J. Appl. Res. Plant Sci. Vol. 4(2), 678-686, 2023, https://doi.org/10.38211/joarps.2023.04.02.194

Research Article

OPEN ACCESS

Available on https://www.joarps.org
Journal of Applied Research in Plant Sciences
(JOARPS)
ISSN: 2708-3004 (Online), 2708-2997 (Print)

Management of Saline-Sodic Soil through Press Mud and Sulfur Application for Wheat-Pearl Millet Cropping System

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Article Received 02-02-2023, Article Revised 20-04-2023, Article Accepted 10-05-2023.

Abstract

Press mud is a nutrient-rich organic residue and elemental sulfur being a reclamation agent in combination or alone can be used for rehabilitation of salt-affected soils on wheat-pearl millet crops. The results of present study revealed that press mud and sulfur hold excellent potential to reclaim the saline-sodic soil and alleviate the salinity stress in wheat and pearl millet crops. However, integrated use of sulfur (S) and press mud (PM) demonstrated ~~the~~ positive effects on soil health and crop resilience. Application of S @ 50% gypsum requirement (GR) with PM @ 10 t ha^{-1} showed better results than all other treatments and increased the plant height, number of tillers, spike length, 1000 grain weight, straw yield and grain yield of wheat by 11.16%, 9.87%, 27.93%, 15.65%, 33.54% and 50.26% respectively. Same trend was observed in pearl millet and the plant height, number of tillers, panicle length, grain panicle^{-1}, 1000 grain weight, and grain yield were increased by 16.66%, 22.85%, 13.11%, 9.74%, 13.64%, and19.37% respectively over control. Integrated use of sulfur and press mud also ameliorated the soil properties and reduced the soil pH (4.57%), EC (15.26%), SAR (56.26%), and BD (10.11%) and increased HC (32.5%). Therefore, the integrated sulfur application @ 50% GR and press mud @ 10 t ha^{-1} are recommended as an effective reclamation strategy to manage the saline-sodic soil for better productivity of wheat and pearl millet crops.

Keywords. *Sulfur, Press Mud, Amendments, Reclamation, Salinity*

Introduction

Worldwide increasing population pressure and alarming velocity of urbanization, industrialization along climate change has increased the food security crises. It is estimated that agricultural products need to be raised by 100% by 2050 to feed such a huge population (Pineda *et al.,* 2021). This situation is forcing the farming community to exploit salt-affected soils. Globally, 1,125 million ha of cultivable land have been degraded by salt stress (Hossain, 2019). Transformation of such salt-affected soil into productive agricultural landscapes is a main challenge for scientists and need top priority in whole world to assure global food security (Abensperg *et al.,* 2004). Reclamation of sodality stressed soils is accomplished through application of organic (farm manure, press mud, poultry manure) or inorganic (gypsum, sulfur, calcium chloride) amendments (Sheoran *et al.,* 2021c). Press mud is a nutrient-rich organic residue of sugar industry with a production of 1.28 million tons annually in Pakistan (Khan *et al.,* 2012). Press mud with pH of 5.0 can recalim sodic soil (Avishek, D., *et al*., 2018). Due to its favorable effects on soil properties, it is primarily used both as a soil reclamation agent and as soil conditioner (Shankaraiah and Murthy, 2005). Being a rich source of nitrogen (N), phosphorus (P), potash (K), copper (Cu) and zinc (Zn) it is expected to increase the soil fertility (Avishek, D., *et al.,* 2018). Thus, press mud is nutrient rich and easily metabolizable soil reclaimant for rehabilitation of salinity induced degraded land. Integrated use of press mud with some inorganic reclaimant seems to be rational solution of arresting the sodicity problem and to sustained agriculture productivity (Basak *et al.,* 2021). Press mud after the decomposition released the organic acid and electrolytes which mobilizes the native $CaCO_3$ and produced soluble Ca^{2+} which replaced the Na^+ from exchange sites (Sheoran, *et al.,* 2021a). Conjunctive use of press mud (PM) with gypsum alleviates the drastic effects of sodicity by improving the carbon(C) sequestration, decreasing the soil pH and sustain the productivity of rice and wheat crops (Sheoran *et al.*, 2021 b). Press mud @ 10 Mg ha^{-1} may increase wheat yield by 16.7% and rice yield by 18.9% in moderately sodic soils (Sheoran *et al.*, 2021c). They recommended press mud as an efficient, easily available and affordable ameliorant that capture the sodicity problem by reducing the soil exchangeable sodium percentage (10.4-20.1%) and soil pH (1.6-3.6%) and its potential use in agriculture needs to be scaled up for soil and crop resilience. Muhammad and Khattak (2009) studied the ameliorating properties of PM @ 0, 5, 10 and 20 t ha^{-1} in salt-affected soil. They reported that plant height and biomass yield of maize increased with each increment of press mud. Due to its favorable effects on soil properties, they suggested the press mud as an effective reclamation agent for saline-sodic soils. Negim (2015) evaluated the reclamation efficiency of press mud and gypsum alone or in combination. Results revealed that addition of PM and gypsum in combination was more effective treatment to reduce the soil electrical conductivity (EC) and exchangeable sodium percentage (ESP) than their individual application. Sulfur is also a well-known reclamation agent for rehabilitation of degraded sodic or saline-sodic soils (Jaggi *et al.,* 2005). Sulfur can be used as an alternative amendment for gypsum (Ahmed *et al*., 2016). Sulfur @ 100 % GR significantly increased the grain yield of rice and wheat and improved the soil health by decreasing soil pH, electrical conductivity (EC) and sodium adsorption ratio (SAR) (Ahmed *et al.*, 2017). According to Wei *et al*. (2006), ~~S~~ulfur application is recommended for soil with pH over 6.6 to increase the availability of phosphorus and micro nutrients. In calcareous soil, added S is microbially oxidized into sulfuric acid which mobilizes the Ca_2CO_3 to form $CaSO_4$ (El-Hady and Shaaban, 2010) that provided the soluble Ca^{2+} which replace the Na^+ from exchange site hence reduced the soil sodicity (Abdelhamid *et al.,* 2013). According to Stamford *et al.* (2002) sulfur act as soil conditioner and improved the yield of bean and cow pea by reducing the soil EC from 15.3 to 1.7 dS m^{-1}. Kubenkulov *et al.*, (2013) investigated the ameliorating properties of S and recommended it as a comprehensible soil ameliorant. Favorable effects of sulfur on the properties of salt-affected soils and increased salinity tolerance have been reported in canola (Al-Solimani *et al*., 2010), rice and wheat (Ahmed *et al.,* 2016). Therefore, the current field trial was aimed to investigate the comparative reclamation efficiency of PM and S in combination or alone, and to determine the optimum dose of these amendments for better yield of wheat and pearl millet ~~crops~~ under saline-sodic conditions.

Materials And Methods

Experimental site and crop rotation: A three-year (2017 to 2020) field trial was executed following wheat- pearl millet crop rotation. A saline-sodic field {pH_s = 8.97, SAR = 40.70, EC_e = 4.52 dS m^{-1}, GR = 2.50 (t. acre^{-1}), BD = 1.68 Mg m^{-3} and HC = 0.40 cm hr^{-1}} was selected at farm of Soil Salinity Research Institute, Pindi Bhattian, Pakistan.

Experimental design, treatment details and data collection: The experiment was laid out in randomized complete block design with three replications having plot size 6 x 4 m^2. The treatments tested were~~;~~ T1 = control, T2 = S @ 50% GR, T3 = S @ 100% GR, T4 = PM @ 20 t ha^{-1}, T5 = PM @ 10 t ha^{-1}+S @ 50% GR, T6 = PM @ 15 t ha^{-1} + S @ 25% GR. Elemental sulfur (90%) and press mud (Total N = 1.94%, Total P =0.95%, Total K = 0.78%) were applied on 10-10-2017 at the start of study according to the treatment plan.

During the 2ndweek of November wheat variety ‘‘Faisalabad 2008’’ was sown in lines by rabi drill. Fertilizers @ 120-110-70 NPK kg ha^{-1} were applied as urea, single super phosphate (SSP) and sulphate of potash (SOP). All the phosphorus and potassium were applied at sowing, while N was applied in three splits. Adequate agronomical and management practices (irrigation~~s~~, insect~~s~~, disease~~s~~ and weed~~s~~ control) were carried out uniformly as per recommendations in all the treatments. Crop was harvested in last week of March and data regarding plant height, number of tillers, spike length, 1000 grain weight, straw and grain yield was recorded. In the same lay out, during the 1st week of July, pearl millet variety ‘‘Pioneer’’ was sown in lines by rabi drill. Fertilizers @ 80-60-60 NPK kg ha^{-1} were applied. All phosphorus and potassium were applied basally, while N was applied in three splits. Crop was harvested in 1st week of November and data regarding plant height, number of tillers, panicle length, grain panicle^{-1}, 1000 grain weight and grain yield was recorded. Composite soil samples were collected at the end of study and analyzed for pH of the saturation extract (pH_s), electrical conductivity of soil extract (EC_e), sodium adsorption ratio (SAR), hydraulic conductivity (HC) and bulk density (BD) (Richards L.A., 1954). Soil pH was measured by using pH meter (Microcomputer pH-vision cole parmer model 05669-20). Electrical conductivity was measured with the help of conductivity meter (WTW conduktometer LF 191). The Na^+ contents were determined by flame photometer (digiflame code DV 710) while Ca^{2+} and Mg^{2+} were determined titrimetrically. SAR was calculated as follows where ionic concentration of the saturation extracts is given in $mmol_e$ L^{-1}. SAR = Na^+ / $[(Ca^{2+} + Mg^{2+})/2]^{1/2}$. Soil BD was measured by core method (Blake and Hartge 1986). Hydraulic conductivity was measured by using falling head hydraulic conductivity apparatus (Richards L.A., 1954).

Statistical Analysis: The collected data were subjected to analysis of variance (ANOVA) and treatment means were compared through the least significance difference (LSD) test at $p \leq 0.05$ (Steel *et al*., 1997) using STATISTIX 8.1 package software.

Results

Effect of press mud and sulfur on wheat crop: Application of amendments either single or in combination significantly affected the growth attributes of wheat crop (Table 1). Pooled data of three seasons showed that PM or S had positive effect on plant height of wheat ~~crop,~~ and a significant increase in plant height was observed when both amendments were used in combination. The tallest plants (70.40 cm) were observed where PM @ 10 t ha^{-1} was applied with S @ 50% GR followed by PM @ 20 t ha^{-1}. Whereas, control treatment (without amendment) showed the minimum plant height of 63.33 cm. Similarly, maximum number of tillers (144.67) were recorded with integrated use of PM and S (T5) and minimum tillers for wheat (131.67) were recorded in T1. Data about spike length showed that higher value for spike length (9.16 cm) was recorded for combine application of PM + S in T5, however, it was non-significant with PM @ 20 t ha^{-1}. At the same time, minimum spike length (7.16 cm) was observed where no amendment was applied. Data regarding the 1000-grain weight in Table 2 displayed that maximum grain weight (29.10 cm) was divulged with PM @ 10 t ha^{-1} + S @ 50% GR but statically non-significant with PM @ 20 t ha^{-1}. PM and S significantly improved grain and straw yield of wheat crop and effect was more remarkable where both amendments were applied collectively. Maximum straw (2.11 t ha^{-1}) and grain (2.81 t ha^{-1}) yield were produced where S @ 50% GR and PM @ 10 t ha^{-1} were applied in combination, however, these values were significant only from control and no significant difference was noted in the treatments where these amendments were applied individually.

Effect of press mud and sulfur on pearl millet crop: Data of succeeding pearl millet crop revealed that growth and yield parameters response positively to added sulfur and press mud either alone or in combination (Table 3). Higher value for ~~the~~ plant height (219.67 cm) was noted with addition of PM @ 20 t ha^{-1} which was non-significant from PM @ 10 t ha^{-1}+ S @ 50% GR and PM @ 15 t ha^{-1} + S @ 25% GR. On contrary, minimum plant height of 178 cm was documented in control (no amendment). Similarly, maximum number of tillers (43.33) were produced with application of PM @ 20 t ha^{-1} statistically at par with PM @ 10 t ha^{-1} + S @ 50% GR, whereas, minimum tillers (35) were recorded in control. Combined application of sulfur (S @ 50% GR) and press mud (PM @ 10 t ha^{-1}) significantly increased panicle length (28.73 cm) and grain $panicle^{-1}$ (1890) than all other treatments, while minimum values for panicle length (25.40 cm) and grain $panicle^{-1}$ (1606.7) were recorded in the treatment where no amendment was applied i.e., control. Results (Table 4) also showed that maximum 1000 grain weight (11.73 g) and grain yield (1.65 t. ha^{-1}) were produced with integrated use of PM @ 10 t ha^{-1} and S @ 50% GR, statistically non-significant with PM @ 20 t ha^{-1}. At the same time minimum 1000 grain weight (9.38 g) and grain yield (1.29 t ha^{-1}) were noted in T1 (without any amendment).

Effect of press mud and sulfur on soil properties: Sulfur and press mud application either alone or in combination significantly improved the soil properties of saline-sodic field as depicted in Table 5. With respect to soil pH maximum decrease of 5.23% over its initial value was documented with PM @ 20 t ha^{-1} while combined use of S and PM decreases the pH by 4.57 % as compared to initial value at the start of study. Minimum reduction (1.78%) in pH was observed in control. Similarly, maximum reduction of 15.26% and 56.26% was observed for EC and SAR respectively with combined use of S @ 50% GR and PM @ 10 t ha^{-1}. Soil physical properties in the term of bulk density (BD) and hydraulic conductivity (HC) were substantially improved with addition of sulfur and press mud. Co-application of PM @ 10 t ha^{-1} and S @ 50% GR decreased the BD by 10.11% over its initial value, whereas, minimum decrement of 1.78% was observed in T1 (Fig. 1). HC was also increased remarkably with application of amendments and maximum increase (32.5%) was recorded in the treatments that received the S @ 50% GR and PM @ 10 t ha^{-1} (T5) and S @ 100% GR (T3). While minimum increase (5%) was observed in control.

Table 1: Effect of press mud and sulfur on growth of wheat (average of three seasons)

Treatments	Plant height (cm)	Number of tillers m^{-2}	Spike length (cm)
Control	63.33 d	131.67 d	7.16 d
S @ 50% GR	64.13 cd	134.00 d	7.80 c
S @100% GR	65.10 bcd	138.00 c	7.93 bc
PM @ 20 t ha^{-1}	67.36 b	141.33 b	8.80 a
PM @ 10 t ha^{-1}+ S @ 50% GR	70.40 a	144.67 a	9.16 a
PM @ 15 t ha^{-1}+S @ 25% GR	66.43 bc	140.00 bc	8.33 b
LSD	2.5347	2.4782	0.4254

Table 2: Effect of press mud and sulfur on growth of wheat (average of three seasons)

Treatments	1000 Grain Weight	Straw Yield (t. ha^{-1})	Grain Yield (t. ha^{-1})
Control	25.16 d	1.58 b	1.87 c
S @ 50% GR	25.76 cd	1.74 ab	2.19 bc
S @100% GR	26.26 c	1.82 ab	2.67 a
PM @ 20 t ha^{-1}	28.63 a	1.96 ab	2.49 ab
PM @ 10 t ha^{-1} + S@ 50% GR	29.10 a	2.11 a	2.81 a
PM @ 15 t ha^{-1}+ S @ 25% GR	27.30 b	2.01 ab	2.59 ab
LSD	0.8215	0.5265	0.4011

Table 3: Effect of press mud and sulfur on growth of pearl millet (average of three seasons)

Treatments	Plant height (cm)	Number of tillers m^{-2}	Panicle length (cm)
Control	178.00 c	35.00 b	25.40 d
S @ 50% GR	188.67 bc	36.66 b	26.23 cd
S @100% GR	198.33 bc	37.66 b	26.36 cd
PM @ 20 t ha^{-1}	219.67 a	43.33 a	27.73 b
PM @ 10 t ha^{-1}+S@ 50% GR	207.67 ab	43.00 a	28.73 a
PM @ 15 t ha^{-1}+S @ 25% GR	205.00 ab	38.33 b	27.10 bc
LSD	20.975	3.8306	0.9907

Table 4: Effect of press mud and sulfur on growth of pearl millet (average of three seasons)

Treatments	Grain $Panicle^{-1}$	1000 Grain Weight	Grain Yield (t. ha^{-1})
Control	1606.7 d	9.38 b	1.29 d
S @ 50% GR	1626.7 cd	9.78 ab	1.39 cd
S @100% GR	1690.0 c	10.78 ab	1.41 c
PM @ 20 t ha^{-1}	1763.3 b	10.66 ab	1.54 ab
PM @ 10 t ha^{-1}+ S @ 50% GR	1890.0 a	11.73 a	1.65 a
PM @ 15 t ha^{-1} + S @ 25% GR	1790.0 b	11.45 ab	1.48 bc
LSD	66.899	2.1202	0.1218

Table 5: Effect of press mud and sulfur on soil chemical properties at the end of study

Treatments	pH_s	Percent decrease over initial value	EC (dS m^{-1})	Percent decrease over initial value	SAR	Percent decrease over initial value
Control	8.81	1.78	4.26	5.75	30.11	26.01
S @ 50% GR	8.54	4.79	4.03	10.84	23.95	41.15
S@100% GR	8.52	5.01	3.86	14.60	18.55	54.42
PM @ 20 t ha^{-1}	8.50	5.23	3.87	14.38	19.20	52.82
PM @ 10 t ha^{-1}+ S @ 50% GR	8.56	4.57	3.83	15.26	17.80	56.26
PM @ 15 t ha^{-1}+S @ 25% GR	8.55	4.68	3.90	13.71	20.59	49.41

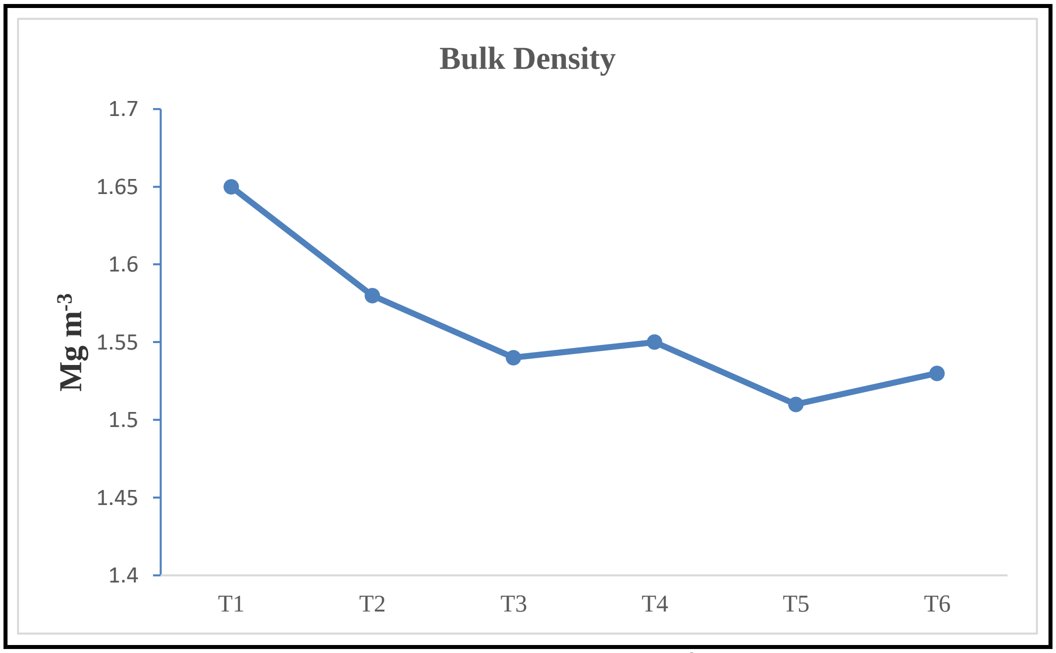

Fig. 1. Effect of press mud and sulfur on bulk density (Mg m^{-3}) of soil at the end of study.

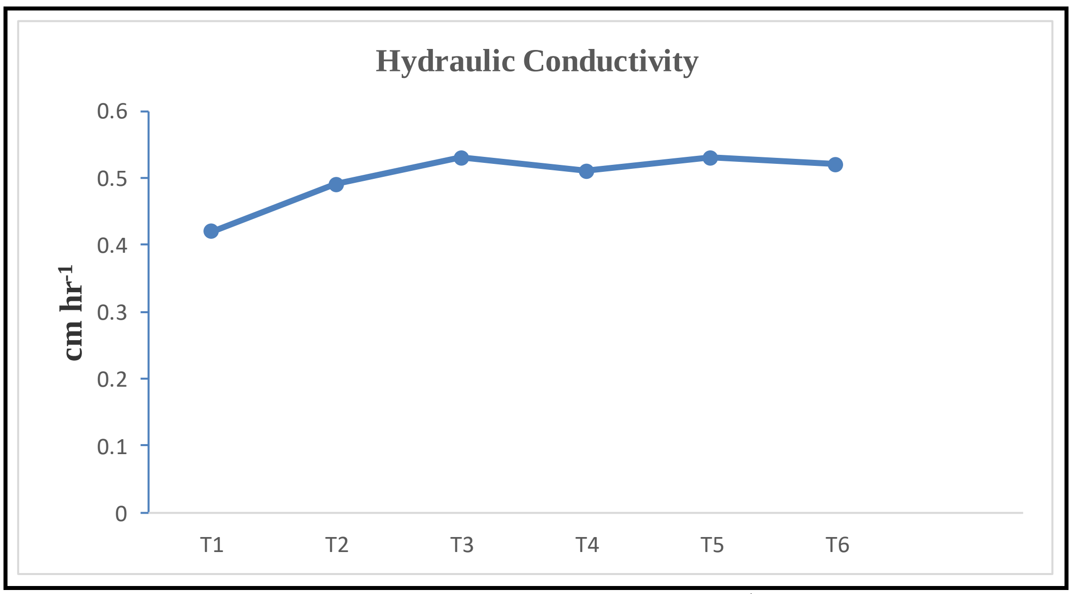

Fig. 2. Effect of press mud and sulfur on hydraulic conductivity (cm hr^{-1}) of soil at the end of study

Discussion

Removal of Na^{+} out of root zone through organic or inorganic amendments is the most familiar methods for reclamation of sodic or saline sodic soils (Feizi *et al.*, 2010). In current study, results revealed that varying levels of PM and S significantly increased the growth and yield of wheat and pearl millet than non-amended soil, however, effects were more pronounced with integrated use of PM and S than their alone application. Pooled data of three seasons showed that S @ 50% GR + PM @ 10 t ha^{-1} proved more superior to increased plant height, number of tillers, 1000 grain weight and grain yield of wheat and pearl millet crops. This improved growth and yield performance of wheat and pearl millet crops in the treatment receiving combined application PM and S can be explained by the ameliorative and nutritional properties of these amendments that counteract the detrimental effects of salinity and sodicity. Press mud being a rich source of calcium and phosphate (Thai *et al.*, 2015) organic matter, total nitrogen (Said *et al.*, 2010) zinc and copper (Avishek, D., *et al.*, 2018) is anticipated to increase the soil fertility. Due to its favorable effects on soil health and microbial activity, it is also considered as a good soil conditioner (Shankaraiah and Murthy, 2005). The addition of press mud increased the organic matter and nutrient availability and reduced the uptake of toxic ions resulting in improved growth and yield of crops (Azhar *et al*., 2019). Application of PM @ 15 t ha^{-1} with recommended dose of chemical fertilizer increased the yield of sugarcane up to 21% (Shankaraiah and Murthy, 2005). Similarly, Imran *et al.* (2021) observed an increase of 77% in wheat grain yield in salt-affected soil with application of PM @ 15 g kg^{-1} soil. Furthermore, press mud is metabolizable amendments and generate CO_2 and organic acid on decomposition that dissolved the native $CaCO_3$ and produced soluble Ca^{2+} which replaced the Na^+ from exchange sites and ultimately reduced the soil sodification (Sheoran *et al.,* 2021). Press mud due to its chelation ability adsorbed the toxic metals (Mahmood, 2010) and reduces the uptake of toxic Na consequently improves the crop growth and productivity (Saleem *et al.,* 2015). Our results are in aligning of Muhammad and Khattak (2011) who reported an increase of 27 to 36% in wheat grain yield with application press mud, gypsum and gypsum + press mud in saline-sodic soil.

Sulfur is one of the essential macro nutrients required for plant growth in same amount as P (Ali *et al.,* 2008). For the optimum crop yield it is very important to supply a balance fertilization of S along with other essential nutrients (Jez, 2008) as it is involved in synthesis of chlorophyll and vitamins (Kacar and Katkat, 2007; Abdallah *et al.,* 2010). S application in salt-affected soils improves the quality and quantity of produce by increasing the uptake of NPK, Ca and Zn and inhibits the uptake of toxic Na and Cl (Badr uz Zaman *et al.,* 2002; Mahmood *et al.,* 2009). In calcareous soil S is microbially oxidize into sulfuric acid which mobilize the Ca_2CO_3 to form $CaSO_4$ (El-Hady and Shaaban, 2010) that provides the soluble Ca^{2+} to replace the Na from exchange site thus consequently reduces the soil sodicity (Abdelhamid *et al.,* 2013) and improves the soil health and produce the favorable conditions conducive for crop growth. Ameliorative role of sulfur in saline-sodic soils have been reported in sunflower (Badr uz Zaman *et al.,* 2002) wheat (Ali *et al*., 2012) maize (Manesh *et al.,* 2013) rice and wheat (Ahmed *et al*., 2016, 2017). Integrated use of S and PM substantially improved the soil properties and a sharp decline in salinity indices (EC, pH and SAR) was observed. Soil pH is an indicator of plant growth medium depicting the phase and fate of nutrients and salinity/sodicity status, thus any change in soil pH is very important. Results of current study revealed that all the amendments lowered the final value of soil pH, however, integrated use of S and PM proved more better in lowering the pH and maximum reduction of 4.57% was divulged in the treatments receiving S @ 50% GR and PM @ 10 t ha^{-1}. Elemental S is believed a cost-effective ameliorant for reducing the pH value of growth medium (Roig *et al.,* 2004; Tarek *et al.*, 2013) and this low value of pH may be justified by the generation of H_2SO_4 in calcareous soil due to the oxidation of added S (Singh *et al.,* 2006). In addition, release of Ca from $CaSO_4$ which replace the Na^+ from exchange sites are the major reasons for substantial decrease of SAR and EC (Kubenkulov *et al*., 2013; Abdelhamid *et al*., 2013). Furthermore, press mud release the organic acid and discharge H^+ ion that play a key role in neutralizing the soil alkalinity (Sheoran *et al.,* 2021c) and reduce soil pH, EC and SAR. Our results are strengthened by the previous findings of Ahmed *et al*. (2016; 2017) that sulfur application is a very effective reclamation strategy in improving the grain yield of rice-wheat crops and soil health of saline-sodic soil.

The reduction in sodicity and salinity was also reflected in soil physical properties e.g., bulk density and hydraulic conductivity. Usually, saline sodic soils are dispersed and compact (high BD) due to dominant Na^+. Experimental soil had BD of 1.68 Mg m^{-3} indicating its compactness, which was substantially improved with application of amendments and maximum reduction of 10.11% was observed with combine application of S @ 50% GR and PM @ 10 t ha^{-1}. Similarly, hydraulic conductivity also increased manifolds at the end of study and most effective treatment was S @ 50% GR and PM @ 10 t $ha^{-1}$with 32.5% increase over its initial value. Increased value of HC and reduction in BD with S and PM may be associated with supplementation of additional organic matter through press mud (Basak *et al*., 2021) leading to improve soil physical properties. Press mud increase the aggregate stability, soil porosity (Marinari *et al*., 2000; Clark *et al.,* 2007) and gypsum synthesized by added sulfur improve flocculation of dispersed soil (Qadir *et al*., 2002) and enhance removal of Na (Yadav *et al.,* 2009) which in turn reduce the soil compactness (low BD) and increase the hydraulic conductivity. The gypsum marked more SO4-S contents in soil than elemental S that might be due to its binding nature that has long lasting effects on soil. Well drained, light textured soils in high rainfall areas have low SO4-S content and require S fertilization for optimum crop production. (Yunas *et al.,* 2010). Combine application of inorganic and organic sources induced swift reclamation, healthier plant growth and positively influence the soil health (Shaaban *et al.,* 2013; Khalil, A., *et al*., 2015, Anwar zaka *et al*., 2018).

Conclusion

Scaling up the use of organic and inorganic resources seems to be rational solution for restoration of sodicity induction degraded lands. Integrated use of sulfur and press mud ameliorated the soil properties of saline sodic soil and reduced the soil pH, EC, SAR, BD and increased HC that may improve growth and yield of wheat and pearl millet.. Addition of S to soil is imperative for obtaining higher yields particularly high S demanding oilseed crops. However, integrated application of S @ 50% GR and PM @ 10 t ha^{-1} demonstrated more positive effects on soil health and crop resilience.

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