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Relative effectiveness of organic and inorganic nutrient sources in improving yield, seed quality and nutrient uptake of canola

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ABSTRACT

The proper use of organic and inorganic nutrient sources is important to sustain high levels of crop production, while maintaining or enhancing soil and environmental quality. A 4-year (2009 to 2012) field experiment was established in spring 2009 on a Gray Luvisol (Typic Haplocryalf) loam soil at Star City, Saskatchewan, Canada, to determine the effectiveness of organic/biological (compost, wood ash [fine and granular], alfalfa pellets, distiller grain, thin stillage, glycerol, fish food additive, *Penicillium bilaiae*), inorganic/mineral (granular-gypsum, rapid release elemental S [RRES], rock phosphate [granular and fine]) and chemical/synthetic (granular-ammonium nitrate, triple super phosphate and potassium sulphate) nutrient sources (amendments/chemicals) in improving seed yield, straw yield, seed quality and nutrient uptake (N, P, K and S) in seed + straw of canola. Combined application of N, P and S chemical fertilizers (NPS) produced considerably greater seed yield, straw yield and nutrient uptake of canola compared to the unamended control in all four years. In treatments receiving only organic amendments, thin stillage produced the greatest seed yield, straw yield and nutrient uptake in all years, and it was similar to the NPS balanced fertilizer treatment, while fish food additive and distiller grain dry of wheat in 2009, 2011 and 2012, distiller grain dry of corn in 2009 and 2012, and compost and alfalfa pellets in 2011 and 2012 produced significantly greater seed yield, straw yield and nutrient uptake, when compared to the control. In treatments where chemical fertilizers were also applied, in addition to organic amendments, application of N fertilizer increased seed yield, straw yield and nutrient uptake substantially when combined with wood ash fine in 2009, 2010, 2011 and 2012, wood ash granular in 2009, 2011 and 2012, and glycerol in 2009 and 2012 (moderate increase in 2012). In the chemical fertilizer treatments, there was a reduction in seed yield, straw yield and nutrient uptake of canola when only N fertilizer was applied compared to the control (significant in 2010 and 2011). Application of P along with N (NP) increased seed yield, straw yield and nutrient uptake of canola compared to N alone treatment, but was less than the NPS treatment in all years. Application of S along with N (NS) increased seed yield, straw yield and nutrient uptake of canola further compared to the NP treatment, but it was still lower than the NPS treatment in 2010 and 2011. In treatments receiving inorganic/mineral amendments in addition to chemical fertilizers, application of N + P fertilizers substantially increased seed yield, straw yield and nutrient uptake in treatments receiving gypsum and RRES in 2009, 2010, 2011 and 2012. This suggests the potential of gypsum and RRES in preventing S deficiency in organic crops when grown on S-deficient soils, provided other nutrients are not limiting in the soil for crop growth. Seed yield, straw yield and nutrient uptake with application of N and S fertilizers in combination with rock phosphate and/or *Penicillium bilaiae* were similar to N + S treatment in most cases, except in 2011 when application of finely-ground or powder rock phosphate in a combination with N + S produced significantly greater yield and nutrient uptake than N + S with granular rock phosphate. This suggests little contribution of rock phosphate

and/or *Penicillium bilaiae* in improving yield and nutrient uptake of canola, and improves the performance of fine rock phosphate only evident in the third growing season in 2011, after three consecutive applications, but not in 2012. In conclusion, some organic amendments showed potential for improvement in organic crop production, and in some other cases highest yield and nutrient uptake were produced when organic amendments were applied in combination with chemical fertilizers, or from combined application of chemical N, S and P fertilizers. The implications of these findings are that the use of some organic amendments can be feasible for improving crop yields under organic production. These findings also suggest the potential of some inorganic amendments (e.g., RRES and gypsum) in preventing S deficiency in organic crops, provided other nutrients are not limiting in the soil.

Keywords: Inorganic; Nutrient Sources; Nutrient Uptake; Organic; Seed Quality; Yield

1. INTRODUCTION

Any nutrient(s) limiting in soil can cause a substantial reduction in crop yield. In the Canadian Prairies, most soils are deficient in available N, many are low in available P, and some contain insufficient amounts of available S (like many Gray and Dark Gray soils in the Parkland region) and K for optimum crop growth and yield, especially under organic agriculture [1-3]. Nutrient deficiencies in crops can be prevented by using organic and inorganic nutrient sources. Chemical fertilizers, because of their huge yield response, easy availability, and convenient transportation and application, are very attractive and commonly used to enhance crop production [4-7]. However, it is possible that the long-term use of increased amounts of only chemical fertilizers may degrade soil structure and deteriorate productive capacity of soils [8,9]. On the other hand, sole application of organic nutrient sources may not be able to maintain and synchronize the required supply of nutrients to the growing plants for optimum crop production, because of relatively less quantity of plant-available nutrients and more time needed for mineralization to release nutrients for effective plant uptake [10-17]. Judicious/proper use of organic and inorganic nutrient sources is important to decrease the sole dependence on chemical fertilizers for sustainable high crop production by minimizing nutrient losses to the environment and optimizing nutrient use efficiency [18-23]. Integrated/combined use of organic and inorganic amendments or chemicals may be a way to ensure high sustainable soil productivity, fertility and quality, and environmental quality [22,24-30].

In the semi-arid region of the Canadian Prairies, maintaining soil fertility is an important production issue facing organic agriculture [2]. The N deficiency in soils on organic farms can be minimized by growing N-fixing legume crops in the rotations as grain or green manure crops [31-37]. However in soils deficient in available P, K, S or other essential nutrients, the only alternative is to use external nutrient sources because synthetic fertilizers/chemicals cannot be applied to prevent nutrient deficiencies and increase yield in organic crops. Manure/compost and some other organic amendments can provide these nutrients, but often there is not enough manure to apply on all farm fields, or the high cost of transportation of low nutrient content manure makes their use uneconomic [38-44]. On such soils, rock phosphate fertilizer, elemental S fertilizer, gypsum, wood ash (a waste product of forest industry) or other amendments may be useful to correct deficiencies of these nutrients.

The information on the relative comparisons of organic and inorganic nutrient sources in preventing nutrient deficiencies in the same experiment is lacking, especially in the Parkland region of Canada. The objective of this study was to determine the relative effectiveness of organic and inorganic nutrient sources (amendments/chemicals), and their combined applications in preventing nutrient deficiencies in crops, and increasing crop yield, seed quality and nutrient uptake.

2. MATERIALS AND METHODS

The 4-year (2009 to 2012) field experiment was established in the spring of 2009 on a Gray Luvisol (Typic Haplocryalf) loam soil near Star City, Saskatchewan. Soil at this site has shown severe S deficiency in canola in previous years [45], and significant increase in forage yield of timothy from S application as well as non-significant increase in forage yield of timothy from P application [46]. Some characteristics of soils used in this experiment are presented in **Table 1**. Precipitation in the growing season (May, June, July and August) at the nearest Environment Canada Meteorological Station (AAFC Melfort Research Farm) is given in **Table 2**.

A randomized complete block design was used to lay out the treatments in four replications. Each plot was 7.5 m long and 1.8 m wide. There were 31 treatments (except Treatments 27, 30 and 31 missing in 2009, and Treatments 24 and 25 missing in 2012): **1.** Control (no amendment); **2.** Compost @ 20 $Mg \cdot ha^{-1}$; **3.** Wood ash – fine @ 2 $Mg \cdot ha^{-1}$; **4.** Alfalfa pellets @ 2 $Mg \cdot ha^{-1}$; **5.** Alfalfa + canola meal pellets @ 2 $Mg \cdot ha^{-1}$; **6.** Distiller grain (wheat) − wet @ 2 $Mg \cdot ha^{-1}$; **7.** Distiller grain (wheat) − dry @ 1 $Mg \cdot ha^{-1}$; **8.** Thin stillage @ 20,000 $L \cdot ha^{-1}$; **9.** Glycerol @ 1 $Mg \cdot ha^{-1}$; **10.** Fish food additive @ 1 $Mg \cdot ha^{-1}$; **11.** Triple super phosphate (0-45-0) @

Table 1. Some characteristics of soil in spring 2009 at initiation of the field experiment at Star City, Saskatchewan.

Site	Soil Great Group*	Depth (cm)	Texture	Organic matter (%)	pH (1:2 water)	Nitrate-N ($mg\cdot kg^{-1}$)	Extractable P ($mg\cdot kg^{-1}$)	SO_4-S ($mg\cdot kg^{-1}$)	Extractable K ($mg\cdot kg^{-1}$)
StarCity	Gray Luvisol	0 - 15		3.1	6.6	7.5	13.9	4.5	202
		15 - 30				2.4	9.6	2.3	146
		30 - 60				3.0	7.8	1.6	180

*Based on Canadian Soil Classification System.

Table 2. Growing season monthly and total precipitation for the four site-years, and average 30-yr average precipitation and temperature at Star City, Saskatchewan.

Month	Precipitation in the growing season (mm)*				30-yr average (Melfort Research Farm)	
	2009	2010	2011	2012	Precipitation (mm)	Temperature (˚C)
May	21.2	66.6	10.5	72.7	45.6	9.1
June	46.6	113.2	103.5	112.3	65.8	16.9
July	75.6	63.6	73.3	97.8	75.5	18.3
August	81.6	56.8	10.7	68.1	56.8	19.6
Total	225.0	300.2	198.0	350.9	243.7	

*At the nearest Environment Canada Meteorological Station (Melfort Research Farm).

20 $kg\cdot P\cdot ha^{-1}$ + ammonium nitrate (34-0-0) @ 80 $kg\cdot N\cdot ha^{-1}$ + potassium sulfate (0-0-51-17) @ 20 $kg\cdot S\cdot ha^{-1}$; **12.** *Penicillium bilaiae* + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$; **13.** Rock phosphate granular (International Compost) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$; **14.** Rock phosphate finely-ground (International Compost) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$; **15.** Rock phosphate granular (BC Mines) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$; **16.** Rock phosphate finely-ground (BC Mines) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$; **17.** Gypsum @ 20 $kg\cdot S\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot P\cdot ha^{-1}$; **18.** Rapid release elemental S (RRES) @ 20 $kg\cdot S\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot P\cdot ha^{-1}$; **19.** Glycerol @ 1 $Mg\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$; **20.** Wood ash − fine @ 2 $Mg\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$; **21.** Distiller grain (corn) − dry @ 1 $Mg\cdot ha^{-1}$; **22.** Treatment 15 + *Penicillium bilaiae*; **23.** Treatment 16 + *Penicillium bilaiae*; **24.** Rock phosphate + humates granular (BC Mines) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$; **25.** Treatment 24 + *Penicillium bilaiae*; **26.** Rock phosphate [powder] (BC Mines) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$; **27.** N + S − 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$; **28.** Wood ash − granular @ 200 $kg\cdot ha^{-1}$ (applied side band); **29.** Wood ash − granular @ 200 $kg\cdot ha^{-1}$ (applied side band) + 80 $kg\cdot N\cdot ha^{-1}$; **30.** N + P − 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot P\cdot ha^{-1}$; and **31.** N only − 80 $kg\cdot N\cdot ha^{-1}$. Estimated amounts of N, P, K or S applied annually in various treatments are presented in **Table 3**. In 2009, N only (Tr 31), NP (Tr 30) and NS (Tr 27) treatments were not applied. In 2012, we could not obtain rock phosphate + humates granular fertilizer, so Treatments 24 and 25 did not receive any amendments in 2012. Amendments were broadcast on surface and then incorporated to about 10 cm soil depth a few days prior to seeding. Plots were seeded with a double-disc press drill at 17.8 cm row spacing. Data were collected on seed and straw yield, and on concentration of total N, P, K and S in seed and straw. Seed yield was determined by combine harvesting a 7 m long and 1.2 m wide strip in each plot. Seed and straw samples were oven dried (60˚C), and analyzed for total N [47], total P [48], total K [49] and total S [50] to calculate total N, P, K and S uptake in seed and straw by multiplying seed or straw yields by the concentrations of these nutrients in seed or straw.

The data on each parameter were subjected to analyses of variance (ANOVA) using GLM procedure in SAS [51]. The least significant difference at $P \le 0.05$ ($LSD_{0.05}$) was used to determine significant differences between treatment means.

3. RESULTS

3.1. Weather Conditions

The growing season precipitation (GSP) was near long-term average in 2009, with slightly lower than average precipitation in May and slightly higher than average precipitation in August (**Table 2**). In 2010 and 2012, the GSP was much higher than average (especially in June), and relatively cooler air temperatures in the summer. In 2011, the GSP was below average (especially in May during seeding season and in August during seed formation/filling), with relatively cooler air temperatures and wet conditions in June, and relatively warmer/hotter air temperatures and dry moisture conditions in late July

Table 3. Estimated amounts of N, P, K or S applied annually in different treatments at Star City, Saskatchewan.

Treatment		kg·ha^{-1} yr^{-1}			
No	Amendments	N	P	K	S
1	Control (no amendment)	0	0	0	0
2	Compost @ 20 Mg·ha^{-1}	260	128	260	60
3	Wood ash − fine @ 2 Mg·ha^{-1}	0	10	90	26
28	Wood ash − granular @ 200 kg·ha^{-1} (applied side band)	0	1	9	3
4	Alfalfa pellets @ 2 Mg·ha^{-1}	58	4	50	4
5	Alfalfa + canola meal pellets @ 2 Mg·ha^{-1}	42	3	28	4
6	Distiller grain (wheat) − wet @ 2 Mg·ha^{-1}	111	19	24	8
7	Distiller grain (wheat) − dry @ 1 Mg·ha^{-1}	56	8	11	7
21	Distiller grain (corn) − dry @ 1 Mg·ha^{-1}	49	8	11	7
8	Thin stillage @ 20,000 L·ha^{-1}	100	22	32	10
9	Glycerol @ 1 Mg·ha^{-1}	ND*	ND	ND	ND
10	Fish food additive @ 1 Mg·ha^{-1}	97	8	4	7
17	Gypsum @ 20 kg·S·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·P·ha^{-1}	80	20	0	20
18	Rapid release elemental S @ 20 kg·S·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·P·ha^{-1}	80	20	0	20
19	Glycerol @ 1 Mg·ha^{-1} + 80 kg·N·ha^{-1}	80	ND	ND	ND
20	Wood ash − fine @ 2 Mg·ha^{-1} + 80 kg·N·ha^{-1}	80	10	90	26
29	Wood ash − granular @ 200 kg·ha^{-1} (applied side band) + 80 kg·N·ha^{-1}	80	1	9	3
11	Triple superphosphate @ 20 kg·P·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·S·ha^{-1}	80	20	0	20
31	N only—80 kg·N·ha^{-1} (using 34-0-0)	80	0	0	0
30	N + P—80 kg·N·ha^{-1} (using 34-0-0) + 20 kg·P·ha^{-1} (using 0-45-0)	80	20	0	0
27	N + S—80 kg·N·ha^{-1} (using 34-0-0) + 20 kg·S·ha^{-1} (using 0-0-51-17)	80	0	0	20
12	*Penicillium bilaiae* + 80 kg·N·ha^{-1} + 20 kg·S·ha^{-1}	80	0	0	20
13	Rock phosphate granular (International Compost) @ 20 kg·P·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·S·ha^{-1}	80	20	0	20
14	Rock phosphate finely-ground (International Compost) @ 20 kg·P·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·S·ha^{-1}	80	20	0	20
15	Rock phosphate granular (BC Mines) @ 20 kg·P·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·S·ha^{-1}	80	20	0	20
16	Rock phosphate finely-ground (BC Mines) @ 20 kg·P·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·S·ha^{-1}	80	20	0	20
22	Rock phosphate granular (BC Mines) @ 20 kg·P·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·S·ha^{-1} + *Penicillium bilaiae*	80	20	0	20
23	Rock phosphate finely-ground (BC Mines) @ 20 kg·P·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·S·ha^{-1} + *Penicillium bilaiae*	80	20	0	20
24	Rock phosphate + humates granular (BC Mines) @ 20 kg·P·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·S·ha^{-1}	80	20	0	20
25	Rock phosphate + humates granular (BC Mines) @ 20 kg·P·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·S·ha^{-1} + *Penicillium bilaiae*	80	20	0	20
26	Rock phosphate [powder] (BC Mines) @ 20 kg·P·ha^{-1} + 80 kg·N·ha^{-1} + 20 kg·S·ha^{-1}	80	20	0	20

*ND refers to nutrient analysis was not determined in glycerol, because it was expected to contain very little available nutrients, if any.

and August.

3.2. Seed and Straw Yield

Combined application of N, P and S chemical fertilizers (NPS) produced considerably greater seed yield of canola compared to the unamended control in all four years (**Table 4**). In treatments with only organic amendments, thin stillage produced the highest seed yield in all years, and it was similar (or even slightly greater in some years) to the NPS balanced fertilization treatment. Compared to the control, fish food additive and distiller grain dry of wheat in 2009, 2011 and 2012, distiller grain dry of corn in 2009 and 2012, compost in 2011, and alfalfa pellets in 2011 and 2012 produced significantly greater seed yield. There was also a moderate increase in seed yield with compost and alfalfa pellets in 2009, alfalfa +

Table 4. Seed yield of canola with various amendments applied annually in 2009, 2010, 2011 and 2012 at Star City, Saskatchewan.

Treatment		Seed yield ($kg \cdot ha^{-1}$)			
No	Amendments	2009	2010	2011	2012
1	Control (no amendment)	809	463	410	1099
2	Compost @ 20 $Mg \cdot ha^{-1}$	997	534	651	1118
3	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$	985	453	493	1297
28	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band)	887	362	481	1000
4	Alfalfa pellets @ 2 $Mg \cdot ha^{-1}$	985	563	628	1467
5	Alfalfa + canola meal pellets @ 2 $Mg \cdot ha^{-1}$	1029	458	567	1369
6	Distiller grain (wheat) − wet @ 2 $Mg \cdot ha^{-1}$	831	396	611	1249
7	Distiller grain (wheat) − dry @ 1 $Mg \cdot ha^{-1}$	1422	541	989	1909
21	Distiller grain (corn) − dry @ 1 $Mg \cdot ha^{-1}$	1340	396	614	1505
8	Thin stillage @ 20,000 $L \cdot ha^{-1}$	1976	853	1088	2264
9	Glycerol @ 1 $Mg \cdot ha^{-1}$	663	512	321	1118
10	Fish food additive @ 1 $Mg \cdot ha^{-1}$	1451	541	832	1763
17	Gypsum @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	1965	714	1184	2292
18	Rapid release elemental S @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	1960	615	1187	2231
19	Glycerol @ 1 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	1559	308	497	1604
20	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	2015	834	1250	2254
29	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band) + 80 $kg \cdot N \cdot ha^{-1}$	1869	563	814	2213
11	Triple superphosphate @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	1842	835	1262	2301
31	N only—80 $kg \cdot N \cdot ha^{-1}$ (using 34 - 0 - 0)	ND[z]	230	247	989
30	N + P—80 $kg \cdot N \cdot ha^{-1}$ (using 34 - 0 - 0) + 20 $kg \cdot P \cdot ha^{-1}$ (using 0-45-0)	ND	491	854	1753
27	N + S—80 $kg \cdot N \cdot ha^{-1}$ (using 34 - 0 - 0) + 20 $kg \cdot S \cdot ha^{-1}$ (using 0-0-51-17)	ND	680	1083	2367
12	*Penicillium bilaiae* + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	1808	616	986	2170
13	Rock phosphate granular (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	1769	652	984	2146
14	Rock phosphate finely-ground (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	1806	711	1196	2268
15	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	1842	638	1010	2165
16	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	1843	698	1247	2219
22	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	1987	568	974	2213
23	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	2034	702	1218	2434
24	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	1869	552	1126	ND
25	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	2055	667	1045	ND
26	Rock phosphate [powder] (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	1850	689	1310	2233
	$LSD_{0.05}$	250	193	207	361
	SEM[y]	88.7^{***}	68.5^{***}	73.6^{***}	128.3^{***}

[z]ND refers to not determined; [y], ***refers to significant treatment effects in ANOVA at $P \le 0.001$.

canola meal pellets in 2009, 2011 and 2012, with wood ash fine in 2009 and 2012, with distiller grain wet of wheat in 2011 and 2012, and distiller grain dry of corn in 2011, although not significant. This suggests the potential of these treatments possibly with long term repeated annual applications. There was a slight reduction in seed yield of canola from wood ash granular, glycerol, distiller grain wet of wheat and distiller grain dry of corn in a few years.

In treatments where chemical fertilizers were also applied in addition to organic amendments, application of N fertilizer increased seed yield substantially in wood ash fine treatment in all years. This suggests that wood ash fine was lacking in N, and its application along with N fertilizer supplied the nutrients lacking in this soil (mainly S, and also possibly P to some extent). Application of N fertilizer also increased seed yield in wood ash granular treatment but mainly in 2009, 2011 and 2012, and to a lesser extent than wood ash fine. The poorer performance of wood ash granular than wood ash fine was most likely due to poor availability and/or possibly unequal distribution of nutrients to canola plants from sparse application of wood ash granules in relation to canola plants/roots. There was no beneficial effect of glycerol on seed yield, and application of N increased seed yield in glycerol treatment but only in 2009 and 2012 and seed yield was usually much less than gypsum + N + P or NPS fertilizer treatment, suggesting the lack of N, S, and/or P in this treatment for optimum crop growth.

Compared to the unamended control, there was a considerable reduction in canola seed yield in 2010 and 2011, and a slight/moderate reduction in 2012, when only N fertilizer was applied without any sulphate-S. Application of P along with N (NP) resulted in some increase in seed yield compared to the N alone treatment, butnot significantly better than the control. The combined application of N (as ammonium nitrate) + P (as triple super phosphate) + S (potassium sulphate) chemical fertilizers (NPS) produced considerably higher seed yield of canola compared to the control. This suggests that seed yield of canola can be improved significantly by using balanced NPS fertilization/nutrition on this soil, extremely deficient in plant-available N and S, and possibly containing insufficient amount of available P for optimum yield, especially with canola being a particular S-sensitive crop. Application of rapid release elemental S (RRES), along with N + P fertilizer, usually produced seed yield similar to gypsum + N + P treatment. Seed yields with both gypsum and RRES treatments were significantly greater than with the N only treatment, but slightly less than with the NPS treatment in some years.

Application of N + S, in combination with finely-ground or powder rock phosphate, produced seed yield greater than that with granular rock phosphate, and it was similar to or only slightly lower than the NPS treatment, but only in 2011. This suggests the positive contribution of finely-ground or powder rock phosphate in increasing availability of P and improving seed yield of canola in the third growing season. The lower seed yield obtained with granular rock phosphate and/or *Penicillium bilaiae*, in combination with N + S, than the NPS treatment in all years suggests the poor performance of granular rock phosphate and/or *Penicillium bilaiae* in increasing P availability and improving seed yield of canola. The response trends of straw yield to all organic and inorganic amendments were generally similar to seed yield in most cases, with only a few exceptions (**Table 5**). For example, unlike seed yields, the straw yields were similar between NP and NPS treatments in 2011, and also there was some increase in straw yield with only N treatment compared to no amendment control in 2012.

3.3. Protein and Oil Concentration in Seed

Treatments including only organic amendments (*i.e.*, without any chemical fertilizers) usually resulted in little or no significant effects on protein concentration in canola seed, although protein concentrations were increased or decreased in a few cases compared to the no amendment control treatment (**Table 6**). For example, there was an increase in protein concentration with thin stillage, fish food additive or distiller grain in 2011 or 2012, and a reduction in protein concentration in canola seed using compost and wood ash treatments in 2010 and 2011. In treatments where chemical fertilizers were also applied, in addition to amendments, protein concentration in canola seed increased or tended to increase with glycerol, gypsum, RRES or wood ash treatments in some years. There was no beneficial effect of any amendment + chemical fertilizer treatment on oil concentration in canola seed, but there was a tendency of decrease in oil concentration in canola seed in the N, glycerol + N and NP treatments in 2010, 2011 and 2012, and in the NS or NPS treatment in 2011 (**Table 7**).

3.4. Nutrient Uptake in Seed + Straw

The response trends of uptake of total N, P, K and S in seed and straw to organic and inorganic amendments were generally similar to the corresponding seed and straw yields, respectively (data not shown). The results on uptake of total N, P, K and S in seed + straw of canola are presented in **Tables 8-11**. In treatments with only organic amendments, total N uptake in seed + straw with thin stillage was similar (or even slightly higher in some cases) to the NPS balanced fertilization treatment (**Table 8**). Compared to the control, fish food additive in all four years, distiller grain dry of wheat in 2009, 2011 and 2012, distiller grain dry of corn in 2009 and 2012, and alfalfa pellets in 2012 produced significantly greater total N uptake in seed + straw. There was also a moderate increase in total N uptake in seed + straw with compost and alfalfa pellets in 2009 and 2011, alfalfa + canola meal pellets in 2009, 2011 and 2012, with wood ash fine in 2009 and 2012, with distiller grain wet of wheat in 2011 and 2012, and distiller grain dry of corn in 2011, although not significant. There was a slight reduction in total N uptake in seed + strawof canola from wood ash granular, glycerol, distiller grain wet of wheat and distiller grain dry of corn in a few years.

Table 5. Straw yield of canola with various amendments applied annually in 2009, 2010, 2011 and 2012 at Star City, Saskatchewan.

Treatment		Straw yield ($kg \cdot ha^{-1}$)			
No	Amendments	2009	2010	2011	2012
1	Control (no amendment)	2579	1781	2545	2864
2	Compost @ 20 $Mg \cdot ha^{-1}$	3284	1766	2781	2604
3	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$	3169	1817	2363	2894
28	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band)	2689	1500	2201	2356
4	Alfalfa pellets @ 2 $Mg \cdot ha^{-1}$	3118	2330	2810	3594
5	Alfalfa + canola meal pellets @ 2 $Mg \cdot ha^{-1}$	3285	1697	2689	2916
6	Distiller grain (wheat) − wet @ 2 $Mg \cdot ha^{-1}$	2705	1365	2858	2831
7	Distiller grain (wheat) − dry @ 1 $Mg \cdot ha^{-1}$	4462	2001	3118	3675
21	Distiller grain (corn) − dry @ 1 $Mg \cdot ha^{-1}$	3817	1756	2621	2998
8	Thin stillage @ 20,000 $L \cdot ha^{-1}$	5477	3004	3301	3917
9	Glycerol @ 1 Mg ha^{-1}	2130	1726	1776	2500
10	Fish food additive @ 1 $Mg \cdot ha^{-1}$	4753	2553	3247	3470
17	Gypsum @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	5461	2912	3961	4198
18	Rapid release elemental S @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	5910	2427	4537	3768
19	Glycerol @ 1 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	4388	1175	2624	3840
20	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	5376	3753	4090	4241
29	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band) + 80 $kg \cdot N \cdot ha^{-1}$	5384	2051	4114	4327
11	Triple superphosphate @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	5972	3206	4154	4568
31	N only—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0)	ND[z]	1112	1937	3546
30	N + P—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0) + 20 $kg \cdot P \cdot ha^{-1}$ (using 0-45-0)	ND	2007	4516	3875
27	N + S—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0) + 20 $kg \cdot S \cdot ha^{-1}$ (using 0-0-51-17)	ND	2489	4088	3815
12	*Penicillium bilaiae* + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	4895	2992	3896	4114
13	Rock phosphate granular (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	5323	2212	3716	4367
14	Rock phosphate finely-ground (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	5564	2521	3751	4614
15	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	5333	2645	3783	3984
16	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	5168	2699	4381	4144
22	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	5082	2415	3513	4078
23	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	5767	2441	3996	4176
24	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	5243	2260	3777	ND
25	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	5876	2338	4414	ND
26	Rock phosphate [powder] (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	5491	2556	4837	3337
	$LSD_{0.05}$	860	908	1009	1006
	SEM[y]	305.6***	323.2***	359.1***	357.8***

[z]ND refers to not determined; [y], ***refers to significant treatment effects in ANOVA at $P \leq 0.001$.

In treatments where chemical fertilizers were also applied, in addition to organic amendments, application of N fertilizer substantially increased total N uptake in seed + straw with wood ash fine treatment in all years. This indicates that wood ash fine was lacking in N, and its application along with N fertilizer supplied the nutrients lacking in this soil (mainly S, and also possibly P to some extent), resulting in increased N uptake. Application of N fertilizer also increased total N uptake in seed + straw with wood ash granular treatment but mainly in 2009, 2011 and 2012, but to a lesser extent than with wood ash fine. The poor performance of wood ash granular

Table 6. Protein concentration in canola seed with various amendments applied annually in 2009, 2010, 2011 and 2012 at Star City, Saskatchewan.

Treatment		Protein concentration in seed ($g \cdot kg^{-1}$)			
No	Amendments	2009	2010	2011	2012
1	Control (no amendment)	206	233	228	234
2	Compost @ 20 $Mg \cdot ha^{-1}$	207	215	204	237
3	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$	204	213	208	227
28	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band)	209	221	215	238
4	Alfalfa pellets @ 2 $Mg \cdot ha^{-1}$	204	227	231	241
5	Alfalfa + canola meal pellets @ 2 $Mg \cdot ha^{-1}$	208	229	224	246
6	Distiller grain (wheat) − wet @ 2 $Mg \cdot ha^{-1}$	203	232	239	248
7	Distiller grain (wheat) − dry @ 1 $Mg \cdot ha^{-1}$	201	228	253	253
21	Distiller grain (corn) − dry @ 1 $Mg \cdot ha^{-1}$	209	228	229	259
8	Thin stillage @ 20,000 $L \cdot ha^{-1}$	207	232	276	263
9	Glycerol @ 1 $Mg \cdot ha^{-1}$	216	230	215	227
10	Fish food additive @ 1 $Mg \cdot ha^{-1}$	199	241	266	254
17	Gypsum @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	213	221	267	248
18	Rapid release elemental S @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	215	234	271	252
19	Glycerol @ 1 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	215	252	267	242
20	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	219	221	263	240
29	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band) + 80 $kg \cdot N \cdot ha^{-1}$	222	238	279	243
11	Triple superphosphate @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	202	229	271	245
31	N only—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0)	ND^z	244	267	250
30	N + P—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0) + 20 $kg \cdot P \cdot ha^{-1}$ (using 0-45-0)	ND	244	279	252
27	N + S—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0) + 20 $kg \cdot S \cdot ha^{-1}$ (using 0-0-51-17)	ND	238	283	251
12	*Penicillium bilaiae* + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	213	235	285	257
13	Rock phosphate granular (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	208	243	288	256
14	Rock phosphate finely-ground (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	207	239	277	254
15	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	208	234	284	253
16	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	209	233	262	251
22	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	214	238	276	255
23	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	215	228	279	247
24	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	209	233	281	ND
25	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	209	238	287	ND
26	Rock phosphate [powder] (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	210	231	271	251
	$LSD_{0.05}$	9.9	14	14	10
	SEM^y	3.5**	5.1***	4.9***	3.5***

^{z}ND refers to not determined; $^{y, **}$ and *** refer to significant treatment effects in ANOVA at P ≤ 0.1 and P ≤ 0.001, respectively.

compared to wood ash fine was most likely due to poor availability and/or possibly unequal distribution of nutrients to canola plants from sparse application of wood ash granules in relation to canola plants/roots. There was no beneficial effect of glycerol on total N uptake in seed + straw. Application of N fertilizer increased total N uptake in seed + straw with glycerol treatment only in 2009 and 2012, but total N uptake was usually much less than with gypsum + N + P or NPS fertilizer treatment, suggesting the lack of N, S, and/or P in this treatment for

Table 7. Oil concentration in canola seed with various amendments applied annually in 2009, 2010, 2011 and 2012 at Star City, Saskatchewan.

Treatment		Oil concentration in seed ($g \cdot kg^{-1}$)			
No	Amendments	2009	2010	2011	2012
1	Control (no amendment)	506	469	451	458
2	Compost @ 20 $Mg \cdot ha^{-1}$	507	479	479	449
3	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$	510	488	477	466
28	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band)	507	475	468	452
4	Alfalfa pellets @ 2 $Mg \cdot ha^{-1}$	509	470	444	457
5	Alfalfa + canola meal pellets @ 2 $Mg \cdot ha^{-1}$	508	471	465	452
6	Distiller grain (wheat) − wet @ 2 $Mg \cdot ha^{-1}$	511	470	455	448
7	Distiller grain (wheat) − dry @ 1 $Mg \cdot ha^{-1}$	517	469	437	448
21	Distiller grain (corn) − dry @ 1 $Mg \cdot ha^{-1}$	509	463	466	430
8	Thin stillage @ 20,000 $L \cdot ha^{-1}$	504	457	418	432
9	Glycerol @ 1 $Mg \cdot ha^{-1}$	500	473	473	465
10	Fish food additive @ 1 $Mg \cdot ha^{-1}$	511	444	421	445
17	Gypsum @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	493	470	422	450
18	Rapid release elemental S @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	491	458	414	449
19	Glycerol @ 1 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	492	436	419	453
20	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	493	483	415	463
29	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band) + 80 $kg \cdot N \cdot ha^{-1}$	487	457	385	459
11	Triple superphosphate @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	502	469	410	451
31	N only—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0)	ND[z]	428	387	415
30	N + P—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0) + 20 $kg \cdot P \cdot ha^{-1}$ (using 0-45-0)	ND	439	383	437
27	N + S—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0) + 20 $kg \cdot S \cdot ha^{-1}$ (using 0-0-51-17)	ND	461	404	453
12	*Penicillium bilaiae* + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	499	470	406	450
13	Rock phosphate granular (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	503	459	410	449
14	Rock phosphate finely-ground (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	498	459	415	450
15	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	500	458	403	448
16	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	498	452	355	453
22	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	497	462	392	455
23	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	495	481	413	457
24	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	500	470	408	ND
25	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	503	473	412	ND
26	Rock phosphate [powder] (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	495	476	423	453
	$LSD_{0.05}$	11	20	39	19
	SEM[y]	4.1^{***}	7.0^{***}	13.8^{***}	6.8^{**}

[z]ND refers to not determined; [y], ** and *** refer to significant treatment effects in ANOVA at $P \leq 0.01$ and $P \leq 0.001$, respectively.

optimum crop growth.

Compared to the control, there was a substantial reduction in total N uptake in seed + straw of canola in 2010 (also slight in 2011), when only N fertilizer was applied without any sulphate-S. Application of P along with N (NP) resulted in some increase in total N uptake in seed + straw compared to the N alone and control treatments. The combined application of N (as ammonium nitrate) + P (as triple super phosphate + S (potassium sulphate) chemical fertilizers (NPS) produced

Table 8. Total N uptake in seed + straw of canola with various amendments applied annually in 2009, 2010, 2011 and 2012 at Star City, Saskatchewan.

Treatment		Total N uptake in seed + straw ($kg \cdot N \cdot ha^{-1}$)			
No	Amendments	2009	2010	2011	2012
1	Control (no amendment)	38.5	33.6	35.1	55.8
2	Compost @ 20 $Mg \cdot ha^{-1}$	45.3	31.3	37.7	51.2
3	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$	44.8	30.5	33.3	60.2
28	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band)	40.5	27.5	37.9	49.4
4	Alfalfa pellets @ 2 $Mg \cdot ha^{-1}$	45.1	40.3	42.7	72.6
5	Alfalfa + canola meal pellets @ 2 $Mg \cdot ha^{-1}$	48.3	33.0	38.9	67.3
6	Distiller grain (wheat) − wet @ 2 $Mg \cdot ha^{-1}$	41.2	28.1	46.7	64.6
7	Distiller grain (wheat) − dry @ 1 $Mg \cdot ha^{-1}$	64.3	37.9	64.8	93.3
21	Distiller grain (corn) − dry @ 1 $Mg \cdot ha^{-1}$	60.8	32.2	43.4	76.1
8	Thin stillage @ 20,000 $L \cdot ha^{-1}$	85.7	57.9	80.1	113.8
9	Glycerol @ 1 $Mg \cdot ha^{-1}$	32.7	35.4	24.0	52.6
10	Fish food additive @ 1 $Mg \cdot ha^{-1}$	64.2	46.9	65.7	88.8
17	Gypsum @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	93.5	48.8	80.0	112.1
18	Rapid release elemental S @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	94.7	44.7	94.6	102.1
19	Glycerol @ 1 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	72.0	25.9	50.6	82.6
20	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	92.1	57.0	85.8	105.8
29	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band) + 80 $kg \cdot N \cdot ha^{-1}$	89.5	41.8	78.4	103.7
11	Triple superphosphate @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	80.3	57.3	91.5	109.4
31	N only—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0)	ND^z	20.6	33.2	69.3
30	N + P—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0) + 20 $kg \cdot P \cdot ha^{-1}$ (using 0-45-0)	ND	37.8	86.8	89.2
27	N + S—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0) + 20 $kg \cdot S \cdot ha^{-1}$ (using 0-0-51-17)	ND	50.3	88.3	106.1
12	*Penicillium bilaiae* + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	84.2	53.3	83.0	106.7
13	Rock phosphate granular (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	80.3	46.9	83.8	108.2
14	Rock phosphate finely-ground (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	83.6	52.4	86.8	113.8
15	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	83.8	49.2	81.7	105.2
16	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	83.3	50.9	92.0	107.3
22	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	90.4	44.6	76.0	107.0
23	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	92.0	46.9	102.5	115.9
24	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	85.9	42.1	86.1	ND
25	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	91.4	48.1	100.3	ND
26	Rock phosphate [powder] (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	85.1	48.8	99.6	101.5
	$LSD_{0.05}$	12.7	12.9	16.7	14.0
	SEM^y	4.53***	4.60***	5.96***	4.99***

^{z}ND refers to not determined; $^{y,\ ***}$refer to significant treatment effects in ANOVA at $P \le 0.001$.

considerably higher total N uptake in seed + straw of canola, compared to the control, in all four years. This suggests that total N uptake in seed + straw of canola can be improved significantly by using balanced NPS fertilization/ nutrition on this soil, extremely deficient in plant-available S and possibly containing insufficient amount of available P for optimum crop growth, especially for canola being a particular S-sensitive crop. Application of RRES along with N + P fertilizer usually produced total N uptake in seed + straw of canola, similar

Table 9. Total P uptake in seed + straw of canola with various amendments applied annually in 2009, 2010, 2011 and 2012 at Star City, Saskatchewan.

Treatment		Total P uptake in seed + straw ($kg\cdot P\cdot ha^{-1}$)			
No	Amendments	2009	2010	2011	2012
1	Control (no amendment)	9.8	6.4	6.5	10.7
2	Compost @ 20 $Mg\cdot ha^{-1}$	11.4	7.7	8.9	12.7
3	Wood ash − fine @ 2 $Mg\cdot ha^{-1}$	10.7	7.2	6.9	12.5
28	Wood ash − granular @ 200 $kg\cdot ha^{-1}$ (applied side band)	9.2	5.5	5.9	9.3
4	Alfalfa pellets @ 2 $Mg\cdot ha^{-1}$	10.8	7.7	7.3	12.9
5	Alfalfa + canola meal pellets @ 2 $Mg\cdot ha^{-1}$	10.9	6.4	6.6	12.5
6	Distiller grain (wheat) − wet @ 2 $Mg\cdot ha^{-1}$	9.6	4.8	7.8	11.5
7	Distiller grain (wheat) − dry @ 1 $Mg\cdot ha^{-1}$	15.5	7.5	10.0	16.9
21	Distiller grain (corn) − dry @ 1 $Mg\cdot ha^{-1}$	13.8	6.9	6.8	14.0
8	Thin stillage @ 20,000 $L\cdot ha^{-1}$	18.3	11.7	11.1	22.2
9	Glycerol @ 1 $Mg\cdot ha^{-1}$	8.4	6.8	4.9	11.2
10	Fish food additive @ 1 $Mg\cdot ha^{-1}$	14.7	8.7	8.5	15.1
17	Gypsum @ 20 $kg\cdot S\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot P\cdot ha^{-1}$	19.6	10.8	11.3	23.1
18	Rapid release elemental S @ 20 $kg\cdot S\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot P\cdot ha^{-1}$	19.1	9.2	12.9	20.8
19	Glycerol @ 1 $Mg\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$	14.5	4.0	5.9	12.1
20	Wood ash – fine @ 2 $Mg\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$	17.7	11.3	10.3	17.1
29	Wood ash – granular @ 200 $kg\cdot ha^{-1}$ (applied side band) + 80 $kg\cdot N\cdot ha^{-1}$	16.8	7.0	8.7	15.8
11	Triple superphosphate @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$	17.9	11.4	13.2	22.2
31	N only—80 kg $N\cdot ha^{-1}$ (using 34-0-0)	ND^{z}	3.2	4.1	10.9
30	N + P—80 kg $N\cdot ha^{-1}$ (using 34-0-0) + 20 $kg\cdot P\cdot ha^{-1}$ (using 0-45-0)	ND	6.8	11.3	17.4
27	N + S—80 kg $N\cdot ha^{-1}$ (using 34-0-0) + 20 $kg\cdot S\cdot ha^{-1}$ (using 0-0-51-17)	ND	7.8	9.3	16.1
12	*Penicillium bilaiae* + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$	16.4	7.8	8.6	14.5
13	Rock phosphate granular (International Compost) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$	15.8	7.5	9.0	17.2
14	Rock phosphate finely-ground (International Compost) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$	17.6	9.5	11.2	20.1
15	Rock phosphate granular (BC Mines) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$	17.1	8.1	8.8	16.6
16	Rock phosphate finely-ground (BC Mines) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$	17.4	8.6	10.7	17.8
22	Rock phosphate granular (BC Mines) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$ + *Penicillium bilaiae*	17.2	7.3	8.3	16.1
23	Rock phosphate finely-ground (BC Mines) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$ + *Penicillium bilaiae*	17.8	8.1	11.2	18.4
24	Rock phosphate + humates granular (BC Mines) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$	17.3	6.6	9.4	ND
25	Rock phosphate + humates granular (BC Mines) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$ + *Penicillium bilaiae*	18.1	7.3	10.3	ND
26	Rock phosphate [powder] (BC Mines) @ 20 $kg\cdot P\cdot ha^{-1}$ + 80 $kg\cdot N\cdot ha^{-1}$ + 20 $kg\cdot S\cdot ha^{-1}$	17.6	8.4	11.8	16.6
	$LSD_{0.05}$	2.5	2.7	2.0	2.2
	SEM^{y}	0.87***	0.98***	0.70***	0.77***

^{z}ND refers to not determined; $^{y,\ ***}$refer to significant treatment effects in ANOVA at $P \le 0.001$.

to gypsum + N + P treatment. Total N uptake in seed + straw with both gypsum and RRES treatments were significantly greater than with the N only treatment, but only slightly less than with the NPS treatment in some years.

Application of N + S, in combination with rock phosphate and/or *Penicillium bilaiae*, did not produce any significant increase in total N uptake in seed + straw compared to the N + S treatment. This suggests little or no contribution of rock phosphate and/or *Penicillium bilaiae*

Table 10. Total K uptake in seed + straw of canola with various amendments applied annually in 2009, 2010, 2011 and 2012 at Star City, Saskatchewan.

Treatment		Total K uptake in seed + straw ($kg·K·ha^{-1}$)			
No	Amendments	2009	2010	2011	2012
1	Control (no amendment)	22.0	15.3	61.0	26.9
2	Compost @ 20 $Mg·ha^{-1}$	24.8	17.9	66.3	25.3
3	Wood ash − fine @ 2 $Mg·ha^{-1}$	22.3	17.8	52.6	28.7
28	Wood ash − granular @ 200 $kg·ha^{-1}$ (applied side band)	18.7	14.2	48.7	25.1
4	Alfalfa pellets @ 2 $Mg·ha^{-1}$	23.1	18.0	71.9	33.2
5	Alfalfa + canola meal pellets @ 2 $Mg·ha^{-1}$	25.5	18.2	60.4	34.0
6	Distiller grain (wheat) − wet @ 2 $Mg·ha^{-1}$	21.1	13.7	66.8	30.7
7	Distiller grain (wheat) − dry @ 1 $Mg·ha^{-1}$	36.9	19.5	76.5	42.7
21	Distiller grain (corn) − dry @ 1 $Mg·ha^{-1}$	32.4	20.4	59.5	35.0
8	Thin stillage @ 20,000 $L·ha^{-1}$	54.1	25.1	96.9	58.3
9	Glycerol @ 1 $Mg·ha^{-1}$	21.2	13.6	39.7	29.5
10	Fish food additive @ 1 $Mg·ha^{-1}$	46.3	27.0	82.5	44.4
17	Gypsum @ 20 $kg·S·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·P·ha^{-1}$	52.3	21.8	98.6	63.8
18	Rapid release elemental S @ 20 $kg·S·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·P·ha^{-1}$	52.5	19.5	105.7	44.3
19	Glycerol @ 1 $Mg·ha^{-1}$ + 80 $kg·N·ha^{-1}$	44.0	12.7	58.5	39.9
20	Wood ash − fine @ 2 $Mg·ha^{-1}$ + 80 $kg·N·ha^{-1}$	53.4	25.7	111.0	43.5
29	Wood ash − granular @ 200 $kg·ha^{-1}$ (applied side band) + 80 $kg·N·ha^{-1}$	54.5	17.6	96.8	47.6
11	Triple superphosphate @ 20 $kg·P·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·S·ha^{-1}$	50.8	22.4	110.5	58.1
31	N only—80 $kg·N·ha^{-1}$ (using 34-0-0)	ND[z]	10.9	40.9	37.8
30	N + P—80 $kg·N·ha^{-1}$ (using 34-0-0) + 20 $kg·P·ha^{-1}$ (using 0-45-0)	ND	13.9	105.3	39.4
27	N + S—80 $kg·N·ha^{-1}$ (using 34-0-0) + 20 $kg·S·ha^{-1}$ (using 0-0-51-17)	ND	19.4	96.3	53.5
12	*Penicillium bilaiae* + 80 $kg·N·ha^{-1}$ + 20 $kg·S·ha^{-1}$	57.3	22.2	97.5	49.8
13	Rock phosphate granular (International Compost) @ 20 $kg·P·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·S·ha^{-1}$	54.0	22.1	102.9	55.8
14	Rock phosphate finely-ground (International Compost) @ 20 $kg·P·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·S·ha^{-1}$	50.9	22.4	106.2	65.4
15	Rock phosphate granular (BC Mines) @ 20 $kg·P·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·S·ha^{-1}$	54.1	23.5	98.4	54.0
16	Rock phosphate finely-ground (BC Mines) @ 20 $kg·P·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·S·ha^{-1}$	52.1	18.2	122.4	51.5
22	Rock phosphate granular (BC Mines) @ 20 $kg·P·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·S·ha^{-1}$ + *Penicillium bilaiae*	55.3	21.0	98.8	55.9
23	Rock phosphate finely-ground (BC Mines) @ 20 $kg·P·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·S·ha^{-1}$ + *Penicillium bilaiae*	64.8	21.0	120.3	52.6
24	Rock phosphate + humates granular (BC Mines) @ 20 $kg·P·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·S·ha^{-1}$	56.7	16.5	93.5	ND
25	Rock phosphate + humates granular (BC Mines) @ 20 $kg·P·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·S·ha^{-1}$ + *Penicillium bilaiae*	56.6	18.2	116.9	ND
26	Rock phosphate [powder] (BC Mines) @ 20 $kg·P·ha^{-1}$ + 80 $kg·N·ha^{-1}$ + 20 $kg·S·ha^{-1}$	54.3	17.6	120.4	54.4
	$LSD_{0.05}$	8.6	7.9	23.4	15.8
	SEM[y]	3.06^{***}	2.82^{**}	8.32^{***}	5.62^{***}

[z]ND refers to not determined; [y], ** and *** refer to significant treatment effects in ANOVA at $P \le 0.01$ and $P \le 0.001$, respectively.

Table 11. Total S uptake in seed + straw of canola with various amendments applied annually in 2009, 2010, 2011 and 2012 at Star City, Saskatchewan.

Treatment		Total S uptake in seed + straw ($kg \cdot S \cdot ha^{-1}$)			
No	Amendments	2009	2010	2011	2012
1	Control (no amendment)	9.6	5.1	8.2	8.8
2	Compost @ 20 $Mg \cdot ha^{-1}$	13.2	5.4	11.2	11.7
3	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$	13.2	5.2	10.1	15.7
28	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band)	10.5	4.1	7.8	10.1
4	Alfalfa pellets @ 2 $Mg \cdot ha^{-1}$	11.1	6.0	9.7	11.2
5	Alfalfa + canola meal pellets @ 2 $Mg \cdot ha^{-1}$	12.2	4.4	9.6	9.8
6	Distiller grain (wheat) − wet @ 2 $Mg \cdot ha^{-1}$	9.7	3.7	10.6	10.3
7	Distiller grain (wheat) − dry @ 1 $Mg \cdot ha^{-1}$	17.4	5.5	14.6	15.5
21	Distiller grain (corn) − dry @ 1 $Mg \cdot ha^{-1}$	14.9	4.9	11.3	14.4
8	Thin stillage @ 20,000 $L \cdot ha^{-1}$	22.5	9.2	14.7	18.8
9	Glycerol @ 1 $Mg \cdot ha^{-1}$	7.8	4.9	6.1	8.0
10	Fish food additive @ 1 $Mg \cdot ha^{-1}$	15.6	7.0	11.4	12.7
17	Gypsum @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	23.9	9.0	20.7	27.9
18	Rapid release elemental S @ 20 $kg \cdot S \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot P \cdot ha^{-1}$	21.3	6.7	19.0	17.0
19	Glycerol @ 1 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	16.8	3.2	8.8	10.3
20	Wood ash − fine @ 2 $Mg \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$	26.0	10.5	21.6	20.8
29	Wood ash − granular @ 200 $kg \cdot ha^{-1}$ (applied side band) + 80 $kg \cdot N \cdot ha^{-1}$	20.5	6.1	14.7	14.7
11	Triple superphosphate @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	23.4	9.7	22.4	22.1
31	N only—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0)	ND[z]	2.3	4.1	7.6
30	N + P—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0) + 20 $kg \cdot P \cdot ha^{-1}$ (using 0-45-0)	ND	5.4	14.0	10.9
27	N + S—80 $kg \cdot N \cdot ha^{-1}$ (using 34-0-0) + 20 $kg \cdot S \cdot ha^{-1}$ (using 0-0-51-17)	ND	8.0	20.4	22.0
12	*Penicillium bilaiae* + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	23.0	8.5	19.7	22.0
13	Rock phosphate granular (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	23.0	7.3	21.2	24.9
14	Rock phosphate finely-ground (International Compost) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	22.8	8.2	19.3	25.5
15	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	21.1	8.7	20.3	21.9
16	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	22.2	8.4	19.8	22.2
22	Rock phosphate granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	23.2	7.4	17.5	22.6
23	Rock phosphate finely-ground (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	25.1	8.2	23.5	22.5
24	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	22.4	6.5	21.2	ND
25	Rock phosphate + humates granular (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$ + *Penicillium bilaiae*	26.8	7.3	24.6	ND
26	Rock phosphate [powder] (BC Mines) @ 20 $kg \cdot P \cdot ha^{-1}$ + 80 $kg \cdot N \cdot ha^{-1}$ + 20 $kg \cdot S \cdot ha^{-1}$	24.2	7.4	24.2	20.6
	$LSD_{0.05}$	4.4	2.5	5.4	6.5
	SEM[y]	1.58***	0.88***	1.93***	2.30***

[z]ND refers to not determined; [y], ***refers to significant treatment effects in ANOVA at $P \leq 0.001$.

in increasing P availability to canola. The response trends of total P, K and S uptake in seed + straw of canola to various organic and inorganic amendments were usually similar to total N uptake in seed + straw in most cases (**Tables 9-11**).

4. DISCUSSION

Our study investigated many alternative nutrient sources (ANS) that can be potentially used to prevent/ eliminate nutrient deficiencies in organic and/or conventional cropping systems. In our study, we included a treatment with combined application of N, P and S chemical fertilizers (NPS) to prevent all major nutrient deficiencies in soil at the experimental site in order to obtain the best yield and nutrient uptake, so that all other organic and inorganic/mineral amendments can be compared to this NPS treatment for their relative effectiveness. The NPS treatment in our study produced considerably higher seed yield, straw yield and nutrient uptake of canola compared to the no amendment control. In the following sections, we discussed results on amendments applicable to organic crop production as well as to conventional farming systems separately.

In treatments receiving only organic amendments (applicable to organic crop production), thin stillage produced the highest seed yield, straw yield and nutrient uptake in both years, and it was similar to the NPS balanced fertilization treatment. This suggests a great potential of thin stillage as an organic amendment to prevent any nutrient deficiencies and subsequently increase crop yield by increasing the availability of nutrients to crop plants. Compared to the control, fish food additive (in both years) and distiller grain dry of both wheat and corn (in 2009) produced significantly higher seed yield, straw yield and nutrient uptake. The significant increase in nutrient uptake in seed + straw with fish food additive, distiller grain dry of both wheat and distiller grain of corn compared to control also suggest the potential of these amendments in increasing the availability of nutrients and subsequently improving yield of organic crops. There was a moderate (but non-significant) increase in seed yield, straw yield and nutrient uptake from compost, alfalfa + canola meal pellets, alfalfa pellets and wood ash fine, suggesting the potential of these amendments after perhaps a long-term use. Similarly, earlier studies have shown potential yield benefits of both organic and mineral amendments and soil activators/inoculants on crop yields, produce quality and nutrient uptake [34,36,52-59]. There was a slight reduction in seed yield, straw yield and nutrient uptake from glycerol, and this was most likely due to immobilization of N and S due to wide C:N ratio in this product. Composted manure is a good supplier of N, P, K, S, and other nutrients, and is expected to increase crop yields when these nutrients are liming in soil for optimum crop growth/yield [34]. Similarly, alfalfa pellets have narrow C:N ratio in plant materials and are expected to supply N, P and other nutrients after mineralization [60]. However, in our study, composted manure and alfalfa pellets generally were not very effective in increasing crop yield and nutrient uptake, when canola was the test crop. This was probably due to low yield potential of canola at this site, especially in 2010 because of adverse weather conditions during the growing season.

In treatments where chemical fertilizers were also applied in addition to organic amendments, application of N fertilizer substantially increased seed yield, straw yield and nutrient uptake when in combination with both fine and granular wood ash treatments (especially fine wood ash), suggesting the lack of N in these treatments. Application of N in combination with glycerol also increased seed yield, straw yield and nutrient uptake, but crop yield and nutrient uptake were much less than with the gypsum + N + P treatment, as discussed in following paragraph, suggesting the lack of both N and S in glycerol.

Earlier research has suggested that gypsum can be a suitable source of S to prevent S deficiency in grass when N is also applied [61]. Sulphur deficiency in canola can also be minimized and seed yield increased by proper application of elemental S fertilizers using broadcast spread/spray applications of fine particle elemental S as a suspension (or powder) on the surface of S-deficient soils [62]. Similarly, in our present study, the use of rapid release elemental S (RRES) granular along with N + P fertilizers produced seed yield, straw yield and nutrient uptake similar to gypsum + N + P treatment, and these two treatments produced seed yield, straw yield and nutrient uptake considerably higher than the unamended control. Based on the history of this site in relation to severe S deficiency in canola in previous years and considerable reduction in canola seed yield when only N was applied without any S fertilizer in 2010 and 2011, and also in previous years [45], it is possible that spring-applied RRES has the potential to provide available S to the crop in the same growing season to the same level as gypsum or other sulphate-S sources. These results with mineral S sources suggest that gypsum and RRES can prevent S deficiency in organic crops, provided N and other nutrients are not lacking in soil.

This soil is extremely deficient in available S, and has shown severe S deficiency in canola in the growing season and considerable reduction in canola seed yield when only N was applied without any S fertilizer. Based on the history of this site in relation to severe S deficiency in canola in the growing season in previous years [45] and our present results, the reduction in seed yield with only N application was most likely due to N and S imbalance in the plants [63,64]. Our results suggest the potential of gypsum and RRES in preventing S deficiency in organic crops when grown on S-deficient soils, provided other nutrients are not limiting in soil for crop growth. Our findings also suggest that RRES has the potential to prevent S deficiency in canola by providing available S to the crop in the growing season similar to gypsum, but seed yields of canola in our experiment were relatively lower than normal for this area, especially in 2010 and 2011. The lower than normal seed yields in our study were possibly because of the choice of a *juncea* canola cultivar in 2009, 2010 and 2011 (with relatively lower yield potential compared to hybrid canola), plus using moderate rate of N at 80 $kg \cdot N \cdot ha^{-1}$, and very wet and cool weather conditions in 2012. In our other adjacent experiment, comparing granular RRES and sulphate S fertilizers applied in the previous autumn and in spring at seeding using various methods of placement on the same farm (with relatively high seed yield of hybrid canola grown at 120 $kg \cdot N \cdot ha^{-1}$), spring applied RRES increased seed yield of canola compared to the zero-S control in the first year of application but seed yield was much less than sulphate-S fertilizer. Therefore, it is possible that under high seed yield conditions, spring applied sulphate-S may be more effective in increasing seed yield of canola than spring applied RRES, when broadcast/incorporated into soil in spring. In 2012, we replaced the *juncea* canola cultivar with a high yielding hybrid canola to find if RRES can be as effective as sulphate-S in preventing S deficiency in canola under high seed yield conditions. As mentioned earlier, that seed yield of hybrid canola in 2012 was lower than normal for this area, and the cumulative effect of RRES after four annual applications in increasing productivity, seed yield was almost similar to the similarly-applied sulphate-S fertilizer treatment in this study.

Research has shown that crops with deep taproots can absorb nutrients from deeper soil layers [65,66]. But, if the soil profileis low in available P, then the only alternative is to add external P source [67]. For example, the use of vesicular-arbuscularmychorrhiza (VAM), *Penicillium bilaiae*, rock phosphate, or bone meal can increase the release of P from soil and organic P fertilizers/amendments in order to prevent P deficiency in P-deficient soils and increase crop yields [52-54,57-59,68-70]. In a field study in Saskatchewan, Takeda [68] did not find any benefit of rock phosphate application on crop yield and P uptake over two years at any of three sites, but showed increases in crop yield and P uptake at two sites from the application of rock phosphate in combination with *Penicillium bilaiae*. Gleddie *et al*. [71] also reported positive responses to *Penicillium bilaiae* inoculation on soils that were extremely deficient in P for optimum growth. However, in our study, there was no effect of rock phosphate and/or *Penicillium bilaiae* on yield and P uptake of canola in any year, at this S-deficient site with also a potential of P-deficiency [46]. It is possible that the soil at this site may not be deficient in available P to a level the may limit yield of canola because of its low yield, especially in 2010. We expected increase in crop yield and/or P uptake from the finely ground rock phosphate, because of the increase in surface area, but it did not happen. As explained earlier, this could be due to low yield potential of canola, and also possibly the released P from the fine rock phosphate fertilizer may have become again immobilized/fixed into the soil organic fraction due to greater microbial or chemical reaction of P in the finely ground rock phosphate in soil.

5. CONCLUSION

Some organic amendments showed potential for improvement in organic crop production, and in some other cases highest seed yields were obtained when both organic amendments and chemical fertilizers were applied together, or from combined application of chemical N, S and P fertilizers. These findings suggest that some organic amendments can be used to improve crop yields under organic production. These findings also suggest the potential of some inorganic amendments (e.g., rapid release elemental S and gypsum) in preventing S deficiency in organic crops, provided other nutrients are not limited in soil. The implications of these findings are that it may be possible to increase the sustainability of crop production by improving nutrient use and water use efficiency through better plant and root growth under both organic and conventional farming systems. It may also result in higher net returns to producers, improved soil quality, by returning more residues to soil, and minimize environmental damage of nitrate-N (leaching to ground water and nitrous oxide emissions), by leaving less residual nitrate-N in soils.

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