Australian Journal of Crop Science AJCS

AJCS 17(1) 8-13 (2023) ISSN:1835-2707

Supplementary data

Change in soil chemical attributes and yield of a common-bean crop in response to steel slag application

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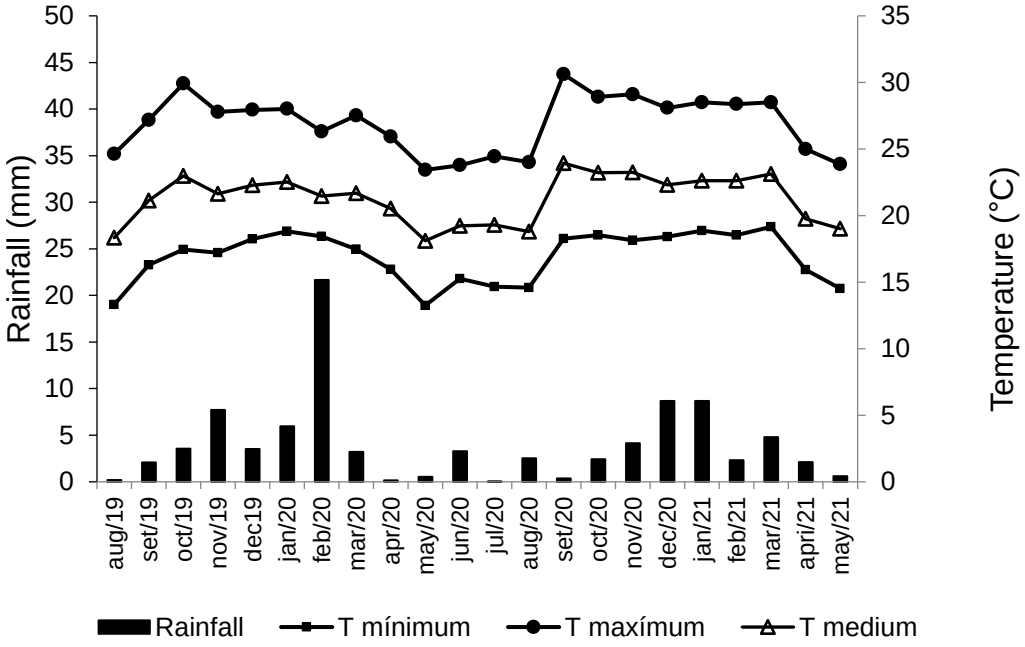

Supplementary Fig 1. Monthly precipitation and minimum, maximum and average temperature in Botucatu, State of São Paulo, Brazil during the study period, from August 2019 to May 2021.

Supplementary Table 1. Chemical characterization of the soil before the installation of the experiment, according to the different treatments and form of application.

Correctives	Application	pH $CaCl_2$	M.O. g/dm³	P resina mg/dm³	H+Al	K	Ca	Mg	SB	CEC	BS
					----------mmolc dm^{-3}---------						%
T1	I	5.1	26	21	39	1.2	70	11	76	94	63
T2	I	5.3	26	13	35	1.0	45	12	60	76	63
T3	I	4.9	27	12	46	0.9	37	10	48	68	51
T4	I	4.8	27	14	50	0.9	36	10	49	69	49
T5	I	4.9	29	15	49	1.1	36	12	51	67	52
T6	I	4.5	28	14	63	1.1	31	10	42	64	41
T1	S	5.4	32	24	29	1.3	72	14	85	97	73
T2	S	5.1	30	21	46	1.3	71	14	78	89	61
T3	S	5.1	30	18	40	1.1	79	15	89	104	64
T4	S	5.0	30	21	53	0.8	52	12	67	83	56
T5	S	5.0	29	17	52	1.0	45	12	58	71	54
T6	S	4.8	30	18	53	1.0	49	13	57	81	51
Média		4.9	29	17	46	1.1	52	12	63	87	44
C	I	4.9	27	15	78	0.9	24	6	31	80	56
T	S	5.0	30	29	82	1.3	32	8	41	80	56

Steel slag (T1), wollastonite (T2), ladle furnace slag (T3), Stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control (C) without co rrectives. S: Superficial and I: Incorporated. BS: Base saturation. CEC: Cation exchange capacity.

Supplementary Table 2. Chemical and physical characterization of soil acidity correctives.

Correctives	Result in %					
	CaO	MgO	RE	NP	PRNT	Moisture
Stainless steel slag	39.67	11.33	70.97	86	61	2.2
Steel slag	35.30	13.10	73.00	72	53	0.9
Calcined dolomitic lime	52.30	17.90	97.00	139	134	0.2
Dolomitic lime	31.18	16.29	89.36	82	74	1.9
Ladle slag	33.35	6.05	74.11	68	51	1.2
Wollastonite	33.38	4.40	99.64	65	64	0.1

RE= reactivity, expresses the corrective percentage that reacts in three months; NP= neutralizing power, expresses the corrective chemical potential, in $CaCO_3$ equivalent.

Supplementary Table 3. Decomposition of the acidity corrective × application form interaction for soil S content.

Corrective*	S (mmldm³)	
	Incorporated	Surface
	10 – 20 cm	
C	84 aA	32 Ba
T1	34 aC	27 Aa
T2	34 aB	42 aA
T3	61 aBC	55 aA
T4	44 a BC	54 aA
T5	73 aB	56 aA
T6	68 aC	39 bA

*Steel slag (T1), wollastonite (T2), ladle furnace slag (T3), Stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control (C) without correctives. Capital letters correspond to the comparisons between the soil acidity correctives within the same mode of application. Lower case letters correspond to comparisons between the mode of application for the same soil acidity correction by the Tukey test at a level of 5% (*) and 1% (**) probability.

Supplementary Table 4. Mean values of Fe, Cu, Mn and Zn in the soil after 10 months of incorporated application and on the surface of Steel slag (T1), wollastonite (T2), ladle furnace slag (T3), Stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control (C) without correctives.

Treatments	Fe			Cu			Mn			Zn		
	----------mmolc/dm³ ----------											
	layers (cm)											
Application(A)	0-10	10-20	20-40	0-10	10-20	20-40	0-10	10-20	20-40	0-10	10-20	20-40
Incorporated	0,8 a	23 a	19 a	5,7 a	5,8 a	5,6 a	22 a	26 a	10 a	0,8 a	0,5 a	0,7 a
Surface	0,9 a	23 a	18 a	5,0 a	5,6 a	5,5 a	12 a	12 b	10 a	0,9 a	0,6 a	0,6 a
F	0,4^{ns}	0,1^{ns}	0,5^{ns}	23^{ns}	2,7ns	1,1^{ns}	22*	241*	0,0^{ns}	8,6^{ns}	6,8^{ns}	0,0^{ns}
Corrective (C)												
C	33 a	24 ab	22 a	6,3 a	5,7ab	6,0 a	27 a	19 a	11 a	0,8 a	0,6 a	0,7 a
T1	22 b	19 b	19 ab	5,1 b	5,6 ab	5,4 b	21 b	19 a	11 a	0,9 a	0,6 a	0,6 a
T2	17 c	21 ab	17 bc	4,9 b	5,7 ab	5,3 b	17 c	19 a	8 a	0,9 a	0,6 a	0,6 a
T3	20 bc	23 ab	20 ab	5,2 b	5,5 b	5,7 ab	22 b	19 a	12 a	0,9 a	0,5 a	0,7 a
T4	21 bc	25 ab	20 ab	5,3 b	5,7 ab	5,5 b	11 d	19 a	10 a	0,9 a	0,6 a	0,7 a
T5	18 c	26 a	15 c	5,2 b	6,1 a	5,4 b	16 c	18 a	9 a	0,8 a	0,5 a	0,6 a
T6	22 b	23 ab	18abc	5,5 b	5,8 ab	5,5 b	17 c	19 a	10 a	0,8 a	0,5 a	0,6 a
F	13,1*	2,8*	7,3**	9,7**	2,0*	5,6**	48*	0,3^{ns}	1,8^{ns}	0,4^{ns}	0,8^{n}s	1,6^{ns}
A x C	2,8*	2,1^{ns}	1,2^{ns}	1,0^{ns}	1,4^{ns}	0,6^{n}s	37*	7,1**	1,1^{ns}	1,3^{ns}	5,2**	0,8^{ns}
CV (%) plot	19	14	33	9	6	8	15	18	41	19	22	49
CV (%) subplot	18	15	11	7	7	4	11	17	25	18	21	15

Averages followed by different letters in the columns differ among themselves. By the Tukey test at 5% (*) and 1% (**) probability. VC: Coefficient of variation; Aplication (A); Correctives (C).

Supplementary Table 5. Decomposition of the acidity corrective × application form interaction for the Mg and Mn contents in the soil.

Corrective*	Mg		Mn	
	---------- mg dm³ ----------			
	Form of Application			
	Incorporated	Surface	Incorporated	Surface
C	4.7 aB	4.8 aBCD	661 aA	199 bA
T1	3.4 aB	3.5 aD	195 aB	212 aA
T2	4.7 aB	3.9 aCD	170 aB	162 aA
T3	6.1 aA	4.2 bBCD	229 aB	229 aA
T4	6.2 aA	4.5 bBCD	171 aB	169 aA
T5	6.7 aA	5.0 bAB	177 aB	171 aA
T6	6.7 aA	5.1 bA	212 aB	210 aA

*Steel slag (T1), wollastonite (T2), ladle furnace slag (T3), Stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control (C) without correctives. Capital letters correspond to the comparisons between the soil acidity correctives within the same mode of application. Lower case letters correspond to comparisons between the mode of application for the same soil acidity correction by the Tukey test at a level of 5% (*) and 1% (**) probability.

Supplementary Table 6. Relative water content in leaf tissue (RWC), electrolyte loss (EL) and pigment content: chlorophyll a (Clo a), chlorophyll b (Clo b) and carotenoids (Car), photosynthesis (Photo), stomatal conductance, internal CO2 concentration and transpiration as a function of the effect of application and soil acidity correctives in beans cultivate IAC-IMPERADOR.

Treatments	RWC	EL	Clo a	Clo b	Car	Photo	Stomatal Conduct	Internal Conduc of CO_2	Transpiration
	%	µg cm^{-2} de folha				(µmol CO_2 m^{-2})	(µmolH_2O m^{-2} s^{-1})	(µmol CO_2mol^{-1})	(mol H_2O m^{-2} s^{-1})
Application (A									
Incorporated	77 a	34 a	10 a	10 a	2 a	12.4 b	0.2 b	280 a	3 a
Surface	74na	32 a	10 a	11 a	2a	14.4 a	0.3 a	286 a	4 a
F	2.8*	0.2^{ns}	0.1^{ns}	1.0^{ns}	0.1^{ns}	15.4*	19.2*	6.2^{ns}	9.1^{ns}
Corrective (C)									
C	79 a	19 b	10 a	10 a	2 a	12.9 a	0.29 a	291 a	4 a
T1	75 a	38 a	10 a	11 a	2 a	13.6 a	0.28 a	277 a	4 a
T2	74 a	39 a	9 a	12 a	2 a	13.2 a	0.29 a	288 a	4 a
T3	74 a	36 a	10 a	11 a	2 a	13.1 a	0.26 a	278 a	4 a
T4	76 a	31ab	11 a	11 a	2 a	13.5 a	0.31 a	288 a	4 a
T5	78 a	39a	9 a	10 a	2 a	14.3 a	0.28 a	279 a	4 a
T6	74 a	28ab	11a	11 a	2 a	13.2 a	0.27 a	281a	4 a
F	0.6^{ns}	2.2*	0.8^{ns}	0.9^{ns}	0.9^{ns}	0.19^{ns}	0.26^{ns}	1.2^{ns}	0.2^{ns}
A x C	0.3^{ns}	2.0^{ns}	0.4^{ns}	1.0^{ns}	0.2^{ns}	1.06^{ns}	0.45^{ns}	0.4^{ns}	0.8 ^{ns}
CV (%) plot	10	56	33	27	27	15	22	3	20
CV(%)subplot	10	42	29	15	31	21	32	4	22

Means followed by different letters in the columns differ from each other by Tukey's test at 5% (*) and 1% (**) probability. CV: coefficient of variation. Steel slag (T1), wollastonite (T2), ladle furnace slag (T3), Stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control (C) without correctives.

Supplementary Table 7. Mean leaf nutrient and Si (silicon) contents in common-bean plants (cultivar IAC-IMPERADOR) as a function of incorporated and surface application of soil acidity corrective materials.

Treatments	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	Si
Application(A)	---------- g kg^{-1} ----------						---------- mg kg^{-1} ----------					g kg^{-1}
Incorporated	41 a	2.3 a	17 a	16 a	5.4 a	1.5 a	26 a	11.9 a	1107 a	262 a	30 a	5.1 a
Surface	39 a	2.5 a	21 a	12 b	4.4 b	1.4 a	27 a	11.2 a	1042 a	188 b	28 a	6.2 a
F	2.2^{ns}	1.9^{ns}	20.7*	11.3*	48.4*	4.0^{ns}	0.9^{ns}	0.2^{ns}	0.3^{ns}	37.8*	11.2*	17.3^{ns}
Corrective (C)												
C	39 a	2.5 a	18 b	15 ab	3.7 d	1.5 a	26 a	9.8 a	1021 a	203 b	28 c	5.1 a
T1	40 a	2.5 a	19 b	15 ab	4.0 d	1.5 a	26 a	14.3 a	1060 a	175 b	28 bc	6.4 a
T2	41 a	2.6 a	24 a	11 b	4.7 c	1.4 a	27 a	11.2 a	1130 a	430 a	34 a	2.6 b
T3	42 a	2.3 a	18 b	16 a	5.1 bc	1.5 a	29 a	11.7 a	999 a	234 b	27 c	5.2 a
T4	40 a	2.4 a	18 b	14 ab	5.4abc	1.4 a	28 a	11.1 a	1108 a	151 b	32 ab	5.5 a
T5	40 a	2.3 a	19 b	13 ab	5.8 ab	1.5 a	25 a	11.5 a	1081 a	174 b	30abc	5.2 a
T6	41 a	2.1 a	17 b	14 ab	6.0 a	1.5 a	25 a	11.3 a	1123 a	208 b	27 c	5.3 a
F	0.9^{ns}	0.8^{ns}	5.9**	2.8*	30**	0.5^{ns}	0.9^{ns}	1.1^{ns}	0.2^{ns}	23.7*	7.0**	3.4*
A x C	1.0^{ns}	1.1^{ns}	0.7^{ns}	2.1^{ns}	7.4**	0.4^{ns}	0.9^{ns}	1.7^{ns}	0.6^{ns}	19.6*	2.1^{ns}	1.9^{ns}
CV (%) plot	12	27	16	23	10	12	22	45	10	20	9	36
CV(%)subplot	6	19	14	19	9	14	15	30	25	24	9	21

Means followed by different letters in the columns differ from each other by Tukey's test at 5% (*) and 1% (**) probability. CV: coefficient of variation. Steel slag (T1), wollastonite (T2), ladle furnace slag (T3), stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control (C) without correctives.

Supplementary Table 8. Decomposition of the acidity corrective × application form interaction for the Mg and Mn contents in the plant.

Corrective*	Mg		Mn	
	---------- mg dm^3 ----------			
	Forms of Application			
	Incorporated	Surface	Incorporated	Surface
C	4.7 aB	4.8 aBCD	661 aA	199 bA
T1	3.4 aB	3.5 aD	195 aB	212 aA
T2	4.7 aB	3.9 aCD	170 aB	162 aA
T3	6.1 aA	4.2 bBCD	229 aB	229 aA
T4	6.2 aA	4.5 bBCD	171 aB	169 aA
T5	6.7 aA	5.0 bAB	177 aB	171 aA
T6	6.7 aA	5.1 bA	212 aB	210 aA

*Steel slag (T1), wollastonite (T2), ladle furnace slag (T3), Stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control (C) without correctives. Capital letters correspond to the comparisons between the soil acidity correctives. Uppercase letters correspond to comparisons between soil acidity correctives under the same application form. Lowercase letters correspond to comparisons between application forms under the same soil acidity corrective by Tukey's test at the 5% (*) and 1% (**) probability levels.

Supplementary Table 9. Plant height (AP), leaf dry mass (LDW), stem dry mass (SDW), total soluble protein content (PTS), Superoxide dismutase (SOD), Catalase (CAT) and Peroxidase (POD) enzyme activity as a function of the application and corrective effects of soil acidity.

Treatments	AP	LDW	SDW	PTS	SOD	CAT	POD
	cm	(g plant-^{1})	(mg g-^{1})			(Uμg protein)	
Application (A							
Incorporated	46 a	16 a	4 a	11.9 a	1.0 b	577 a	918 a
Surface	44 a	16 a	4 a	11.4 a	2.0 a	496 a	972 a
F	3.4^{ns}	0.0^{ns}	2.7^{ns}	0.2^{ns}	11.8*	6.8^{ns}	0.8^{ns}
Corrective (C)							
C	48 a	17 a	4 abc	12.1 a	1.3 a	460 bc	815 b
T1	46 a	16 a	5 ab	10.9 a	1.3 a	641 a	1058 ab
T2	39 a	15 a	3 c	11.4 a	1.2 a	397 c	1325 a
T3	46 a	17 a	4 ab	12.6 a	1.2 a	593 ab	832 b
T4	44 a	16 a	3 bc	11.5 a	1.4 a	609 ab	991 ab
T5	45 a	16 a	4 abc	12.3 a	1.0 a	444 bc	780 b
T6	46 a	14 a	5 a	10.7 a	1.6 a	610 ab	815 b
F	1.8^{ns}	1.3^{ns}	4.7**	0.5^{ns}	1.6^{ns}	2.6*	5.4**
A x C	0.3^{ns}	0.4^{ns}	9.0**	0.3^{ns}	0.7^{ns}	0.8^{ns}	4.0**
CV (%) plot	12	35	23	28	15	21	22
CV(%)subplot	13	15	22	22	31	31	25

Means followed by different letters in the columns differ from each other by Tukey's test at 5% (*) and 1% (**) probability. CV: coefficient of variation; steel slag (T1), wollastonite (T2), ladle furnace slag (T3), stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control (C) without correctives.

Supplementary Table 10. Decomposition of the acidity corrective × application form interaction for stem dry weight (SDW) and peroxidase (POD) enzyme activity in the plant.

Corrective*	SDW		POD	
	---------- g plant -^{1} ---------		----------UI μprotein-^{1}----------	
	Forms of Application			
	Incorporated	Surface	Incorporated	Surface
C	4 aC	2 bBC	1379 aA	1290 aA
T1	4 aAB	4 aC	797 aB	803 aA
T2	6 aA	4 bC	1367 aA	749 bA
T3	3 aBC	6 aA	634 aB	1029 bA
T4	4 aC	4 aBC	826 aB	1157 aA
T5	5 aAB	3 bC	708 aB	853 aA
T6	4 aAB	6 aAB	718 aB	911 aA

*Steel slag (T1), wollastonite (T2), ladle furnace slag (T3), Stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control (C) without correctives. Uppercase letters correspond to comparisons between soil acidity correctives under the same application form. Lowercase letters correspond to comparisons between application forms under the same soil acidity corrective by Tukey's test at the 5% (*) and 1% (**) probability levels.

Supplementary Table 11. Mean values for the variables Number of pods per plant, Number of grain per pod, 100-grain mass and yield as a function of application and corrective effects of soil acidity in the IAC-IMPERADOR Bean cultivar.

Treatments	Number of pods per plant	Number of grain per pod	100-grain mass	Yield (t ha $^{-1}$)
Application (A)				
Incorporated	9 a	6 a	26 a	1,14 a
Surface	9 a	7 a	26 a	1,59 a
F	0,94^{ns}	1,00^{ns}	3,80^{ns}	4,86^{ns}
Corrective (C)				
C	9 a	7 a	26 ab	1,21 a
T1	9 a	7 a	28 a	1,45 a
T2	10 a	7 a	28 a	1,56 a
T3	10 a	7 a	28 a	1,61 a
T4	9 a	7 a	28 a	1,18 a
T5	9 a	7 a	23 ab	1,52 a
T6	9 a	6 a	21 b	1,22 a
F	1,15^{ns}	0,64^{ns}	5,59*	2,45^{ns}
A x C	0,59^{ns}	1,53^{s}	2,41^{ns}	2,02^{ns}
VC (%) plot	42	43	10	46
VC (%) subplot	30	23	11	29

Mean followed by different letters in the columns differ from each other by Tukey's test at 5% (*) and 1% (**) probability. CV: coefficient of variation; steel slag (T1), wollastonite (T2), ladle furnace slag (T3), stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control (C) without correctives.