by the precipitation reactions. The precipitation and immobilization of some elements upon slag application was reported to be regulated by pH modification in different studies [Gu et al., 2011; Nejad et al., 2017; Yang et al., 2021]. These findings highlighted that EAF slag-driven EC dynamics could be altered in different soil environments at various sampling times.

Extractable macronutrient concentrations in the soil incubation experiment varied depending on the nutrient types, soil properties, and sampling times. The bioavailability of P in alkaline soil tended to increase at the final sampling, which implied the delayed effect of EAF slag on P availability, potentially because of the gradual dissolution with soil mineral phases [Wang et al., 2018; Das et al., 2020]. In contrast, extractable P levels in acidic soil enhanced at the initial sampling across all EAF slag treatments (Table 4.6). This immediate effect could be attributed to the improved P desorption from soil particles due to EAF slag-induced neutralization in acidic soil (Table 4.3). The availability of K showed a decreasing tendency upon EAF slag application in alkaline soil at all sampling times (Table 4.5). This decline could be explained by the increased cation exchange interactions, leading to K fixation in soil [Yadav and Sidhu, 2016]. Extractable Ca levels in alkaline soil tended to reduce consistently upon EAF slag application at all sampling times (Table 4.7). The maintenance of this effect at t2 could imply the role of EAF slag in precipitation or adsorption mechanisms, causing reduced Ca availability in alkaline environment. Conversely, Ca bioavailability in acidic soil had a tendency to be improved by the slag amendment at all sampling times, particularly upon the ground slag treatment (Table 4.8). These findings indicated not only the role of EAF slag in Ca fertilization but also its function to regulate the soil pH that led to an enhanced retention and bioavailability of Ca in acidic soil [Barrow and Hartemink, 2023].

Soil incubation experiment also demonstrated the notable impact of EAF slag amendment on the availability of micronutrients and trace elements in both alkaline and acidic soils. The significant enhancement in Fe availability upon the highest dose of ground slag treatment unveiled the role of steel slag as a potential Fe source in alkaline environments (Table 4.9). Although relatively slight Fe improvement was observed, EAF slag was confirmed to be a potential Fe fertilizer in acidic soil as well,

particularly in short-term period covering three months (**Table 4.10**). The bioavailability of Zn was drastically improved by EAF slag treatment across either type of soil (**Table 4.9; 4.10**). Although pH increases generally reduced extractable Zn level through Zn adsorption onto soil particles by forming Zn hydroxides or carbonates, the improvement of Zn in alkaline soil could be attributed to EAF slag composition rather than its physicochemical properties modifying the soil pH [Yang et al., 2021]. As a direct source of Zn, EAF slag was effective in enhancing the available Zn concentration in either soil types (**Table 4.1; 4.2**). The bioavailability of B positively responded to EAF slag amendment in both soil types, with the effect being especially pronounced in acidic soil (**Table 4.11; 4.12**). The significant enhancement in extractable B concentration in different soil types revealed that EAF slag not only served as a direct B source but also regulated the soil properties that facilitated the long-term release and retention of B in soil. Extractable B concentration in soil below 0.5 mg/kg generally indicates a risk of boron deficiency. In acidic control soil, the extractable B level was 0.09 ppm, which could be defined as B-deficient soil. The addition of EAF slag, however, significantly enhanced the B level to 0.19 ppm (**Table 4.12**). Furthermore, the extractable B concentration at t1 in acidic soil treated with EAF slag dramatically elevated and reached at 0.73 ppm (**Table 4.12**). This result implied that steel slag could be effective in enhancing B level in deficient soils, particularly in acidic environments.

The accumulation of potentially toxic metals upon steel slag incorporation with soil remains a major concern regarding environmental pollution risk [Das et al., 2019; Wang et al., 2021]. In our study, all investigated heavy metals (Cd, Cr, and Pb) were found in the permissible limit in slag-applied soil [EU Commission Regulation, 2006]. The extractable Cd level remained unaffected by EAF slag treatment in either type of soil in our study (**Table 4.15; 4.16**). The availability of Pb, on the other hand, had a tendency to reduce in response to ground EAF slag amendment across both soil conditions (**Table 4.15; 4.16**). These findings related to unchanged or reduced bioavailability of these toxic metals suggested that EAF slag could promote Cd and Pb stabilization in soil, likely through adsorption or immobilization mechanisms, as indicated in previous studies [Gu et al., 2011; Nejad et al., 2017; Yang et al., 2021].

5.2. Crop Experiments

Electric-arc-furnace slag amendment had considerable impact on crop growth in our study, especially in acidic soil. Dry biomass results of the crops grown on ground slag-treated acidic soil showed drastic enhancement over control (**Figure 4.3B; 4.6B; Table 4.45**). These findings were supported by previous studies that investigated the fertilization effect of steel slag on maize shoot and rice straw [Ali and Shahram, 2007; Das et al., 2020]. The beneficial effect pronounced only in acidic soil could be explained by the physicochemical properties of the soil types used in these experiments. The growth parameters of wheat and lettuce in alkaline soil were not responsive to the treatment in general (**Figure 4.3A; 4.6A; Table 4.45**). The shoot weight of wheat grown on non-ground slag treated alkaline soil, however, showed significant improvement (**Figure 4.3A**). Further increase in soil pH by means of ground EAF slag addition could not improve the growth of plants in the alkaline environment. This result demonstrated that the crops used in this study could tolerate EAF slag-induced alkalinity up to a certain threshold without being negatively affected in terms of shoot growth under these conditions.

The particle size of slag was also confirmed to be an important parameter in fertilization. It significantly altered the response of crop growth in acidic soil, regardless of the fertilization type (**Figure 4.3; 4.6; Table 4.45**). The ground slag particles pronounced the beneficial effects more clearly in terms of plant growth in acidic soil (**Figure 4.1; 4.2; 4.5; 4.7**). Due to the relatively increased surface area of ground slag particles in soil as compared to non-ground ones, it has relatively higher release rate of elements into the environment, thereby enhancing plant growth in a shorter period of time [Li et al., 2024]. The comparison between <50-micron and <100-micron slag particle sizes revealed that the foliage yield of spinach (*Spinacia oleracea* L.) responded more positively to <100-micron slag treatment than that of <50 micron [Mulodia et al., 2024]. In alkaline soil, on the other hand, non-ground slag amendment was effective in significantly improving the shoot weight of wheat (**Figure 4.3A**). This effect could result from the contribution of non-ground slag particles to soil structure. The coarser slag particles may have ensured well-aeration of soil by creating pore spaces, leading to reduced soil compaction that could facilitate the root growth and crop productivity [Yang et al., 2022]. The aeration and compaction of soil

is also critical in terms of microbial activity, which can contribute to enhanced nutrient availability, root growth, and plant development [Nawaz et al., 2013]. The non-ground slag material might have improved the physical properties of soil through increasing the macroporosity [Herath et al., 2013].

The increase in wheat chlorophyll content in acidic soil upon EAF slag amendment aligned with the improved shoot biomass data in acidic soil (Table 4.17; 4.31). This observation could be explained by the enhanced physiological status of plant in response to the slag treatment. Leaf chlorophyll content is one of the most precise indicators of plant physiological status and photosynthetic capacity [Wang et al., 2020; Zhang et al., 2022]. According to our results, the healthier and denser appearance of the shoot parts grown on EAF-slag treated acidic soil could be related to their improved photosynthetic capacity. The gradual improvement in NBI values upon increasing EAF-slag doses suggested a dose-dependent effect on N balance within the plants (Table 4.17). In alkaline soil, no significant change was obtained in NBI values, which implied that relatively low N bioavailability may have avoided the potential benefits related to N balance within the leaf tissue.

The fertilization regime was effective in elevating the chlorophyll content of wheat leaves, regardless of the slag amendment (Table 4.31). This increase could be explained by the elevated N and P levels in soil, both of which are key in chlorophyll synthesis. Sufficient N directly enhanced overall photosynthetic capacity through contributing to biosynthesis of chlorophyll molecules [Taiz et al., 2015]. The critical role of P in biosynthetic pathways enabled the required ATP production for chlorophyll formation, which may have improved the chlorophyll content and overall photosynthetic capacity [Raghothama, 1999]. Therefore, the elevated levels of N and P in acidic soil under 2X-NP condition could ensure the enhanced chlorophyll content in wheat.

The leaf mineral composition provided key insights into nutrient behavior upon slag amendment. The significant improvements were observed in the P and K concentrations of wheat shoot in acidic soil, particularly under 1X-NP condition (Table 4.19; 4.33). These findings indicated that EAF slag amendment may have enhanced P and K bioavailability in lower-fertilized acidic soil, leading to the increased uptake of these nutrients. Previous experiments on maize and wheat also revealed that steel slag contributed to improved N, P, and K uptake [Radic et al., 2013;

Samara et al., 2017]. Although the leaf N level did not dramatically change upon EAF slag application in the subsequent wheat experiment of our study, the enhancement of the leaf P and K level still aligned with the previous research (**Table 4.33**). This could be attributed to liming function of steel slag in neutralizing the acidic soil pH, as indicated in recent studies [**Deus et al., 2020; Díaz-Piloneta et al., 2022**]. Increased Ca concentration of wheat shoots in alkaline soil under 2X-NP condition indicated fertilization-related impact rather than the slag treatment itself (**Table 4.18; 4.32**). In lettuce, on the other hand, the leaf Ca level tended to enhance upon EAF slag application in acidic soil under higher fertilization condition, which could be associated with the high Ca content of EAF slag used in this study (**Table 4.1; 4.2; 4.47**).

Previous studies reported that steel slag amendment improved the leaf Fe concentration of maize and mustard [**Radic et al., 2013; Islam et al., 2022**]. In contrast to these results, EAF slag treatment had no significant effect on Fe level of wheat shoot or lettuce leaf in both soil types under both fertilizations in our study (**Table 4.20; 4.21; 4.34; 4.35; 4.48; 4.49**). The leaf Zn concentration of both crops tended to enhance in alkaline soil under either fertilization types in response to the slag amendment (**Table 4.20; 4.34; 4.48**). Since this observation has not been specifically reported in the previous literature, the leaf mineral composition results in our study showed the potential of EAF slag as an effective Zn fertilizer in alkaline soil, especially under relatively lower fertilization conditions. The element analysis of wheat leaves also provided important outcomes in terms of B levels (**Table 4.20; 4.21; 4.34; 4.35**). Under both fertilization conditions, all doses of EAF slag treatment in both soil types drastically boosted the leaf B concentration. Due to the lack of research that investigated the steel slag-driven B level changes in plant tissues, this study was introductory in exhibiting the promising role of EAF slag as a B fertilizer across both types of soil. The critical boron concentration causing visual deficiency symptoms in wheat during the vegetative stage has been reported as 1 mg/kg [**Asad et al., 2001**]. While control leaves of wheat had 1 ppm B in acidic soil in our study, EAF slag amendment raised the B concentration to 23 ppm (**Table 35**). The sufficient level of B in wheat leaves was reported between 5-15 ppm. Our result revealed that EAF slag addition into acidic soil could ensure the efficient B fertilization, leading to sufficient amount of B in the leaf part of wheat. The notable enhancement in leaf Mo

concentration upon the slag amendment in alkaline and acidic soil showed the EAF slag's function as a substantial Mo source (**Table 4.20; 4.21; 4.34; 4.35**).

The main risk associated with steel slag use in agriculture lies in possible toxic metal accumulation in plant tissues, which can raise concerns about the food safety [**Gwon et al., 2018; Das et al., 2019**]. In our study, the Cd level of wheat leaves remained unaffected upon EAF slag treatment in both soil types, except for the non-ground slag doses that caused a slight increase in alkaline soil under lower fertilization (**Table 4.22; 4.23**). Furthermore, ground EAF slag application into acidic soil significantly reduced the leaf Cd concentration in a dose-dependent manner in both the subsequent wheat and lettuce experiments under lower fertilization type, which could be associated with the dilution effect observed in these treatment groups (**Table 4.37; Table 4.51**). Chromium is the main concern in terms of agricultural use of steel slag since its concentration in steel slag is relatively higher than other potentially toxic non-essential elements (**Table 4.1**). Potentially toxic metals in leaf tissues such as Cr, V, and Pb were unaffected in response to EAF slag amendment in both soil types under either type of fertilization in all crop experiments (**Table 4.22; 4.23; 4.36; 4.37; 4.50; 4.51**).

The grain results of wheat experiments provided significant outcomes related to yield and nutritional quality parameters, which has been largely studied in context of both food safety and food security [**Curtis and Halford, 2014; Albahri et al., 2023**]. Electric-arc-furnace slag treatment in both wheat experiments led to a notable enhancement in terms of grain yield and grain number in acidic soil under either fertilization conditions, regardless of the slag particle size (**Table 4.24; 4.38**). These findings supported the previous studies that observed the improvement in the yield of barley, wheat, and rape [**European Commission: Directorate-General for Research and Innovation, 2017**]. Other studies that focused on rice also demonstrated that steel slag treatment was effective in improving the grain yield [**Wang et al., 2015; He et al., 2017; Das et al., 2020**].

The grain mineral composition upon EAF slag application is of critical importance in terms of balanced human diet/nutrition and food safety [**Das et al., 2019**]. Our results showed that the grain Fe and Zn concentration tended to elevate considerably over control in alkaline soil under lower fertilization (**Table 4.27; 4.41**). These findings uncovered the promising role of EAF slag in enhancing the grain composition with the

two most important micronutrients in the human diet, Fe and Zn. Since Fe and Zn deficiencies are widespread in the world, EAF slag implementation in sustainable crop production might be an alternative solution to address hidden hunger problem. The improvement in the grain Mo level was also observed in response to EAF slag amendment in acidic soil under both types of fertilization in either wheat experiments (**Table 4.28; 4.42**).

The long-term exposure to or consumption of heavy metals such as Cd, Pb, and Cr could result in various disorders, including but not limited to nervous and vascular system disorders, lung and skin cancers, and osteoporosis or coronary heart diseases in humans [**Genchi et al., 2020; Fathy et al., 2021; Hossini et al., 2022**]. In contrast to the main concerns associated with the possible accumulation of toxic metals in the edible parts of the plants, there was no significant increase in the grain Cd, Cr, V, or Pb concentrations obtained in both types of soil and fertilization condition in our study (**Table 4.29; 4.30; 4.43; 4.44**). Moreover, the grain Cd level in both wheat experiments tended to decrease upon EAF slag amendment in a particle size-dependent manner in acidic soil under lower fertilization (**Table 4.30; 4.44**). Since maximum limit of Cd in wheat germ was set at 0.20 ppm by the EU Commission Regulation, our study showed that the obtained grains did not pose any Cd-related risk to human nutrition [**EU Commission Regulation, 2023**]. Overall, these findings highlighted the agricultural potential of EAF slag utilization in sustainable wheat and lettuce production, as it caused no toxicity-related problems in the edible parts of the plants, emphasizing the food safety aspect of the material.

6. CONCLUSION

This study has revealed key insights into the utilization of EAF slag in sustainable crop production and soil management. Electric-arc-furnace slag was reported to have a considerable impact on the growth, yield, and nutritional status of wheat and lettuce crops, particularly in acidic environments. These effects were proved to be achieved through soil pH modification and direct mineral supplementation, which highlighted both soil amendment and fertilizer aspects of the material. The contribution to soil structure was also attained by non-ground slag amendment that ensured well-aeration and reduced compaction of soil. Beside the significant improvements in P and K concentration of wheat and lettuce crops observed in acidic soil, EAF slag application was also showed to be a promising micronutrient fertilizer due to its contributions to enhanced leaf Zn and B levels. Electric-arc-furnace slag-induced benefits could be attributed to increased bioavailability of essential nutrients in soil, which has been revealed by the soil incubation experiment. Moreover, no notable changes in potentially toxic metal concentrations in both plant tissues and soil demonstrated that EAF slag application could be a promising strategy in terms of food safety and environmental sustainability. In addition, EAF slag may have served as a potential alternative to chemical fertilizers, whose production and long-term use could lead to soil pollution and high emission of GHGs. Overall, the different responses obtained in alkaline and acidic environments upon various slag treatments emphasized the importance of soil properties in terms of EAF slag implementation in agricultural systems. Future research focusing on the long-term influence of slag amendment on soil health and various plant species are required to address the safety of EAF slag, particularly in field conditions.

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