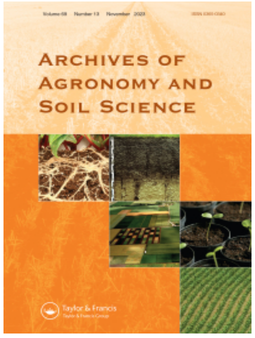

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Carbon-rich lime slag as a lime source in agriculture – effects on germination, plant growth and elemental content

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ABSTRACT
The use of decarbonized virgin lime is connected to environmental problems like high CO_2 emissions, high energy utilization and negative impact from open-pit lime mines. Recycling of used lime would reduce many of these problems. The effect of carbon-rich lime slag (CLS) from the metallurgical industry on germination, growth, and elemental content in barley, oilseed radish and sugar beet was investigated on two soils (clay and sand). CLS without and with water (CLSW) were compared to limestone in the sandy soil, primarily used to increase pH, and hydrated lime, primarily used to increase aggregation, in clay soils. CLS addition did not reduce the germination of the seeds as compared to the control. Including fertilization to the CLS treatment reduced the germination up to 23% in oilseed radish after 16 days. The germination of sugar beet seeds was delayed but had recovered after 16 days. Shoot biomass was higher in plants with CLS and CLSW, in both soils without fertilization. Plants grown in the CLS had lower Cd content compared to plants grown with hydrated lime. We can conclude that CLS show a high potential to be used on agricultural land from a crop growth perspective.

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Liming; steel slag; sugar beet; barley; oilseed radish

Introduction

Soil acidification and soil compaction are two of the major factors that negatively affect the soil's ability to support high crop yields (Goulding 2016), and much effort is put into mitigating these adverse impacts on food production. One action is to increase soil pH (Li et al. 2019) and improve the soil structure (Blomquist and Berglund 2021) by applying lime. Lime is mined in open-pit quarries that may be associated with negative impact on the local environment. In addition, the energy requirement is high, and the CO_2 evolution from decarbonizing limestone is the main factor contributing to the negative climate impact from lime-based industries (Laveglia et al. 2023). The use of lime by-products from the steel industry could decrease the environmental impact of lime use on arable land (Das et al. 2019).

Carbon-rich lime slag (CLS) is a by-product from the production of sponge iron (or direct reduced iron) in tunnel kilns and could be of agricultural value to improve the fertility of soils due to both its content of charcoal and the lime effect. In general, steel slag has a high pH and could therefore be used as a liming agent to increase soil pH (Ning et al. 2016; White

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et al. 2017; Haynes and Zhou 2018). However, different steps in the steel production result in different types of slag by-products, and their physio-chemical properties may vary. Large amounts of limestone are used in the sponge production, and there are converted into a carbon-rich lime slag. This slag is currently deposited in landfills but have been suggested as an alternative to virgin lime on arable land (Tozsin and Öztas 2023). To evaluate the use of lime slag in agriculture, the effect needs to be similar as the virgin lime and presents no adverse effects on the environment. This paper will be the first to compare carbon-rich lime slag to conventional liming agents and is the first step towards reusing lime from steel production.

It is common practice to use lime to improve soil structure, increase soil pH, increase base saturation, and bind toxic compounds, like Cd, to the soil in agriculture. One effect of lime in soil is to increase soil aggregation preventing soil compaction. An aggregated soil will contain many pores in the soil reducing the resistance and benefit root growth by reducing the risk of anaerobicity (Perata and Alpi 1993). It is common to use structure liming on clay soils in Sweden, even at neutral to fairly high pH as it improves aggregate stability and aggregate size distribution that is important for creating an optimal seedbed (Blomquist et al. 2018). The improved aggregate stability has also been shown to reduce the P losses from clay soils. Another environmentally friendly aspect of structural liming on clay soils is that the fuel consumption can be reduced due to less draught requirement (Blomquist et al. 2023). For specific crops, like sugar beet, farmers apply lime, to both sandy and clayey soils, to maintain a pH above 7 to secure a high yield.

The pH of the soil is very important for many of the factors supporting plant growth including the germination of seeds. Low pH breaks exogenous chemical dormancy (Mayer and Poljakoff-Mayber 1982); therefore, lime-slag addition may postpone seed germination (Pérez-Fernández et al. 2006). The availability of many nutrients like phosphorus, iron, and manganese that are vital for plant growth are as highest at neutral to low pH (Marschner 1995). The effect on the nutrient availability of lime-slag needs to be evaluated before implementing large-scale use.

High pH causes fixation of many detrimental metals like cadmium. Cadmium is also similar to calcium, and their circulation is interconnected. Cadmium may be toxic to both plants, animals and humans. Since Cd availability in soil generally decreases with increasing pH, it is recommended to apply lime on Cd polluted soil to avoid toxic Cd levels in the crop (Öborn et al. 1995; Sauvé et al. 2000). However, it has been shown that application of high amounts of Ca, as calcium nitrate, can increase the Cd content in plants, probably due to exchange of colloid-bound Cd in field trials (Larsson Jönsson and Asp 2011). A carbon-rich lime slag, with a potential to increase cation exchange capacity, may reduce this negative Cd effect, still providing a higher pH and improved growth conditions. More studies are needed to evaluate the potential and risks of carbon-rich lime slag amendment on crop germination and growth.

In addition to the effect of the lime, the charcoal content of the carbon-rich lime slag might improve the soil conditions in a way similar to biochar (Bashir et al. 2018). Biochar is well known to have positive effects in soils, such as improved soil structure, increased porosity, increased pH and higher nutrient availability (Lehmann et al. 2006; Atkinson et al. 2010). However, the carbon in slag is generally of fossil origin and will not mitigate climate change. Plant-based charcoal has recently been tested (Ibitoye et al. 2024) to reduce the carbon footprint of the steel and that will improve the value of the by-product by reducing the CO_2 imprint.

The aim of this project is to study the effects of carbon-rich lime slag on seed germination, plant growth and elemental content of crop plants by comparing the carbon-rich lime slag with soil specific commercial virgin lime products used in temperate agricultural soils today. To the best of our knowledge, no studies have simultaneously examined both the germination and growth of commercially significant crops in carbon-rich lime slag amended soils. Both factors are crucial for achieving successful cultivation under field conditions.

Materials and methods

We tested the effect of a carbon-rich lime slag used to replace liming on the growth of common crops in two types of highly productive agricultural soils, a sandy slightly calcareous soil and a heavy clay soil, both in need of liming for supporting high yield. The carbon-rich slag investigated in this study is derived from coal and lime used in a metallurgical process and containing high amounts of CaO, C and SiO_2 (Table 2) that are important for soil fertility and plant growth. This is compared to common agricultural practice where limestone is used in sandy soils, mainly for increasing pH, and hydrated lime in clay soils mainly to improve the soil structure.

Experimental conditions

The experiments were carried out in a greenhouse chamber during the period March-June. Deep pots (3.5 L) were used for the growth study and wide trays (1 L) were used for the germination study. Plants were grown in two different types of highly productive Scandinavian soils, one sandy soil (8% clay and 75% sand) and one with high clay content (47% clay and 17% sand). The chemical and physical properties of the two soils are shown in Table 1. The sandy soil was mixed with limestone (<0.25 mm, 2 tons CaO ha^{-1}) or with two levels of carbon-rich lime slag (CLS, <3 mm, 2 or 4 tons CaO ha^{-1}). Two different formulations of the CLS were used; CLS without added water and CLSW with water added at the industry to facilitate storage. The clay soil was mixed with hydrated lime (<32 µm, 2.2 tons CaO ha^{-1}) or with two levels (2.2 or 4.4 tons CaO ha^{-1}) of the two different CLS formulations. The added CaO corresponds to the levels recommended for liming in Swedish agriculture at similar soil conditions and liming products. The chemical properties of the CLS, the limestone and the hydrated lime are presented in Table 2. According to the analysis, the Cd content was below 0.2

Table 1. Chemical and physical properties of the soils.

	Clay soil	Sandy soil
Clay content, %	47	8
Humus content, %	5.7	2.3
pH	6.2	7.5
Ca-AL, mg $(100\ g)^{-1}$	410	310
K-AL, mg $(100\ g)^{-1}$	13	11
Mg-AL, mg $(100\ g)^{-1}$	16	4.6
P-AL, mg $(100\ g)^{-1}$	3.4	14
Cd, mg kg^{-1}	0.22	0.24
Cu, mg kg^{-1}	17	8.0
Zn, mg kg^{-1}	70	31

Table 2. Chemical analysis of the carbon-rich lime slag (CLS), limestone and hydrated lime, % (w/w), except for Cd, Cu, and Zn (mg kg^{-1}).

% (w/w)	CLS	Limestone	Hydrated lime
CaO	37*	49.5	72.5
C	24	0	0
Mg	0.6	0.3	1.1 (MgO)
SiO_2	18	9	1.1
Al_2O_3	8	0.6	0.5
Fe_2O_3	9	0.3	0.2
K	1	0.3	0.12 (K_2O)
Na_2O	0.3	0.1	0.03
S	1.3	0.02	0.06
P	0.1	0.06	0.01
mg kg^{-1}			
Cd	<0.2	0.6	<0.2
Cu	21	2	4
Zn	6	9	24

*22 (active CaO).

Table 3. pH and soil conductivity, µs, in the different soil mixtures at the experimental start of the growth study. CLS = carbon-rich lime slag. CLS without added water, CLSW added water before storage.

Treatment	pH	Soil conductivity, µS	Treatment	pH	Soil conductivity, µS
Clay soil			*Sandy soil*		
Control	6.4	66.7	Control	7.7	81.5
Hydrated lime	8.0	213	Limestone	7.8	84.8
CLS level 1	7.7	216	CLS level 1	8.5	137.8
CLS level 2	8.5	363	CLS level 2	9.0	193.8
CLSW level 1	7.7	253	CLSW level 1	8.4	151.8
CLSW level 2	8.0	315	CLSW level 2	8.7	210

mg kg^{-1} in both CLS and hydrated lime, while the limestone contained 0.6 mg kg^{-1}. pH and conductivity were measured in the soil mixtures before sowing (Table 3).

Germination

Twelve seeds of oilseed radish (*Raphanus sativus* var cv. Colonell), spring barley (*Hordeum vulgare* cv. Quench) and sugar beet (*Beta vulgaris* subsp. *vulgaris* cv. Sabrina) were sown in four pots of each treatment. Each pot consisted of 12 seeds per species, divided in two rows. The pots were filled with either pure sandy soil as a control (without CLS) or sandy soil mixed with CLS at three different levels (2, 4 and 6 tons CaO ha^{-1}) both under fertilized (150 kg N ha^{-1} NPK 11-5-18, YaraMila ProMagna) and unfertilized conditions. The lime, CLS and the fertilizer were applied and mixed into the soil one day before sowing. The emergence was observed every fourth day for 16 days in total.

Growth

Oilseed radish (cv. Colonell) was sown in the sandy soil mixtures, and spring barley (cv. Quench) was sown in both soil mixtures. Oilseed radish does not develop in heavy clay soils making this combination irrelevant for practice. 150 kg N ha^{-1} NPK 11-5-18 (YaraMila ProMagna) was applied to the soil in the fertilized treatment before sowing. Each treatment was replicated four times. Five oilseed radish seeds and seven barley seeds were sown in each pot. After emergence, two oilseed radish plants and all the barley plants were left in the pots. Every tenth day, shoot length was measured in both crops, and tillers (basal vegetative shoots) were counted in barley. The pots were watered and weighed at the experimental start and then watered to maintain constant soil moisture. Six weeks after emergence, the oilseed radish was fertilized with 70 kg N ha^{-1} and the barley was fertilized with 20 kg N ha^{-1} as liquid ammonium nitrate in accordance with the Swedish recommendations for these crops. Twelve weeks after emergence the crops were harvested. The length and dry weight of the aboveground biomass were determined and then dried at 60 °C, milled and stored dry at room temperature awaiting nutrient analysis.

Chemical and statistical analyses

Total C and N in the oilseed radish leaves and barley shoots were measured by a combustion NC analyzer (Flash 2000 NC analyzer), and B, Ca, Cu, Cd, Fe, K, Mg, Mn, P, S and Zn were measured after wet-digestion in HNO_3 (65%) using ICP-OES and ICP-MS. The pH and soil conductivity were measured after distilled water extraction (soil: solution, 1:5, ISO 10,390:2005 IDT). Statistical analyses were carried out using one-way ANOVA (Minitab Statistical software v. 18). Tukey's test was used for pair-wise comparisons of means, and significance was determined at $p < 0.05$.

Results

Germination

The CLS alone did neither delay nor reduce the germination of any species at the tested levels compared to both the control and lime treatment. However, germination was on average delayed and inhibited when CLS was combined with NPK fertilizer at the higher CLS levels (Table 4). The germination was only 23% of the sowed seeds in pots containing soil amended with NPK and CLS level 3 (6 tons CaO ha^{-1}). The germination was slightly delayed when NPK was added alone but eventually the germination reached the same level as the control.

The different crops, barley, sugar beet and oilseed radish, showed different germination sensitivity to both NPK fertilizer and CLS amendment. The germination in sugar beet (control and CLS level 1) was delayed by NPK application, but after 16 days the germination frequency equaled the control (Table 4). The combined treatment, NPK and CLS, in levels 2 and 3 also showed a delayed germination but did not reach the germination level of the control within 16 days after sowing (DAS). The germination was only 75% for those treatments, to be compared with 100% germination in the control without fertilizer treatment. The oilseed radish seeds also had a high germination in the control and CLS treatments without NPK fertilizer, 75–90%. Compared to the sugar beet, the germination of oilseed radish was more inhibited by the CLS amendment, especially in CLS level 3. Even after 16 days, the germination in the combined NPK and CLS levels 2 and 3 only reached 65 and 23%, respectively.

Table 4. Mean number of germinated seeds in sugar beet, oilseed radish and barley, 6–16 days after sowing (DAS). The treatments were control, carbon-rich lime slag (CLS) in three levels compared under both fertilized and unfertilized conditions in a sandy soil. Maximum 12 seeds per pot and species. Mean values within each species that are followed by a different letter are significantly different at $p < 0.05$, $n = 4$.

		Germinated seeds (no)		
Treatment	DAS			
	6	9	13	16
Sugar beet				
Control	11.5a	11.8a	12.0a	12.0a
CLS level 1	11.8a	11.8a	11.8ab	11.8a
CLS level 2	11.0a	11.5a	11.5ab	11.5a
CLS level 3	8.5ab	11.3a	11.3ab	11.3a
Control + NPK	5.3bc	9.3ab	11.0ab	11.5a
CLS level 1 + NPK	4.5 cd	9.8ab	11.3ab	11.3a
CLS level 2 + NPK	1.0de	6.5bc	9.0ab	9.25a
CLS level 3 + NPK	0.5e	4.5c	8.3b	9.0a
Oilseed radish				
Control	9.8a	10.5a	10.5a	10.5a
CLS level 1	10.3a	10.5a	10.8a	10.8a
CLS level 2	9.8a	10.5a	10.5a	10.5a
CLS level 3	6.5ab	7.8ab	8.0ab	9.0a
Control + NPK	10.0a	10.3a	10.3a	10.3a
CLS level 1 + NPK	7.8a	9.8a	10.0ab	10.3a
CLS level 2 + NPK	2.8bc	4.8bc	6.3b	7.8a
CLS level 3 + NPK	0c	1.5c	2.3c	2.8b
Barley				
Control	3.0a	3.5a	4.0a	4.0a
CLS level 1	3.8a	5.3a	5.3a	5.8a
CLS level 2	3.0a	3.3a	3.8a	3.8a
CLS level 3	3.8a	5.0a	5.5a	5.8a
Control + NPK	2.5a	3.5a	3.8a	3.8a
CLS level 1 + NPK	3.0a	5.0a	5.5a	5.8a
CLS level 2 + NPK	2.0a	5.0a	5.5a	6.0a
CLS level 3 + NPK	0.3a	4.0a	4.8a	4.8a

Generally, the barley seeds had a low germination and never reached more than 50% of the sowed seeds. However, in the growth study, the barley seeds germinated at a satisfactory level and in both the germination and the growth study, barley seeds were not significantly affected by NPK fertilizer or slag amendment.

Growth and development

The plants had different growth response to the slag and lime additions in the two soils. There was a difference in the growth response to CLS in barley, when grown in the sandy soil compared to the clay soil (Figure 1, Table S1). In sandy soil, the unfertilized barley plant shoots treated with all levels of CLS were significantly taller than both the control plants and the limestone treated plants, after 11 days. The barley plants treated with CLS level 2 were taller throughout the whole experiment indicating a positive fertilization effect. However, the barley plants grown in sandy soil and treated with CLS level 2 that were fertilized were significantly shorter after 11 days, but the growth was

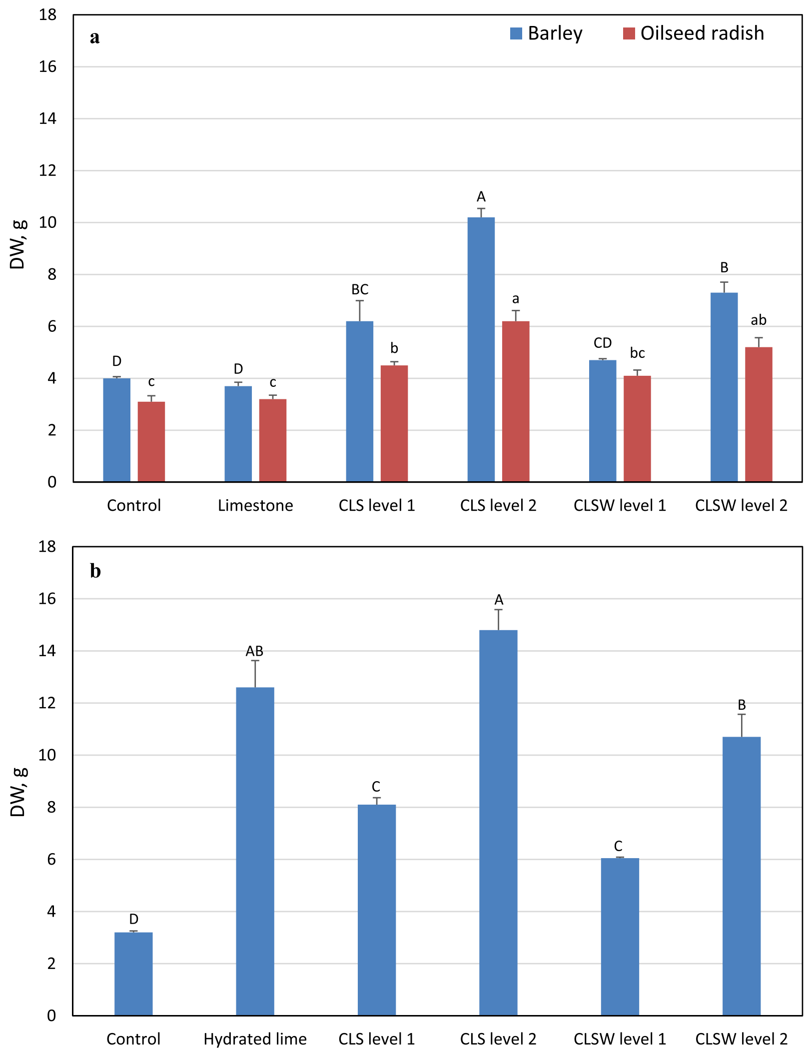

Figure 1. Dry weight at harvest of unfertilized barley and oilseed radish grown in sandy soil (a) and unfertilized barley grown in clay soil (b). Means with different letters (within each dataset) are significantly different at $p < 0.05$, $n = 4$.

recovered after four weeks. The growth response in barley grown in clay soil was different as the unfertilized plants treated with CLS were not taller compared to the control after 11 days. At harvest, the control plants were significantly shorter than the other treatments in the clay soil (Table S1). When the barley plants were grown in fertilized clay soil, there were no significant differences in height at 11, 32 or 63 days after emergence.

About two weeks after emergence, the fertilized oilseed radish plants applied with CLS level 2 were much shorter compared to the plants in the other treatments (Table S1). However, this reduced growth at the higher CLS levels was not significant after four weeks. Even, before adding NPK-fertilizer, the CLS level 2 treated sandy soil had a higher pH and almost twice as high soil conductivity compared to the control (Table 3).

Both barley and oilseed radish had a significantly higher shoot biomass (DW) at harvest when grown in unfertilized soil applied with CLS levels 1 and 2 compared to the control (Figure 1a). Plants grown in the CLS and hydrated lime treated unfertilized clay soil had a significantly higher shoot biomass as compared to the control (Figure 1b, Figure S1). Barley grown in clay soil mixed with hydrated lime resulted in similar shoot biomass as those plants grown in clay soil mixed with CLS level 2. Limestone had no effect on shoot biomass either in barley or oilseed radish (Figure 1). Independently of soil type and crop, the highest increase in shoot biomass (DW) was found when CLS was applied (Figure 1).

The number of tillers (vegetative basal shoots) were counted in barley and the results showed that CLS level 2 had a stimulating effect on the amounts of tillers when compared to control plants, all grown under unfertilized conditions. Unfertilized control plants did not produce any tillers but the application of CLS level 2 resulted in 2–3 tillers per plant and the fertilized plants all produced more than 3 tillers.

Elemental content

The N concentration in unfertilized barley shoots, generally decreased with CLS/CLSW addition and in the sandy soil, the decrease was statistically significant for all CLS/CLSW treatments (Table 5). The oilseed radish followed the same pattern as the barley, but the decrease was only significant for CLS level 2. The addition of lime in unfertilized soil did not influence the plant N concentration, regardless of crop or soil type. There were no significant differences in plant N concentration between the plants in different soil treatments, when grown in fertilized sandy soil. The N concentration in barley grown in fertilized clay soil was significantly higher in the lime treated plants and showed a different pattern compared to the sandy soil where there were no significant differences.

According to the results, level 2 of the CLS had the largest impact on the nutrient concentrations in barley shoots. Barley grown in unfertilized clay soil contained significantly higher concentrations of Ca, Mn and S but lower concentrations of K, P, B, Zn and Cu in shoots, when CLS was applied (Table 5). Barley grown in the unfertilized sandy soil also contained significantly lower concentrations of P, B and Cu and showed a decreasing tendency in Zn concentration compared to the control and limestone (Table 5). Barley grown in the fertilized clay soil had a somewhat different pattern compared to the unfertilized soil, with significantly increased concentrations of Ca, Mg and Cu when slag, especially CLS without water, was applied. The concentration of Ca increased significantly in fertilized barley that was applied with CLS/CLSW level 2 in sandy soil. The elemental analysis in oilseed radish leaves did not show any significant differences due to large variations among the plants (Table 5).

Interestingly, the content of Cd in barley shoots increased in all treatments, both in unfertilized and fertilized plants grown in clay soil (Table 5). Even the fertilization increased the Cd, the unfertilized control contained 2.10 µg Cd g^{-1} DW compared to the fertilized control that contained 6.33 µg Cd g^{-1} DW. The content of Cd in barley shoots almost

Table 5. Effects of the treatments on elemental content in barley shoots and oilseed radish grown in sandy soil and barley grown in clay soil with different formulas of slag. Mean values within each category that are followed by a different letter are significantly different at $p < 0.05$, $n = 4$.

Treatment	Content, mg g^{-1} DW						Content, µg g^{-1} DW					
	N	Ca	Mg	K	P	S	Fe	Mn	B	Zn	Cu	Cd
						Barley sandy soil						
Unfertilized												
Control	9.38a	4.81a	1.28ab	21.10ab	3.85a	2.03 cd	0.037bc	5.02b	8.66ab	29.96a	5.24a	1.99bc
Limestone	9.05a	4.73a	1.27ab	20.37b	3.78a	1.97d	0.034c	5.12b	8.86a	24.24ab	4.90ab	1.70c
CLS level 1	8.00b	5.07a	1.33ab	21.69ab	3.50ab	2.79ab	0.044ab	5.76ab	6.60c	21.20ab	4.96ab	2.80ab
CLS level 2	7.49b	5.12a	1.34ab	20.75b	2.91c	3.25a	0.045a	7.09a	6.33c	19.40b	4.36b	3.13a
CLSW level 1	8.00b	5.22a	1.25b	21.00b	3.35b	2.52bc	0.033c	5.71ab	6.69c	20.21ab	4.43b	2.85ab
CLSW level 2	7.70b	5.10a	1.37a	22.39a	3.32b	3.15a	0.039abc	6.72a	7.08bc	21.83ab	4.96ab	3.00a
Fertilized												
Control	7.08a	2.81b	0.90a	19.67a	1.85a	1.94a	0.025b	6.53a	7.77a	16.26a	2.24c	2.85a
Limestone	7.34a	2.99ab	0.92a	20.08a	1.87a	1.98a	0.029ab	6.38a	8.25a	11.74b	2.36bc	2.75a
CLS level 1	7.54a	3.18ab	0.85a	19.14a	1.90a	1.90a	0.029ab	6.99a	6.38b	12.47ab	2.61bc	2.72a
CLS level 2	6.94a	3.33a	0.91a	19.35a	1.91a	1.90a	0.034a	6.89a	5.84b	13.30ab	3.21a	2.95a
CLSW level 1	7.62a	3.13ab	0.85a	19.20a	1.92a	1.93a	0.028ab	5.46a	5.94b	13.14ab	2.93ab	2.57a
CLSW level 2	7.76a	3.35a	0.93a	19.53a	1.89a	1.93a	0.028ab	6.72a	6.37b	12.45ab	2.67abc	2.90a
						Oilseed radish sandy soil						
Unfertilized												
Control	10.36a	45.03a	2.36a	22.17a	4.67a	2.73b	0.045a	10.46ab	103.21a	18.05a	2.61a	-
Limestone	10.53a	37.01a	2.77a	23.24a	4.29a	3.70ab	0.048a	11.56a	91.24a	15.89a	2.32a	-
CLS1 level 1	9.31ab	32.33a	2.28a	19.57a	3.79a	5.96a	0.035a	10.26ab	74.53a	13.64a	2.00a	-
CLS level 2	8.32b	26.90a	1.99a	15.93a	2.77a	2.91b	0.030a	7.01b	68.48a	12.49a	1.69a	-
CLSW level 1	9.27ab	30.27a	2.24a	17.61a	3.19a	5.10ab	0.033a	7.35a	92.86a	12.61a	1.75a	-
CLSW level 2	9.14ab	30.62a	2.44a	19.11a	3.18a	6.24a	0.035a	8.92ab	76.88a	15.47a	1.76a	-
Fertilized												
Control	9.14a	30.09a	1.92a	18.21a	3.00a	8.23a	0.042ab	15.91ab	100.20a	24.85a	3.06a	-
Limestone	8.43a	41.96a	1.89a	15.42a	2.55a	6.01a	0.044ab	11.19b	104.97a	22.12a	2.59a	-
CLS level 1	9.24a	28.75a	1.65a	15.33a	2.13a	7.30a	0.030b	13.82ab	76.80a	13.78a	1.68a	-
CLS level 2	9.51a	38.43a	2.21a	19.32a	2.21a	6.81a	0.052ab	28.30a	108.50a	17.86a	1.70a	-
CLSW level 1	9.59a	39.79a	2.39a	20.15a	3.17a	10.12a	0.061a	23.63ab	123.30a	25.47a	2.78a	-
CLSW level 2	9.02a	35.55a	1.96a	16.14a	2.60a	5.22a	0.039ab	15.73ab	88.14a	18.59a	1.65a	-
						Barley clay soil						
Unfertilized												
Control	8.35a	4.71c	1.62a	19.04a	3.25a	2.35d	0.038b	11.36c	6.73a	23.21a	5.96a	2.10c
Hydrated lime	8.18ab	5.23bc	1.71a	15.98b	2.19c	1.89d	0.044ab	14.10bc	2.59c	14.20c	4.53c	5.01b
CLS Level 1	7.35bc	6.07b	1.67a	18.11ab	2.82ab	3.50bc	0.037b	12.65c	4.71b	18.13bc	4.95bc	4.92b
CLS Level 2	7.95ab	6.04b	1.81a	15.84b	2.10c	3.07c	0.053a	21.13a	4.70b	17.03bc	4.92bc	6.52a
CLSW Level 1	7.95ab	6.26a	1.67a	19.70a	3.11a	4.02a	0.041ab	12.03c	5.15b	21.09ab	5.15b	4.20b

(*Continued*)

Table 5. (Continued).

Treatment	Content, mg g^{-1} DW						Content, µg g^{-1} DW					
	N	Ca	Mg	K	P	S	Fe	Mn	B	Zn	Cu	Cd
CLSW Level 2	6.95c	5.95ab	1.67a	18.43a	2.52bc	3.60ab	0.044ab	16.74b	5.08b	14.65c	4.66bc	5.08ab
Fertilized												
Control	7.76bc	4.34c	1.22d	18.21ab	1.71b	2.44b	0.041b	25.56a	8.20a	18.05a	4.15c	6.33c
Hydrated lime	9.91a	5.68a	1.62a	19.44a	1.85ab	2.99a	0.054ab	20.13b	5.49c	15.31a	4.89ab	11.20a
CLS Level 1	8.94abc	5.16ab	1.53abc	17.98ab	2.04a	2.82ab	0.053ab	17.06bcd	6.47abc	14.37a	4.51abc	8.80b
CLS Level 2	9.20ab	5.20ab	1.57ab	18.36ab	1.81ab	2.78ab	0.061a	19.17bc	6.02bc	13.25a	4.98a	8.73b
CLSW Level 1	7.70c	4.96abc	1.38 cd	18.21ab	2.00ab	2.63ab	0.039b	15.69 cd	7.57ab	15.09a	4.23bc	6.84bc
CLSW Level 2	8.12bc	4.70bc	1.41bc	17.83b	1.91ab	2.81ab	0.041b	14.67d	5.87bc	13.73a	4.38abc	6.43c

doubled when hydrated lime was applied and reached 11.20 µg Cd g^{-1} DW. In the fertilized plants, the content of Cd in CLS applied plants was significantly lower, compared to the hydrated lime treated plants although significantly higher than the control plants (Table 5). In the sandy soil, the Cd concentration in shoot only increased in unfertilized plants applied with CLS level 2.

Discussion

Germination

The differences in germination among species after addition of carbon-rich slag are consistent with results reported earlier. Tintner et al. (2016) found differences in germination frequency related to increased slag amendment, between the species *Phleum pretense*, *Lepidium sativum*, *Trifolium alexandrium* and *Amaranthus retroflexus*. They also found that there was a difference in germination performance and growth between species when soil was amended with aged slag or fresh slag.

Germination studies after slag amendments are scarce. In the absence of seed germination experiments on slag amended soil conclusions may be drawn from general studies and studies of germination on soils amended with ash that have many similar properties. According to Wong and Wong (1989), germination of *Brassica parachinensis* and *Brassica chinensis* was slightly enhanced at low levels (3 and 6%) of added fly ash but decreased significantly when higher amounts (12 and 30%) were added to both a sandy soil and sandy loam soil. The fly ash used had a high pH but a low organic content and the reduced germination at higher additions was concluded to result from the high conductivity in the soil. Kalra et al. (1997) compared the germination of several crop species and found that mustard was highly sensitive, wheat was moderately sensitive and rice and corn was the least sensitive to fly ash soil amendment. The fly ash used had a carbon content of 28.6% that is similar to the CLS, but a lower pH. The soil conductivity was doubled, and the soil penetration force increased with increasing fly ash amendment indicating low chemical aggregation (Kalra et al. 1997). We found that the germination of sugar beet and oilseed radish was highly affected by the combined addition of CLS and fertilizer. A poor germination performance in seeds may be related to the different sensitivity to changes in pH and soil conductivity. Reduced germination in sugar beet seeds have been shown to be related to high soil conductivity (Jafarzadeh and Aliasgharzad 2007; Zare et al. 2012) and to pH changes (Pérez-Fernández et al. 2006). These studies support the conclusion that the reduced germination was a result of increased conductivity in the soil.

Growth

Our results show that the effects of carbon-rich lime slag for supporting the growth of the crops tested are comparable to the lime products normally used on Swedish agricultural soils today. An increase in plant biomass in response to the addition of carbon-rich lime slag has not been shown before. But growth studies on similar material have been reported. Growth in mung bean and rice was increased by low amounts of added slag or ash (up to 10%), and growth was inhibited when higher amounts were applied (Torkashvand and Shahram 2007; Singh and Agrawal 2010; He et al. 2017; Pietrini et al. 2017). The growth of barley has been shown to increase after addition of wood ash (Patterson et al. 2004) and carbon-rich fly ash in a similar way as lime (Renken et al. 2006). The initial reduction in the growth of the fertilized plants treated with CLS 2 was probably due to unfavorable germination and growth conditions during early development, such as high pH and high soil conductivity as discussed above. The positive effect of carbon-rich slag on plant growth is also supported by the increased tillering in the plants that received the slag amendment. Tillering in grasses is stimulated by several factors where N, P and water availability plays a significant role (Riaz et al. 2023).

Structural liming increases the growth of the crops in more than one way, higher aggregate stability and increased pH (Tang et al. 2003). In the clayey soils with close to neutral pH tested here, chemical aggregation is the main factor affecting plant growth. Increasing the pH above neutral might even be detrimental for the soil nutrition in this soil. More stable and diverse aggregates cause the pore system of the soil to become better at retaining water and aerate the soil. Both these factors are favorable for root growth. There was a visible effect on soil aggregation in the CLS treated soil at harvest (Figure S2) but the aggregation was not quantified in this experiment. No significant difference in growth between the treatments could be detected when fertilizer was added to the different treatments (data not shown).

Elemental content

The reduced N concentration in the CLS treated plants might be a result of dilution in a larger biomass, expressed as sturdier plants and more tillers in barley. This indicates that there was another limitation that was reversed with the amendment. In field studies of wheat, White et al. (2017) found that application of silicate slag both increased soil pH and the amount of available N. We could see no increase in N concentration in the plants with the CLS amendment and the fertilization even reduced the N concentration. The nitrogen is retained to a larger extent incorporated into the microbial community or by electrostatic forces by the positive charges in the material, the cation exchange capacity. It is well known that carbon-rich amendment may cause increased N limitations in soil microbiota (Kamble and Bååth 2014) which competes with the plants for the N. The CLS might have a similar effect on the N availability. A nitrogen retention and immobilization would also explain why the N concentration in the plants is higher in the fertilized pots.

The CLS addition did not increase the leaf K concentration despite high levels in the added material. No increase in leaf P concentration was expected, the levels in CLS is low and a pH increase may reduce the soil P availability. This is consistent with results from soybean that were grown in a number of various types of slag with no increase in K and P leaf concentration (Masud et al. 2014; Deus et al. 2020). The increases in the plant concentrations of different micronutrients, however, increased in response to the CLS amendment. This is consistent with the results from a study on palisade grass. Fonseca et al. (2011) showed that the accumulation of micronutrients in the shoot was similar both in lime and slag treatment. An increased Mn uptake has been detected in maize grown in rice field soil and tea garden soil, both amended with 1–2% (w/w) converter slag (Torkashvand and Shahram 2007). The concentration of Ca, Mg and Mn increased in sunflower leaves in greenhouse experiments with fertilized peat substrate amended with steel slag (Altland et al. 2015). Altland et al. (2015) however concluded that steel slag should not be used as a single micronutrient source, due to limiting concentrations of B and Zn found in tomato shoots. Interestingly, the increased Ca content in barley was similar for the hydrated lime and CLS treatments, which indicates that Ca in the added CLS is readily plant available. Mantovani et al. (2016) also found that steel slag had the ability to supply Ca to coffee plants.

The difference in the soil properties may explain the difference in Cd-uptake in this study, as pH, content of organic matter and CEC are factors highly influencing the Cd availability in soils (Sánchez-Camazano et al. 1998; Grant and Sheppard 2008). The Cd concentration was similar in both soils, but the clay soil had a lower pH, higher clay content and humus content, compared to the sandy soil (Table 1). The results from our study show that the use of CLS instead of hydrated lime, that is common practice on heavy clay soils in Sweden, can result in a lower Cd content in barley shoots. This reducing Cd effect may be a result of the carbon content in CLS, as carbon in different formulations is known to bind cations. In a study by Rehman et al. (2018), the Cd content in both wheat and rice kernels decreased after biochar treatment. The increase in Cd content that was seen after addition of CLS or hydrated lime, may be due to the addition of high amounts of Ca to the soil, that influence the cation exchange, possibly resulting in the exchange of Cd from the colloids. The general increase in Cd content in fertilized compared to unfertilized barley shoots grown in the clay soil was probably due to an accelerated cation exchange when fertilizer was added to the soil. The amounts of CLS used in our study will not add more Cd to the soil compared to the limestone or hydrated lime, and even those soil amendments are far below the limits according to the Swedish regulations for Cd addition today.

Conclusions

Both carbon enriched lime slag (CLS) formulations (with and without addition of water) had a similar effect on the crops as virgin lime in all the tested growth parameters and has a potential to be used as lime substitutes. When the CLS levels were higher (4 tons (sandy) and 4.4 tons (clay) CaO ha^{-1}) than the recommended lime dose, there was a significant growth increase in unfertilized barley, regardless of the soil type. However, caution should be done to avoid high salt levels in the soil solution. The study revealed that is important to distribute the CLS before establishing the crop and not at the same time as the fertilizers to avoid unfavorable germination conditions, especially when cultivating sensitive crops.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

Altland JE, Krause C, Locke JC, Zellner WL. 2015. Micronutrient availability from steel slag amendment in peatmoss substrates. HortScience. 50(11):1715–1720. doi: 10.21273/HORTSCI.50.11.1715.

Altland JE, Locke JC, Zellner WL, Boldt JK. 2015. Steel slag raises pH of greenhouse substrates. HortScience. 50 (4):603–608. doi: 10.21273/HORTSCI.50.4.603.

Atkinson CJ, Fitzgerald JD, Hipps NA. 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil. 337(1–2):1–18. doi: 10.1007/s11104-010-0464-5.

Bashir S, Salam A, Chhajro MA, Fu Q, Khan MJ, Zhu J, Shaaban M, Kubar KA, Ali U, Hu H. 2018. Comparative efficiency of rice husk-derived biochar (RHB) and steel slag (SS) on cadmium (Cd) mobility and its uptake by Chinese cabbage in highly contaminated soil. Int J Phytorem. 20(12):1221–1228. doi: 10.1080/15226514.2018.1448364.

Blomquist JE, Berglund K. 2021. Timing and conditions modify the effect of structure liming on clay soil. Agric Food Sci. 30:96–107. doi: 10.23986/afsci.103422.

Blomquist JE, Englund J-E, Sjöberg C, Kårhammer J, Svensson S-E, Pettersson E, Keller T, Berglund K. 2023. Structure liming reduces draught requirement on clay soil. Soil Tillage Res. 231:105703. doi: 10.1016/j.still.2023.105703.

Blomquist JE, Simonsson M, Etana A, Berglund K. 2018. Structure liming enhances aggregate stability and gives varying crop responses on clayey soils. Acta Agric Scand, Sect B — Soil & Plant Sci. 68(4):311–322. doi: 10.1080/09064710.2017.1400096.

Das S, Kim GW, Hwang HY, Verma PP, Kim PJ. 2019. Cropping with slag to address soil, environment, and food security. Front Microbiol. 10:1320. doi: 10.3389/fmicb.2019.01320.

Deus ACF, Büll LT, Guppy CN, Santos SDMC, Moreira LLQ. 2020. Effects of lime and steel slag application on soil fertility and soybean yield under a no till-system. Soil Tillage Res. 196:104422. doi: 10.1016/j.still.2019.104422.

Fonseca IM, Prado RM, Nogueira TAR, Barbosa JC. 2011. Macronutrients in Marandu palisade grass as influenced by lime slag, and nitrogen fertilization. Commun Soil Sci Plant Anal. 42(7):844–857. doi: 10.1080/00103624.2011.552659.

Goulding KWT. 2016. Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. Soil Use Manag. 32(3):390–399. doi: 10.1111/sum.12270.

Grant CA, Sheppard SC. 2008. Fertilizer impacts on cadmium availability in agricultural soils and crops. Hum Ecol Risk Assess. 14(2):210–228. doi: 10.1080/10807030801934895.

Haynes RJ, Zhou Y-F. 2018. Effect of pH and added slag on the extractability of Si in two Si-deficient sugarcane soils. Chemosphere. 193:431–437. doi: 10.1016/j.chemosphere.2017.10.175.

He H, Tam NFY, Yao A, Qiu R, Li WC. 2017. Growth and Cd uptake by rice (Oryza sativa) in acidic and Cd-contaminated paddy soils amended with steel slag. Chemosphere. 189:247–254. doi: 10.1016/j.chemosphere.2017.09.069.

Ibitoye SE, Loha C, Mahamood RM, Jen T-C, Alam M, Sarkar I, Das P, Akinlabi ET. 2024. An overview of biochar production techniques and application in iron and steel industries. Bioresour Bioprocess. 11(1). doi: 10.1186/s40643-024-00779-z.

Jafarzadeh AA, Aliasgharzad N. 2007. Salinity and salt composition effects on seed germination and root length of four sugarbeet cultivars. Biologia. 62(5):562–564. doi: 10.2478/s11756-007-0111-7.

Kalra N, Joshi HC, Chaudhary A, Choudhary R, Sharma SK. 1997. Impact of fly ash incorporation in soil on germination of crops. Bioresour Technol. 61(1):39–41. doi: 10.1016/S0960-8524(97)84696-2.

Kamble PN, Bååth E. 2014. Induced N-limitation of bacterial growth in soil: effect of carbon loading and N status in soil. Soil Biol Biochem. 74:11–20. doi: 10.1016/j.soilbio.2014.02.015.

Larsson Jönsson EH, Asp H. 2011. Influence of nitrogen supply on cadmium accumulation in potato tubers. J Plant Nutr. 34(3):345–360. doi: 10.1080/01904167.2011.536877.

Laveglia A, Ukrainczyk N, De Belie N, Koenders E. 2023. Decarbonizing the lime-based construction materials industry: a practical guide for cradle-to-gate life-cycle inventory. Sustain Prod Consumption. 40:194–209. doi: 10.1016/j.spc.2023.06.021.

Lehmann J, Gaunt J, Rondon M. 2006. Bio-char sequestration in terrestrial ecosystems – a review. Mitig Adapt Strat Glob Change. 11(2):403–427. doi: 10.1007/s11027-005-9006-5.

Li Y, Cui S, Chang SX, Zhang Q. 2019. Liming effects on soil pH and crop yield depend on lime material type, application method and rate, and crop species: a global meta-analysis. J Soils Sediments. 19(3):1393–1406. doi: 10.1007/s11368-018-2120-2.

Mantovani JR, Campos GM, Silva AB, Marques DJ, Putti FF, Landgraf PRC, de Almeida EJ. 2016. Steel slag to correct soil acidity and as silicon source in coffee plants. Afr J Agric Res. 11(7):543–550. doi: 10.5897/AJAR2015.10535.

Marschner H. 1995. Mineral nutrition of higher plants. London: Academic press.

Masud MM, Li J-Y, Xu R-K. 2014. Use of alkaline slag and crop residue biochars to promote base saturation and reduce acidity of an acidic ultisol. Pedosphere. 24(6):791–798. doi: 10.1016/S1002-0160(14)60066-7.

Mayer AM, Poljakoff-Mayber A. 1982. The germination of seeds. San Diego, (UK): Elsevier Science & Technology.

Ning D, Liang Y, Liu Z, Xiaoo J, Duan A. 2016. Impacts of steel-slag-based silicate fertilizer on soil acidity and silicon availability and metals-immobilization in a paddy soil. PLOS ONE. 11(12):e0168163. doi: 10.1371/journal.pone.0168163.

Öborn I, Jansson G, Johnsson L. 1995. A field study on the influence of soil pH on trace element levels in spring wheat (*Triticum aestivum*), potatoes (*Solanum tuberosum*) and carrots (*Daucus carota*). Water Air Soil Pollut. 85(2):835–840. doi: 10.1007/BF00476933.

Patterson SJ, Acharya SN, Thomas JE, Bertschi AB, Rothwell RL. 2004. Barley biomass and grain yield and canola seed yield response to land application of wood ash. Agron J. 96(4):971–977. doi: 10.2134/agronj2004.0971.

Perata P, Alpi A. 1993. Plant responses to anaerobiosis. Plant Sci. 93(1–2):1–17. doi: 10.1016/0168-9452(93)90029-Y.

Pérez-Fernández MA, Calvo-Magro E, Montanero-Fernández J, Oyola-Velasco JA. 2006. Seed germination in response to chemicals: effect of nitrogen and pH in the media. J Environ Biol. 27(1):13–20.

Pietrini F, Iori V, Beone T, Mirabile D, Zacchini M. 2017. Effects of a ladle furnace slag added to soil on morpho-physiological and biochemical parameters of Amaranthus paniculatus L. plants. J Hazard Mater. 329:339–347. doi: 10.1016/j.jhazmat.2017.01.050.

Rehman MZ, Rizwan M, Khalid H, Ali S, Naeem A, Yousaf B, Liu G, Sabir M, Farooq M. 2018. Farmyard manure alone and combined with immobilizing amendments reduced cadmium accumulation in wheat and rice grains grown in field irrigated with raw effluents. Chemosphere. 199:468–476. doi: 10.1016/j.chemosphere.2018.02.030.

Renken RR, McCallister DL, Tarkalson DD, Hergert GW, Marx DB. 2006. Barley seedling growth in soils amended with fly ash or agricultural lime followed by acidification. Soil Sci. 171:414–422. doi: 10.1097/01.ss0000222888.51501.94.

Riaz A, Alqudah AM, Kanwal F, Pillen K, Ye L-Z, Dai F, Zhang G-P. 2023. Advances in studies on the physiological and molecular regulation of barley tillering. J Intgr Agric. 22(1):1–13. doi: 10.1016/j.jia.2022.08.011.

Sánchez-Camazano M, Sanchez-Martin MJ, Lorenzo MF. 1998. Significance of soil properties for content and distribution of cadmium and lead in natural calcareous soils. Sci Total Environ. 218(2–3):217–226. doi: 10.1016/S0048-9697(98)00212-5.

Sauvé S, Hendershot W, Allen HE. 2000. Solid-solution partitioning of metals in contaminated soils: dependence on pH, total metal burden, and organic matter. Environ Sci Technol. 34(7):1125–1131. doi: 10.1021/ES9907764.

Singh A, Agrawal SB. 2010. Response of mung bean cultivars to fly ash: growth and yield. Ecotoxicol Environ Saf. 73:1950–1958. doi: 10.1016/j.ecoenv.2010.07.023.

Tang C, Rengel Z, Diatloff E, Gazey C. 2003. Responses of wheat and barley to liming on a sandy soil with subsoil acidity. Field Crops Res. 80(3):235–244. doi: 10.1016/S0378-4290(02)00192-2.

Tintner J, Matiasch L, Klug B. 2016. Germination and juvenile development of plants on municipal solid waste incineration (MSWI) slag. Ecol Eng. 87:162–167. doi: 10.1016/j.ecoleng.2015.11.037.

Torkashvand AM, Shahram SH. 2007. Converter slag as a liming agent in the amelioration of acidic soils. Int J Agric & Biol. 9:715–720.

Tozsin G, Öztas T. 2023. Utilization of steel slag as a soil amendment and mineral fertilizer in agriculture: a review. J Agric Sci. 29(4):906–913. doi: 10.15832/ankutbd.1197239.

White B, Tubana BS, Babu T, Mascagni H Jr, Agostinho F, Datnoff LE, Harrison S. 2017. Effect of silicate slag application on wheat grown under two nitrogen rates. Plants. 6(4):47. doi: 10.3390/plants6040047.

Wong MH, Wong JWC. 1989. Germination and seedling growth of vegetable crops in fly ash-amended soils. Agric Ecosyst Environ. 26(1):23–35. doi: 10.1016/0167-8809(89)90035-2.

Zare M, Ghaemi M, Mostafavi K. 2012. Role of salt stress on seed germination and growth of sugar beet cultivars. Int J Recent Sci Res. 3(10):800–804.