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Synergistic Effect of Flue Gas Desulfurization (FGD) Gypsum and Arbuscular Mycorrhizal Fungi (AMF) Inoculation Improving Wheat Yield in Sodic Soils

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ABSTRACT

Salt-affected soils (SAS), particularly sodic soils, severely limit agricultural productivity due to poor soil structure, high pH and sodium toxicity. This study evaluated the combined effect of flue gas desulfurization gypsum (FGDG) and arbuscular mycorrhizal fungi (AMF) on wheat performance in sodic soils. Results showed that FGDG significantly improved plant height, tillering, spike traits, grain and straw yield and chlorophyll content. AMF inoculation further enhanced wheat growth and productivity, especially under 100% GR. The FGDG + AMF combination led to maximum yield and physiological improvement, indicating a synergistic effect. These findings suggest that integrating FGDG and AMF is a sustainable strategy for reclaiming sodic soils and improving crop productivity.

Key words: Sodic soils, flue gas desulfurization gypsum, arbuscular mycorrhizal fungi, crop productivity

INTRODUCTION

Agricultural production in salt-affected soils (SAS) and sodicity poses a significant challenge globally, with approximately 932.2 million hectares of saline and approximately 581 million hectares of sodic soils of land affected, respectively. India has 6.73 million hectares of salt-affected soils, with approximately 56% being sodic. These soils are characterized by excess soluble salts and high exchangeable sodium, which hinder water uptake, nutrient availability, microbial activity and plant growth (Basak *et al.,* 2020; Rai *et al*., 2021a). Broadly categorized into saline and sodic soils, SAS severely impact crop productivity. Reclamation of such degraded soils demands the addition of calcium-rich amendments to neutralize soil alkalinity and enhance soil health (Basak *et al*. 2022a). In this context, the use of flue gas desulfurization gypsum (FGDG), a by-product of coal combustion in thermal power plants, offers a sustainable alternative to mineral gypsum for improving sodic soils.

Globally, coal-fired power stations constitute a significant energy source. However, burning coal releases toxic chemicals that are dangerous to the environment and human health, including sulphur oxides (SOx), nitrogen oxides (NOx), heavy metals (HMs) and particulate matter. Thermal power stations have implemented sophisticated air pollution control technologies, such as flue gas desulfurization (FGD) systems, to reduce these emissions. By reacting SOx with wet limestone, FGD technology extracts SOx from flue gases and creates calcium sulfate dihydrate ($CaSO_4.2H_2O$), which is marketed as FGD gypsum (Sundha *et al.,* 2023). The wet FGD technology has been widely used by nations including the US, China, and Germany to efficiently regulate coal emissions.

India imports nearly 80% of the 10 million tonnes (Mt) of gypsum required annually. FGDG offers a viable solution to bridge this demand-supply gap. It contains about 99.6% $CaSO_4.2H_2O$, contributing significantly to soil amendment by supplying soluble Ca^{2+}, which

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replaces exchangeable Na^+ on soil colloids, thereby improving soil structure and reducing sodicity (Rai *et al.,* 2021a). Additionally, India produces approximately 12-17 Mt of FGDG annually, from its thermal power plants, offering immense potential for its use in reclamation of about 6.73 million hectares of SAS, including 3.77 Mha of sodic soils.

However, FGDG contains trace elements from coal combustion, including heavy metals such as Cr, Cd, Ni, As, Pb, Hg and Se. These elements vary in mobility and toxicity depending on their speciation and the environmental conditions (Basak *et al*. 2020; Rai *et al.* 2021a). Several researches indicate that FGDG may contain high levels of bioavailable Mn, Zn and Cd, posing potential environmental risks.

In addition to chemical amendments like FGDG, the integration of biological inputs such as arbuscular mycorrhizal fungi (AMF) has shown promise in ameliorating the adverse effects of soil salinity and sodicity. AMF are obligate biotrophs that form mutualistic relationships with plant roots, enhancing nutrient uptake, especially of phosphorus and micronutrients, improving water relations, and conferring tolerance to abiotic stresses such as salinity and drought (Zhou *et al.,* 2020; Chandra *et al.* 2022; Pellegrino *et al.,* 2022). AMF hyphae expand the root's absorptive surface area, facilitating access to otherwise unavailable nutrients, while also improving soil aggregation, porosity and microbial activity. AMF are particularly important for acquiring phosphorus and nitrogen, which are often limited in the soil. They also enhance the uptake of other essential nutrients. AMF can improve a plant's water uptake and drought tolerance by facilitating water movement into and out of the roots. AMF can help plants cope with various abiotic stresses, including drought, salinity and heavy metal contamination, by improving their physiological and molecular responses. AMF contribute to soil health by improving soil structure, potentially through the production of a glue-like protein called glomalin. Studies have demonstrated the effectiveness of native AMF isolates, particularly those adapted to degraded soils with high pH and low phosphorus availability. These ecotypes are more likely to form effective associations with crop plants in stressed environments (Klinsukon *et al.,* 2021). The mycorrhizal symbiosis has been shown to mitigate salt stress by reducing Na^+ uptake and enhancing ion balance in the host plant, while also contributing to soil carbon sequestration and ecosystem resilience. Hence, the present study was planned to evaluate the interactive effect of AMF and soil amendments such FGDG in improving soil properties and crop productivity in sodic soils.

MATERIALS AND METHODS

A lysimeter experiment was carried out at ICAR-Central Soil Salinity Research Institute, Karnal, Haryana, India. The study site was located at 29°42′′20.7′ N latitude, 76°57′′ 19.79′ E longitude, 243 m above mean sea level. The study site had sub-tropical monsoonal climate and the average annual rainfall of around 700 mm.

The experiment was conducted in lysimeters to evaluate the combined effects of flue gas desulfurization gypsum (FGDG) and arbuscular mycorrhizal fungi (AMF) on the crop performance of wheat. The experiment followed a factorial design comprising the following treatments: Control, 50% gypsum requirement (GR), FGDG at 50% GR (FGD50GR), and FGDG at 100% GR (FGD100GR). Each treatment was further sub-divided based on AMF inoculation either with or without AMF. The efficacy of these treatments was assessed on the salt tolerant wheat variety cv. KRL 210. Wheat was sown in the lysimeters in the second week of November. Prior to sowing, a fine seed bed was prepared with a row to row spacing of 22.5 cm. Recommended dose of fertilizer was applied in wheat crop. Urea was used as a source of N, while diammonium phosphate (DAP) and muriate of potash (MOP) were used as a source of P and K, respectively. Urea was applied at the rate of 150 kg/ha, while DAP and MOP were applied at the rate of 60 and 30 kg/ha, respectively. Half of the nitrogen and the full doses of phosphorus and potassium were applied at sowing. The remaining nitrogen was applied in two equal splits at 21 and 45 days after sowing. All other standard agronomic practices and crop-specific phyto-sanitary measures were followed during the season. A SPAD (Soil Plant Analysis Development) meter was used to measure the relative chlorophyll content in wheat leaves. The wheat crop was harvested in April to record grain and straw yields. Plant samples were collected from a 50 cm running row to evaluate growth such as plant height, tillers per meter running length (MRL), spike length, spikelet per spike, grain weight per spike and yield parameters. Grain and straw samples were oven-dried at 65°C until a constant weight was achieved. Yields were expressed on an oven dry weight basis. The harvest index (HI) was calculated using the following equation:

$$HI = \frac{\text{Grain yield (kg/m}^2)}{\text{Grain yield (kg/m}^2) + \text{Straw yield (kg/m}^2)}$$

RESULTS AND DISCUSSION

Salt-affected soils (SAS), especially sodic soil, pose a significant agricultural challenge due to their deleterious effects on soil structure, nutrient dynamics, microbial activity and overall crop productivity (Basak *et al.*, 2020). The present study was designed to evaluate the synergistic effect of flue gas desulfurization gypsum (FGDG) and arbuscular mycorrhizal fungi (AMF) on wheat performance in sodic conditions.

FGDG is a beneficial soil amendment, rich in calcium and sulphur, with trace beneficial elements (Basak *et al.* 2022b; Sundha *et al.*, 2023). It enhances plant growth and crop productivity, particularly in Ca-demanding crops such as wheat, maize, citrus and alfalfa. In sodic soils, FGDG application improved plant performance in this study. Previous research demonstrated that applying 4.48 Mg/ha of FGDG in Ca-deficient soils significantly increased citrus yield and quality. Similarly, higher FGDG rates boosted shoot Ca levels in forage crops like alfalfa and tall fescue. In acidic soils, 20 Mg/ha improved Ca levels in both top soil and sub-soil, raising dry matter yields and reducing toxic aluminum levels. FGDG is also an effective sulphur source, and enhanced the yield of soybeans, maize and alfalfa. It increases the availability of phosphorus, potassium, magnesium and silicon, contributing to improved crop nutrient content and quality. FGDG ameliorates sodicity and increased soil moisture improving physiological functions including photosynthesis in sunflower.

In the present study also FGDG significantly improved plant growth and productivity of wheat which validates the potential of FGDG in ameliorating sodic soils. The addition of calcium from FGDG replaced exchangeable sodium (Na^+) on soil colloids, reducing dispersion and promoting soil aggregation. This ultimately enhanced root penetration, water infiltration and aeration (Wang *et al.*, 2021). Plant height was significantly improved by FGDG application and AMF inoculation (Fig. 1). Among the soil amendments, plant height was observed highest in the FGD100GR (74.43 cm) and FGD50GR (73.23 cm) treatments, both significantly higher than the control (71.05 cm). AMF inoculated plants recorded a significantly greater plant height (75.45 cm) compared to non-AMF inoculated plants (70.26 cm). Statistical analysis showed that both the inoculation ($P < 0.0001$) and amendment ($P = 0.0087$) had significant effects on plant height, while their interaction (inoculation × amendment) was not significant ($P = 0.391$).

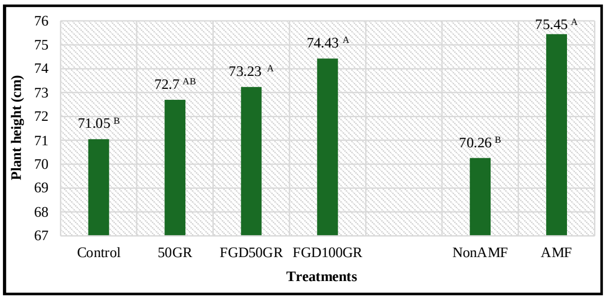

Fig. 1. Effect of AMF inoculation and FGDG application on plant height (cm) in wheat crop under sodic soil. Different letters indicate statistically significant difference at $P \leq 0.05$. 50GR: 50% gypsum requirement (GR), FGD50GR: FGDG at 50% GR; FGD100GR: FGDG at 100% GR. Non-AMF: AMF without AMF inoculation and AMF: with AMF inoculation.

Tillers per MRL were significantly affected by the FGDG application but not by AMF inoculation or their interaction (Fig. 2). Among the soil amendments, the FGD100GR treatment produced the highest number of tillers (142.5), which was significantly greater than all other treatments, including the control (105). Although AMF (117.08 cm) and non-AMF (117.5 cm) treatments had similar tiller numbers with no statistical difference (LSD = 15.401), the effect of amendments was significant ($P=0.0096$). However, inoculation ($P=0.9545$) and inoculation × amendment interaction ($P=0.5755$) did not show significant effects.

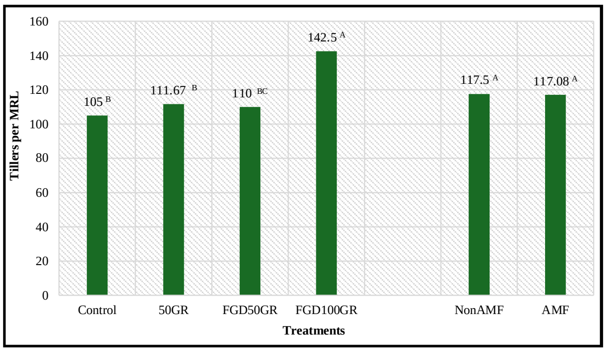

Fig. 2. Effect of AMF inoculation and FGDG application on tillers per MRL under different treatments. Different letters indicate significant differences at P ≤ 0.05. 50GR: 50% gypsum requirement (GR); FGD50GR: FGDG at 50% GR; FGD100GR: FGDG at 100% GR; Non-AMF: AMF without AMF inoculation and AMF: With AMF inoculation.

Spike length was significantly influenced by both the AMF inoculation and FGDG application (Fig. 3). The longest spikes were observed in the FGD100GR treatment (9.52 cm), significantly higher than the control (9.05 cm). AMF inoculated plants (9.44 cm) had significantly greater spike length than non-AMF plants (9.12 cm). The effects of inoculation (P=0.0042) and amendments (P=0.0222) were both statistically significant, whereas their interaction was not statistically significant (P=0.1167).

Spikelets per spike were significantly increased by both FGDG application and AMF inoculation (Fig. 4). Among soil treatments, FGD100GR recorded the highest number of

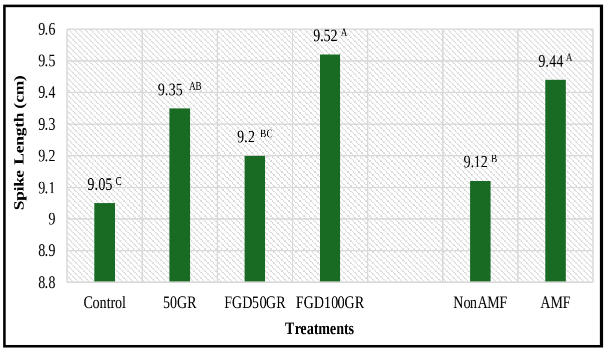

Fig. 3. Effect of AMF inoculation and FGDG application on spike length (cm). Different letters indicate statistically significant differences at P ≤ 0.05. 50GR: 50% gypsum requirement (GR); FGD50GR: FGDG at 50% GR; FGD100GR: FGDG at 100% GR, Non-AMF: AMF without AMF inoculation and AMF: With AMF inoculation.

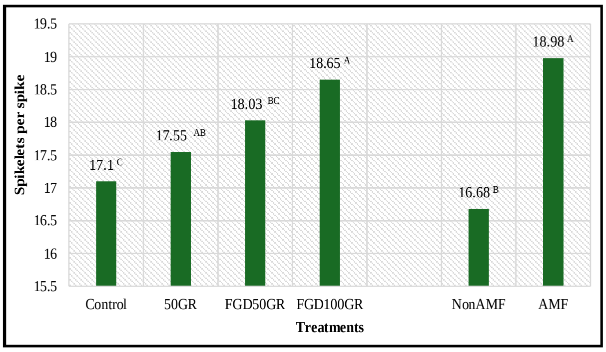

Fig. 4. Effect of AMF inoculation and FGDG application on spikelets per spike under different treatment combinations. Different letters denote statistically significant differences at P ≤ 0.05. 50GR: 50% gypsum requirement (GR); FGD50GR: FGDG at 50% GR; FGD100GR: FGDG at 100% GR, Non-AMF: AMF without AMF inoculation and AMF: With AMF inoculation.

spikelets (18.65), which was significantly higher than the control (17.10). AMF inoculation had a strong positive effect, with AMF treated plants producing significantly more spikelets (18.98) than non-AMF plants (16.68). Both inoculation (P < 0.0001) and amendments (P=0.0017) had significant effects, while their interaction was not significant (P=0.2724).

Grain weight per spike was significantly affected by both the AMF inoculation and FGDG application treatments (Fig. 5). The highest grain weight was recorded in the FGD100GR treatment (3.02 g), significantly higher than the control (2.53 g). Among inoculation treatments, AMF significantly increased grain weight (3.05 g) compared to non-AMF (2.52 g) treatments. Statistical analysis indicated significant effects of both the inoculation (P< 0.0001) and amendments (P=0.0219), whereas the interaction between the two was not significant (P=0.8608).

Straw weight increased significantly with FGDG application and AMF inoculation (Fig. 6). The highest straw yield was recorded under the FGD100GR treatment (1.23 kg/m²), significantly higher than control (0.94 kg/m²). Among inoculation treatments, AMF inoculated plants produced higher straw biomass (1.15 kg/m²) than non-AMF (1.05 kg/m²) treatment. Both inoculation and amendments showed highly significant effects (P < 0.0001), while their interaction was not significant (P=0.1705).

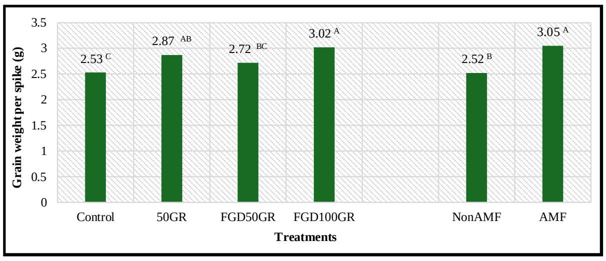

Fig. 5. Effect of AMF inoculation and FGDG application on grain weight per spike (g). Different letters indicate significant differences at P ≤ 0.05. 50GR: 50% gypsum requirement (GR); FGD50GR: FGDG at 50% GR; FGD100GR: FGDG at 100% GR, Non-AMF: AMF without AMF inoculation and AMF: With AMF inoculation.

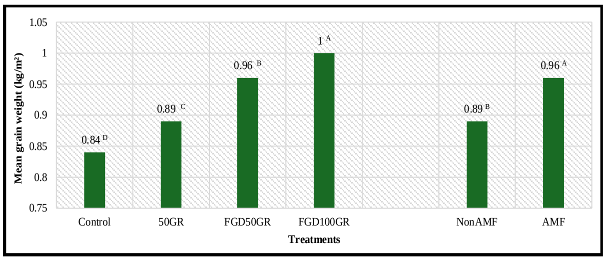

Fig. 7. Effect of AMF inoculation and FGDG application on grain weight (kg/m²). Different letters denote significant differences at P ≤ 0.05. 50GR: 50% gypsum requirement (GR); FGD50GR: FGDG at 50% GR; FGD100GR: FGDG at 100% GR, Non-AMF: AMF without AMF inoculation and AMF: With AMF inoculation.

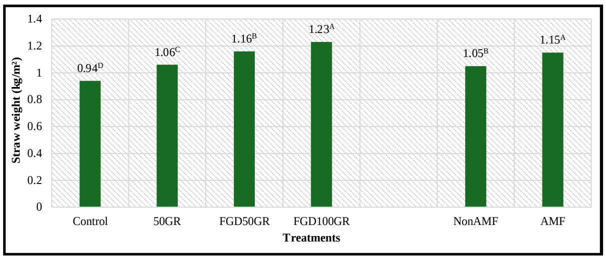

Fig. 6. Effect of AMF inoculation and FGDG application on straw weight (kg/m²). Different letters indicate significant differences at P ≤ 0.05. 50GR: 50% gypsum requirement (GR); FGD50GR: FGDG at 50% GR; FGD100GR: FGDG at 100% GR, Non-AMF: AMF without AMF inoculation and AMF: With AMF inoculation.

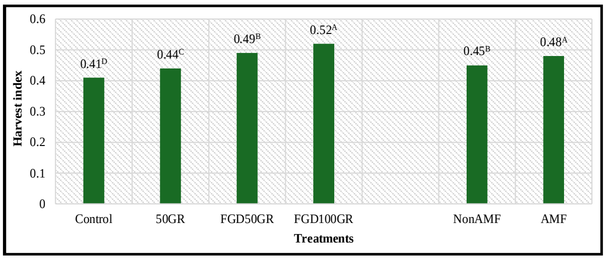

Fig. 8. Effect of AMF inoculation and FGDG application on harvest index. Different letters indicate significant differences at P ≤ 0.05. 50GR: 50% gypsum requirement (GR); FGD50GR: FGDG at 50% GR; FGD100GR: FGDG at 100% GR, Non-AMF: AMF without AMF inoculation and AMF: With AMF inoculation.

Grain weight was significantly affected by both the FGDG application and AMF inoculation (Fig. 7). The highest grain weight was observed in the FGD100GR treatment (1.00 kg/m²), which was significantly greater than that of the control (0.84 kg/m²). Similarly, AMF inoculated plants had significantly higher grain weight (0.96 kg/m²) compared to non-AMF plants (0.89 kg/m²). Both inoculation and amendment effects were highly significant (P<0.0001) and their interaction was also significant (P = 0.0008).

Harvest index varied significantly among the treatments (Fig. 8). The FGD100GR treatment recorded the highest harvest index (0.52), which was significantly greater than that of the control (0.41). Among AMF treatments, inoculated plants (AMF) showed a significantly higher HI (0.48) compared to non-AMF plants (0.45). Both inoculation (P=0.0003) and amendment (P<0.0001) effects were statistically significant, while their interaction was statistically insignificant (P=0.126).

SPAD values, indicating leaf chlorophyll content, significantly differed across treatments (Fig. 9). The highest SPAD value was observed in FGD100GR (42.70) followed closely by FGD50GR (42.60) and 50 GR (42.02) and was significantly higher than control (40.43). AMF inoculated plants (AMF) also exhibited significantly higher SPAD (42.98) than non-AMF treatments (40.9). Both the inoculation (P=0.0002) and amendment (P=0.0061) significantly influenced chlorophyll content, while their interaction was statistically insignificant (P=0.1269).

Notably, plant height and tiller number per plant were significantly higher in FGDG treatments, particularly at 100% gypsum requirement (FGD100GR). This enhancement can be attributed to improved root zone conditions that facilitated greater water and nutrient uptake. FGDG treatments also significantly improved spike length, spikelet number, and grain weight per spike leading to enhanced grain yield. These

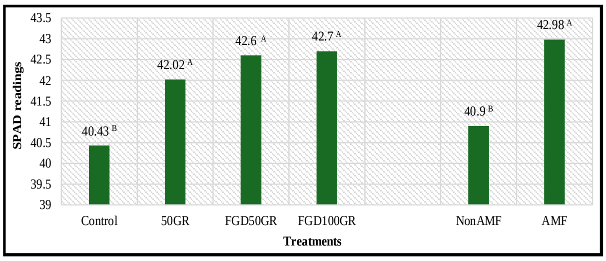

Fig. 9. Effect of AMF inoculation and FGDG application on chlorophyll content. Different letters indicate significant differences at $P \leq 0.05$. 50GR: 50% gypsum requirement (GR); FGD50GR: FGDG at 50% GR; FGD100GR: FGDG at 100% GR, Non-AMF: AMF without AMF inoculation and AMF: With AMF inoculation.

observations suggest not only an improvement in vegetative growth but also a positive effect on reproductive development. These results were consistent with previous researches that demonstrated enhanced nutrient bioavailability and reduced osmotic stress in sodic soils treated with FGDG. Furthermore, the SPAD readings, which reflect chlorophyll content and photosynthetic efficiency, were significantly higher in FGDG treatments. This is likely a consequence of better nutrient availability, particularly nitrogen and magnesium, due to improved cation exchange dynamics. The reduced sodium toxicity and enhanced root health contributed to better N assimilation and chlorophyll biosynthesis. FGDG is an effective source of calcium (Ca^{2+}) for reclaiming sodic soils, improving soil structure by increasing Ca^{2+} and sulphate (SO_4^{2-}) levels. It also enhances leaching of magnesium (Mg^{2+}) and potassium (K^+) by displacing them with Ca^{2+}. FGDG transformed harmful salts like sodium carbonate into more neutral salts such as sodium chloride and sulphate. It also increased exchangeable Ca^{2+} in both the surface and sub-soil layers.

AMF play a pivotal role in plant ecology by forming symbiotic associations with approximately 80% of terrestrial plant species, including both glycophytes and halophytes. These fungi are highly adaptable, thriving in a wide range of environmental conditions, and providing critical ecosystem services. Notably, AMF enhance the physical and chemical properties of the rhizosphere, support ecosystem stability and significantly improve host plant growth and development. Their symbiosis with plant roots often referred to as the "mother of all plant root symbioses" is among the most widespread and effective strategies plants use to cope with both the abiotic and biotic stresses.

AMF is globally distributed in extreme environments, including in saline conditions. AMF associations offer a promising ecological approach for enhancing plant tolerance to salinity. AMF contribute to salinity tolerance by modulating various physiological and biochemical pathways within the host plant. These include improved water and nutrient uptake, enhanced photosynthetic efficiency, activation of antioxidant defence systems, regulation of ion transport, and increased biomass accumulation in both the roots and shoots. Furthermore, AMF influence the expression of aquaporin and membrane transport protein genes, and promote the accumulation of compatible solutes, all of which contribute to enhanced plant resilience under salinity stress. The incorporation of AMF along with FGDG improves wheat growth and yield attributes. AMF play a pivotal role in enhancing nutrient uptake, particularly phosphorus and micronutrients like Zn and Cu, which are often limited in sodic environments (Chandra *et al.,* 2022). The present study confirmed significant increases in plant height, spike length, number of spikelets, grain weight per spike and SPAD values in AMF inoculated treatments.

One of the key mechanisms by which AMF support, plant performance under salt-affected conditions is ionic homeostasis. By reducing Naz uptake and enhancing selective K^+ and Ca^{2+} absorption, AMF help in maintaining a favourable K^+/Na^+ ratio, crucial for enzyme function and cellular integrity. In this study, the observed increase in grain and straw yield in AMF treatments suggests improved ionic balance and metabolic stability under salt stressed conditions (Sharma *et al.,* 2020; Klinsukon *et al.,* 2021).

AMF also enhances soil aggregation and microbial activity via the production of glomalin-related soil proteins (GRSP), which improves soil structure and carbon sequestration (Zhou *et al.,* 2020). This supported wheat crop better soil physical conditions, further enhancing root colonization and nutrient acquisition.

Enhanced chlorophyll content suggests that AMF supports photosynthetic mechanism under salt stress conditions due to reduced Na^+ toxicity and improved P, N and micronutrient uptake mediated by AMF. The maximum grain yield recorded in FGD100GR AMF treatment combination supports the potential of integrated soil management in reclaiming degraded lands. The 36% increase in grain yield over control highlights the importance of FGDG and AMF, both alone and in combination.

CONCLUSION

The application of FGDG, particularly at 100% GR, significantly improves soil health and enhanced wheat growth and yield in sodic soils. The addition of AMF further amplified these benefits by promoting nutrient uptake, improving physiological traits and increasing plant resilience under sodic soil. The combined use of FGDG and AMF led to enhanced grain yield, spike characteristics, straw biomass and chlorophyll content. These findings highlight the potential of integrating chemical (FGDG) and biological (AMF) amendments as a sustainable and efficient strategy for the reclamation of salt-affected soils. Moreover, the utilization of FGDG provided a productive use for an industrial by-product, reducing dependence on gypsum. However, long-term field studies are necessary to assess environmental safety, particularly with respect to heavy metal accumulation and soil microbial health.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

All methods, experimental research, and pot studies on plants complied with relevant institutional, national and international guidelines and legislation. Ethical approval was obtained from the Project Monitoring and Evaluation Cell headed by the Director, CSSRI, Karnal (India).

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