Synergistic Effects of Salicylic Acid, Hydrogel, and Sulphur Sources for Boosting the Yield of Rapeseed under Limited Irrigation

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Preserving global rapeseed production against water shortages requires innovative strategies to enhance crop resistance. Despite its importance, rapeseed remains a water-intensive crop, making traditional irrigation practices unsustainable. Recent studies have explored methods to improve water use efficiency, and this study focuses on applying bioregulators to increase rapeseed yield under water-limited conditions, thereby contributing to food security and sustainability. A field experiment was conducted at the Agricultural Research Farm of Lovely Professional University during the 2021–2022 and 2022–2023 rabi seasons. The experiment, arranged in a split-plot design with 24 treatments, involved gypsum, bentonite sulphur, and elemental sulphur as various sulphur sources in main plots and hydrogel (2.5 kg/ha) and salicylic acid (150 ppm) applications at flowering and pod formation stages in subplots treatments. Gypsum (S1) notably improved seed yield, root length, and root dry weight. Additionally, hydrogel and salicylic acid applied during 50% flowering and 50% pod development (A6) produced the highest seed yield, root length, and root dry weight. This treatment also enhanced siliqua length and seed count, indicating the potential of gypsum and bioregulators in improving *Brassica napus* L. production under water-limited conditions.

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INTRODUCTION

Oilseed crops have a unique significance in the recent era of the energy crisis, as they play a prominent role in the agricultural industries and export trade. In India, the production of oilseeds has seen substantial growth, estimated at 414 lakh tons of oilseeds from 2022 to 2023, increasing by 34 lakh tons from 2021 to 2022 (Ministry of Agriculture and Farmers Welfare 2023). *Brassica napus* L. and *Brassica juncea* are significant members of oil seed crops grown in many temperate and subtropical regions of the world, especially in arid and semi-arid environments (Ashraf and McNeilly 2004; Mahto *et al*. 2023). India is the fourth-largest global producer of rapeseed mustard, producing 8.5 million tons, followed by China, Canada, and the European Union (USDA 2023). Between 2020 and 2023, the area planted with mustard and rapeseed has increased 29%, from 68.6 lakh ha to 88.6 lakh ha (Ministry of Agriculture and Farmers Welfare 2023). Indian mustard (*Brassica juncea* Cosson and Czern L.) is the most common oilseed crop, covering 80% of rapeseed mustard growing land and 31.3% of edible oilseed production (Rathore *et al.* 2020). According to the reports, India imported about ₹1.38 lakh crore of edible oil from 2022 to 2023, compared to ₹1.57 lakh crore in 2021 to 2022.

Rapeseed and mustard from the Brassicaceae family exhibit several similarities. Rapeseed oil contains low erucic acid, rendering it more suitable for human consumption, although mustard oil, characterized by its strong aroma, is more conventional, making rapeseed and mustard complementary in agronomic research and production. Mustard seeds' oil (37% to 49%) is used for diverse purposes: cooking, frying, vegetable ghee, hair oils, medicines, soap making, lubrication, and grease production. It also serves organic fertilizer and feeds livestock. (Bhowmik *et al.* 2014; Meena *et al.* 2023). Mustard production is viable; however, drought, salinity, severe temperatures, and biotic stresses such as pests and diseases can reduce yields. Water stress constitutes a major abiotic challenge that drastically decreases yield. Global water scarcity adversely impacts Indian agriculture, resulting in diminished mustard yields. Water stress, delayed precipitation, and diminished soil moisture reserves result in India's production falling below the global average (Rathore *et al.* 2020b). Therefore, farmers are adopting a variable double cropping method for mustard and beans due to the unpredictable weather patterns, the drop in groundwater tables, and the need for irrigation water (Jain *et al.* 2021; Chakraborty *et al.* 2023).

These challenges can be effectively addressed by adopting suitable and sustainable management practices. Implementing strategies such as the use of superabsorbent polymers and stress mitigators, *viz.*, hydrogel and salicylic acid treatments, can play a crucial role in preserving moisture, alleviating environmental stress, and enhancing soil water retention (Kaur *et al.* 2023; Malik *et al.* 2023)

The increasing water scarcity and diminishing groundwater levels threaten agricultural viability, especially for water-dependent crops such as rapeseed. Pusa hydrogel, a granular form superabsorbent polymer developed by the Indian Council of Agricultural Research (ICAR), was incorporated into the study to mitigate water stress, especially under low water availability settings. The use of superabsorbent polymers with high water holding capacity, biocompatibility, and synthetic flexibility, as well as precise irrigation scheduling and fertigation, under water shortage conditions, builds new hopes for improving crop productivity and water use efficiency (WUE) by enhancing water relations in sandy soils (Manjula *et al.* 2017; Giweta and Garedew 2020). These polymers lock down rainwater and available moisture, releasing it gradually, depending on the crop's water needs, thereby increasing the irrigation interval (Palanivelu *et al.* 2022). The 'hydrogel', a novel semi-synthetic superabsorbent polymer, has shown its potential to achieve higher crop yields in limited water conditions. It can absorb water up to 400 times its weight and gradually release it. Additionally, it has been reported to enhance soil hydro-physical properties such as porosity, aggregate stability, and hydraulic conductivity (Dar *et al.* 2017). Pusa hydrogel is suitable for prolonged agricultural application owing to its biodegradable properties, non-toxic formulation, and tiny ecological impact. It decomposes gradually without producing harmful leftovers, thus safeguarding soil health and microbiological activity. It enhances root development and mitigates the risk of waterlogging by conserving moisture and strengthening soil structure. Moreover, its minimal application rate (2.5 to 5 kg/ha) mitigates the risk of overuse, while its function in water conservation reduces nutrient leaching and salinization. Pusa hydrogel, developed by

ICAR for agricultural use, has undergone comprehensive testing for safety and efficacy, rendering it a sustainable option for enhancing water use efficiency.

Salicylic acid (SA), a phytohormone, regulates plant growth, development, and defense against environmental stresses by increasing plant response to biotic and abiotic stress conditions and System Acquired Resistance (Arif *et al.* 2020; Vishnu *et al.* 2021). It acts as an essential signaling molecule that adds to tolerance against abiotic stresses by activating the antioxidative defense mechanism by decreasing ethylene production and increasing production of osmolytes such as proline and glycine betaine (Landge *et al.* 2023). Numerous studies have demonstrated that SA is crucial in modulating plant responses to various environmental stressors, *viz.*, metal toxicity, osmotic stress, chilling, drought, and thermogenesis (Ali Aazami *et al.* 2014; Guo *et al.* 2019; Wassie *et al.* 2020; Mohi-Ud-din *et al.* 2021; Kumar *et al.* 2022). When applied with hydrogel, it increases the tolerance against stress by regulating the redox balance and some physiological processes under photosynthesis and stomatal conductance (Nazar *et al.* 2015).

Sulphur uptake by crops equals that of phosphorus, except for legumes and crucifers, which require more sulphur than phosphorus (Verma *et al.* 2020). Oilseeds need more sulphur for oil synthesis and bold grain formation (Kumar Udayana *et al.* 2021a). It is crucial in various metabolic processes, root development, drought and cold tolerance, disease and pest control, and crop residue decomposition. Soil sulphur deficiencies arise from inadequate residue recycling, leaching, erosion, and insufficient sulphur-containing fertilizer application, resulting in sub-optimal yields (Ghosh 2012). Sulphur application, including fertilizers and soil amendments such as gypsum, has improved soil properties and availability, with slow-release sources reducing leaching losses.

There are several sources of sulphur, for example, elemental sulphur, ammonium sulphate, superphosphate, rock phosphate, basic slag, sulphate of potash, pyrite, bentonite sulphur, gypsum, *etc*. However, the right source of sulphur should be selected based on the soil's leaching potential, pH, and organic matter content (Mp *et al.* 2022). Another factor that needs to be considered is the requirement for extra nutrients in the sulphur fertilizer. The choice of a particular fertilizer source will also be influenced by the need for an instantly soluble source of sulphur (Zenda *et al.* 2021). Mustard responds to sulphur well, but its behaviour depends upon the sources of sulphur used. As reported in studies, S nutrition, when combined with N and P applications, can enhance enzymatic activities, protein synthesis, and nodulation activities (Sheoran *et al.* 2016; Rashmi *et al.* 2018).

Considering the effect of hydrogel and SA with the combination of different sources of sulphur in the plants under water-restricted conditions, it was hypothesized that these three may synergistically enhance plant growth and development, which may also affect the oil quality and quantity. Therefore, to choose the appropriate source, the current study was undertaken to investigate the synergetic impact of treatments on the growth and productivity of rapeseed under limited irrigation conditions and aim to explore the effective potential strategy for enhancing crop resilience and improving yield in a water-limited environment.

EXPERIMENTAL

Site Description and Soil Characteristics

This study was performed at the Agronomy Research Farm of Lovely Professional University in Phagwara, Punjab, throughout two consecutive rabi seasons of 2021 to 2022 and 2022 to 2023. The study farm is generally 234 m above sea level, with dimensions of 31.2°N latitude and 75.7°E longitude. The area experiences a sub-tropical and semi-arid environment highlighted by extreme summer and winter temperatures. The mean annual precipitation in this region is approximately 700 mm, with most rainfall concentrated in the monsoon season from July to September. In both experimental years, the soil of the experimental field underwent an intensive physicochemical evaluation. The mechanical analysis in Table 1 determined the average values in 2021 and 2022. The soil consisted of 20.9% coarse sand, 58.9% fine sand, 11.4% silt, and 8.9% clay. As a result, the soil falls under the textural class of loamy sand according to the International Pipette method (Piper 1966).

Table 1. Soil Mechanical Analysis of the Experimental Field During Rabi Season of 2021 to 2022

Particulars	2021 to 2022
Coarse Sand (%)	20.9
Fine Sand (%)	58.9
Silt (%)	11.4
Clay (%)	8.9
Textural Class	Loamy Sand

Table 2. Physio-chemical Properties of Soil

Particulars	2021	2022
Physical Properties		
Bulk Density (Mg/m^3)	1.55	1.52
Particle Density (Mg/m^3)	2.63	2.59
Porosity (%)	40.6	41.1
Field Capacity (%)	12.9	12.7
Permanent Wilting Point (%)	2.64	2.69
Chemical Properties		
Organic Carbon (%)	0.23	0.27
Available N (kg/ha)	130	132
Available P_2O_5 (kg/ha)	16.2	15.4
Available K_2O (kg/ha)	148	147
Available S (mg/ha)	9.20	9.24
EC at 25 °C (dS/m)	1.22	1.19
Soil pH (1:2 soil water suspension)	8.21	8.15

The physio-chemical properties of soil are shown in Table 2, where soil's bulk density was measured at 1.55 mg/m^3 in 2021 and 1.52 mg/m^3 in 2022, while the particle density was 2.63 mg/m^3 and 2.59 mg/m^3, respectively. In 2021, the soil's porosity measured 40.6%, which experienced a little increase to 41.1% in 2022. The field capacity in 2021 was 12.9%, but it declined slightly to 12.7% in 2022. In 2021, the permanent wilting point was recorded at 2.64%; in 2022, it increased slightly to 2.69%. As Walkley and Black's quick titration method (Jackson 1973) measured, the soil organic carbon content was 0.23% in 2021 and increased to 0.27% in 2022. The nitrogen (N) level in 2021 was measured to be 130 kg/ha using the alkaline $KMnO_4$ method (Subbiah and Asija 1956). In 2022, the N-content marginally rose to 132 kg/ha. In 2021, the phosphorus (P_2O_5) concentration was measured to be 16.2 kg/ha using Olsen's technique (Olsen *et al.*1954). In 2022, the P-level declined to 15.4 kg/ha. The potassium (K_2O) concentration measured using the Flame Photometric technique (Jackson 1973) was 148 kg/ha and 147 kg/ha in 2021 and 2022, respectively. The sulphur (S) level in 2021 was measured to be 9.20 mg/ha using the Chesnin and Yien method (1951). In 2022, there was a small increase in S-content to 9.24 mg/ha. In 2021, the soil's electrical conductivity (EC) at a temperature of 25 °C was measured to be 1.22 dS/m. In 2022, there was a minor decrease in the EC, with a recorded value of 1.19 dS/m. In 2021, the pH of the soil-water suspension, measured at a ratio of 1:2, was 8.21. In 2022, it slightly declined to 8.15.

Meteorological Data During the Crop Growth

Variations in temperature and precipitation were observed in the weather data from 2021 to 2023. The temperature ranged from 2°C in early January 2022 to 45°C in late April 2022. Precipitation reached around 25 mm in mid-February 2022 and decreased in winter and spring, as shown in Fig. 1. Furthermore, temperatures ranged from a minimum of 5 °C to the highest of 40 °C from October 2022 to April 2023. The most rain was 30 mm in November 2022, January, March, and April 2023, as shown in Fig. 2. Across two years, the data emphasizes temperature variations and sporadic substantial rainfall.

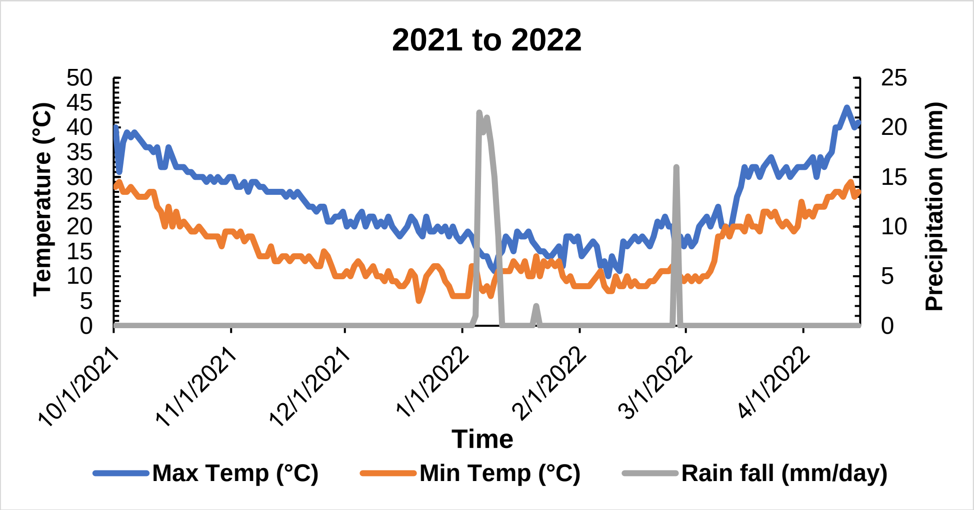

Fig. 1. Standard meteorological mean maximum and minimum temperatures (°C) and average mean precipitation (mm) during the crop season of 2021 to 2022

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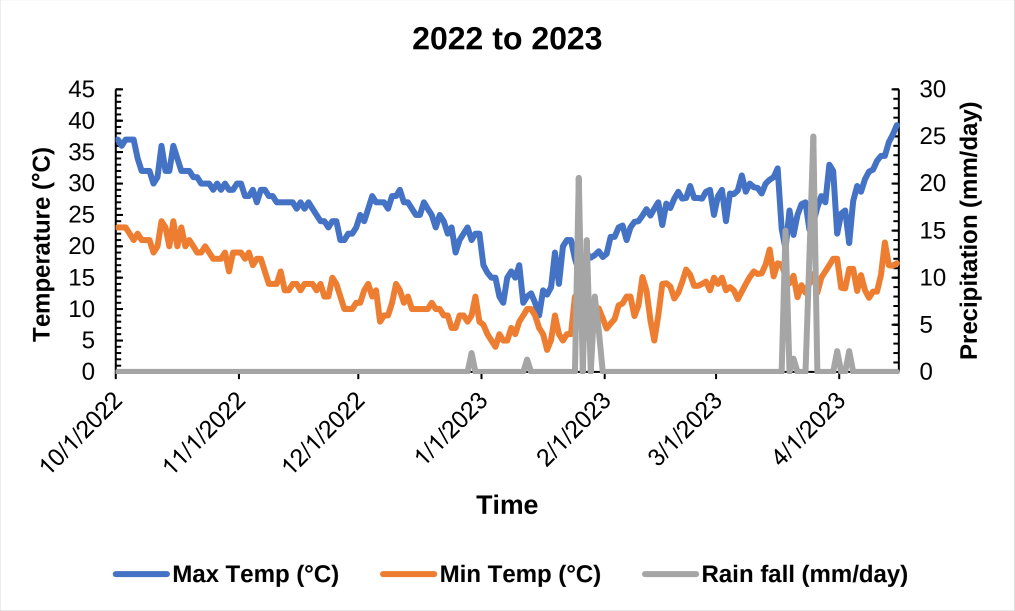

Fig. 2. Standard meteorological mean maximum and minimum temperatures (°C) and average mean precipitation (mm) during the crop season of 2022 to 2023

Cropping System and Seed Description

Evaluating the planting potential of an experimental field based on its cropping history requires assessing several factors, including soil health, crop diversity, productivity patterns, and management techniques. A diverse cropping pattern that includes sesame, barley, cluster beans, and mustard reflects the field's resilience to varying nutrient demands and its capacity for sustainable crop rotation. The field has successfully sustained four years of continuous agriculture without a significant decline in yields, demonstrating robust soil fertility and structural integrity. Additionally, effective crop rotation promotes nutrient cycling and helps reduce the buildup of pests and diseases.

Yield records and soil analyses from previous seasons provide valuable insights into the field's production trends and nutrient status, highlighting its capability for intensive cultivation. Including legumes, such as cluster beans, in the crop rotation increases nitrogen levels, enhancing soil quality for future crops. Furthermore, effective irrigation management and adaptability to environmental changes—including temperature and water availability fluctuations—further improve the field's planting potential. The historical diversity of cropping and consistent productivity suggests the field is well-suited for further agricultural studies and future experiments.

GSC-7 was selected for the study because it aligns with the Package of Practices for Rabi Crops recommended by Punjab Agricultural University (PAU) in Ludhiana for cultivating Gobhi Sarson (*Brassica napus* L.) in the agro-climatic conditions of Punjab. This high-yielding, double-zero cultivar is well-adapted to the subtropical and semi-arid conditions of the region. It is ideally suited for the rabi cropping season, with a medium maturity period of approximately 150 days. GSC-7 was chosen due to its high oil content (around 40%), low levels of erucic acid, and impressive yield potential of 20 to 22 quintals per hectare under optimal management conditions. Additionally, it shows significant resilience to abiotic stresses such as drought and elevated temperatures, factors tested in this study by omitting irrigation. The inclusion of this variety in PAU's recommended list underscores its suitability for local agricultural systems, making the findings of this study practical and applicable to local farmers.

Experiment Outline

The experiment employed three different sources of sulphur in the main plots and hydrogel and SA in eight subplots. It resulted in 24 treatment combinations arranged in a split-plot design and replicated thrice. The experimental treatments include applying hydrogel @ 2.5 kg/ha as a basal dose and a foliar spray of SA at @150 ppm at different subplot stages. The A0 treatment served as absolute control and received recommended irrigation. Other treatments were A1: hydrogel@ 2.5 kg/ha at basal dose, A2: SA@ 150 ppm at 50% flowering, A3: SA@150 ppm at 50% pod formation, A4: hydrogel @2.5 kg/ha + SA@150 ppm at 50% flowering, A5: hydrogel @ 2.5 kg/ha + SA@ 150 ppm at 50% pod formation, A6: hydrogel @ 2.5kg/ha + SA@150 ppm at 50% flowering + 50% pod formation, and A7: Control (Restricted irrigation). The main plots were aligned with three different S-sources: S1 - Gypsum, S2 - Bentonite Sulphur, and S3 - Elemental Sulphur. All treatments (A1 to A7) were given restricted irrigation.

Crop Watering Schedule

A systematic technique is needed to manage irrigation in 576 m^2 ($24 \times 3 = 72$ plots) for the 150-day-maturing GSC-7 mustard variety to maximise growth and production. As per the recommendations of PAU, the initial irrigation should be done 30 to 35 days after sowing (DAS) at the rosette stage, using 34,560 L to 40,320 L of water. This provides enough moisture for growing roots and leaves. The second irrigation offers 60 to 65 DAS during blooming when water uptake needs to rise to support flower production. The third irrigation occurs 90 to 95 DAS during pod production, requiring 34,560 L to 40,320 L to maintain requisite soil moisture. To keep seed weight and oil content, a fourth irrigation of 120 to 125 DAS is needed during seed filling, requiring 34,560 L to 40,320 L. If conditions are dry, a fifth irrigation at 140 to 145 DAS of 28,800 L to 34,560 L of water may be given to finish seed development. Total water needs for the growth season are 166,560 L to 196,320 L. This irrigation strategy maximizes mustard output and quality by moistening plants during critical growth stages.

Irrigation control was a vital component of this experiment. It was intended to replicate water limitation situations and to assess how they affected *Gobhi* Sarson's growth and yield. The irrigation schedule was carefully prepared using a baseline of advised irrigation techniques for control treatments. Water was purposefully withheld for the restricted irrigation treatments during two crucial irrigation cycles: the first irrigation skipped 30 to 35 days after sowing (DAS) at the rosette stage, and the second irrigation skipped during 90 to 95 DAS during pod production. This strategy was chosen to simulate possible water stress situations that crops could encounter in the actual world, especially in areas with limited water resources. The purpose of delaying the first irrigation after planting was to evaluate the plant's capacity to form roots and adjust to the early stages of growth in the presence of restricted water. Similarly, the purpose of delaying the last irrigation during pod formation was to assess the effects of water stress on pod growth and total yield at a later developmental stage. Salicylic acid and hydrogel were utilized to lessen the negative consequences of these water-stress circumstances.

The PUSA hydrogel, a cellulose-based hydrogel developed at the Indian Agricultural Research Institute, has a capacity for water retention up to 300 times its weight and was used in the present work. The granular variant of Pusa hydrogel was mixed into the soil at the root zone, enhancing water retention concerning the plant's roots. The SA has been playing a key role in helping plants deal with water stress. It regulates water balance, boosts antioxidants, activates stress signals, modulates hormones, protects membranes, promotes root growth, and induces stomatal closure. These processes help plants adapt to drought, improving their survival in water-stressed environments.

In addition to hydrogel and SA, S was applied at 40 kg/ha with three different sources: gypsum, bentonite, or elemental sulphur. Their S-contents were 18%, 50%, and 90%, respectively. In each case, the material was incorporated into the soil thoroughly before sowing. Hydrogels support the growth of the root through water absorption, where it retains it in the soil to maintain a consistent level of moisture, which is vital for development. This is helpful in places where there is an extreme shortage of water. They improve soil structure by increasing porosity and reducing compaction, which helps with increased root penetration, aeration, and nutritional uptake. Most hydrogels, therefore, release these nutrients slowly to ensure that the root is constantly fed and that availability is maximized. There is also a reduction in frequent fertilization because they free the root from stresses during bad weather through the maintenance of soil moisture. Their water-holding ability ensures that irrigation can be done less frequently to conserve water and reduce labour, making it eco-friendly. Hydrogels also enhance seed germination by optimizing the moisture for sprouting and strong root growth. Salicylic acid enhances hydrogel properties by positively affecting plant stress and improving root growth. It is a phytohormone in growth activities, photosynthesis, and defense. In drought stress, SA induces water-use efficiency and activates a stress pathway to enhance plant resilience against heat and low water conditions. Integrating hydrogels with SA enhances root growth, especially under conditions where water and nutrient management must be carried out for plants to survive.

The seed application level was 5 kg/ha with 45 × 15 cm^2 interspacing. A thinning operation was carried out at 15 to 20 DAS to keep the plant population stable. The NPK fertilizers were applied uniformly at 120:60:40 kg/ha in the form of urea, diammonium phosphate, and muriate of potash. Throughout the entire plot, all inter-cultivation operations were maintained uniformly. The crop was hand-harvested yearly according to treatments at the physiological maturity stage.

The data obtained from the experiment followed statistical analysis using Statistix 10 software (Analytical Software, Tallahassee, FL, USA) to ascertain the relevance of the treatments on the growth, yield, and yield attributes of rapeseed. The two-way analysis of variance (ANOVA) was conducted to assess the significance of the main effects and interactions among the treatments. The means were compared using the Least Significant Difference (LSD) test at a significance level of 0.05%.

RESULTS AND DISCUSSION

Root Length and Root Dry Weight

Healthy plants and efficient nutrient uptake depend on root length and dry weight. Root dry weight signifies biomass investment in the root system, while longer root lengths improve water and nutrient access. Treatments such as sulphur spraying affect these values, revealing nutrient consumption efficiency. Root development requires sulphur, which affects protein synthesis and enzyme activity, impacting root design and plant growth in Gobhi Sarson (*Brassica napus* L.). Significant variations were observed in root length among different sources of sulphur and agrochemicals treatments in both the years (2021 and 2022). This was apparent in the overall pooled data shown in Table 3.

Among the other sources of sulphur, gypsum (S1) consistently produced the most extended root length with a combined value of 8.83 cm, which was much greater than the root lengths recorded with bentonite sulphur (S2) and elemental sulphur (S3) in both years. The shortest root lengths were recorded with elemental sulphur (S3), with an average value of 8.04 cm. The crucial difference (CD) with a significant level of 0.05 for the substantial influence in S-sources ranged from 0.46 to 0.74 cm over the years. Considerable variations were observed in the effects of different agrochemical treatments. The treatment that used hydrogel @ 2.5 kg/ha, combined with SA at a concentration of 150 ppm, applied at both 50% flowering and 50% pod development (A6), produced the longest roots with a pooled value of 9.10 cm. The roots in the control treatment under restricted irrigation (A7) were the shortest, measuring 7.73 cm on average. However, the roots of the treatment mentioned earlier were much longer. These findings indicate that combining hydrogel and SA during crucial growth phases greatly enhances root elongation in experimental settings.

Table 3. Effect of Superabsorbent Polymer and Salicylic Acid and Different Sulphur Sources on Root Length and Root Dry Weight of *Gobhi* sarson's (*Brassica napus* L.)

Treatments	**Root Length (cm)**			**Root Dry Weight (g)**		
	2021	2022	Pooled	2021	2022	Pooled
Sources of Sulphur						
S1: Gypsum	8.78^{a}	8.87^{a}	8.83^{a}	62.4^{a}	63.9^{a}	63.2^{a}
S2: Bentonite Sulphur	8.50^{a}	8.52^{ab}	8.51^{ab}	60.2^{a}	61.8^{a}	61.0^{a}
S3: Elemental Sulphur	8.02^{b}	8.07^{b}	8.04^{b}	52.3^{b}	53.6^{b}	52.9^{b}
CD (p = 0.05)	0.46	0.74	0.57	5.3	5.1	5.18
Agrochemicals						
A0: Control (Irrigation as per requirement)	8.98^{a}	8.69^{abc}	8.83^{ab}	65.1^{a}	65.1^{a}	65.1^{a}
A1: Hydrogel @ 2.5 kg/ha at basal dose	8.32^{c}	8.36^{bcd}	8.34^{cd}	55.9^{cd}	57.9^{c}	56.9^{c}
A2: Salicylic acid @ 150 ppm at 50% flowering	8.10^{c}	8.16^{de}	8.13^{d}	53.8^{d}	56.0^{c}	54.9^{c}
A3: Salicylic acid @ 150 ppm at 50% pod formation	8.11^{c}	8.22^{cde}	8.17^{d}	54.0^{d}	57.0^{c}	55.5^{c}
A4: Hydrogel @ 2.5 kg/ha + salicylic acid @ 150 ppm at 50% flowering	8.75^{ab}	8.81^{ab}	8.78^{ab}	58.4^{c}	61.8^{b}	60.1^{b}
A5: Hydrogel @ 2.5 kg/ha + salicylic acid @ 150 ppm at 50% pod formation	8.47^{bc}	8.75^{ab}	8.61^{bc}	61.9^{b}	61.5^{b}	61.7^{b}
A6: Hydrogel @ 2.5 kg/ha + salicylic acid @ 150 ppm at 50% flowering + at 50% pod formation	9.05^{a}	9.15^{a}	9.10^{a}	66.2^{a}	66.0^{a}	66.1^{a}
A7: Control (Restricted irrigation)	7.69^{d}	7.77^{e}	7.73^{e}	51.0^{e}	53.0^{d}	52.0^{d}
CD (p = 0.05)	0.39	0.48	0.39	2.7	2.8	2.75

Furthermore, the treatments had a considerable impact on the dry weight of the roots. Gypsum (S1) resulted in the most significant root dry weight compared to other S-sources, with a combined value of 63.2 g. Bentonite sulphur (S2) followed closely with a dry weight of 61.0 g. However, using elemental sulphur (S3) led to the lowest root dry weight, measuring 52.9 g when combined. The CD at a significance level of 0.05 varied between 5.1 g and 5.3 g during the years, suggesting that the observed differences were statistically significant. In the agrochemical treatments, treatment A6, which consisted of hydrogel at a level of 2.5 kg/ha and salicylic acid at a concentration of 150 ppm during both 50% blooming and 50% pod formation, resulted in the highest root dry weight. The average value for this treatment was 66.1 g, which was significantly more than the root dry weight of all other treatments. Conversely, the control group subjected to limited irrigation (A7) exhibited the lowest root dry weight, at 52.0 g. The observed pattern indicates that the combined action of hydrogel and SA greatly amplifies the amount of root biomass, most likely because of the enhanced ability to retain water and alleviate stress during crucial stages of growth.

The application of hydrogel improved the growth attributes of rapeseed, which was attributed to its ability to hold moisture and improve water use efficiency. This enables the rhizosphere to maintain ideal soil moisture levels for longer, ultimately promoting nutrient availability and vital physiological processes primarily responsible for regulating and promoting plant growth. Salicylic acid, however, is known to act as a defense hormone. Several studies have demonstrated that SA regulates plant responses against diverse abiotic challenges, such as metal toxicity, thermogenesis, chilling, drought, and osmotic stress (Khan *et al.* 2015; Nadarajah *et al.* 2021; Yang *et al.* 2023). Further, exogenous application of SA through leaves showed its effectiveness in boosting plant height and branching, facilitating overall crop development. Various scientific studies have also revealed the role of sulphur sources, hydrogel, and SA, individually or in combination, in mitigating stress by imparting resistance *via* the activation of the oxidative defense mechanism. Recent studies also revealed the involvement of SA in mitigating the imposed moisture stress on rapeseed plants by limited irrigation through improved nutrient uptake, soil health, and stress tolerance and by increasing oil content, thus maintaining overall growth and development. (Kumar Udayana *et al.* 2021b; Mahto *et al.* 2023b). Treatment A6 involved actively adopted alternatives at each crucial growth stage to enhance root development, distinguishing it from other treatments. Hydrogel at 2.5 kg/ha was applied at the basal stage to improve soil moisture retention and nutrient accessibility in the root zone, thereby establishing ideal conditions since the beginning. Furthermore, salicylic acid at 150 ppm was used at two critical crop growth stages—50% flowering and 50% pod formation—offering sustained physiological support to the plants. The dual-stage administration of salicylic acid functioned as a growth regulator, boosting stress tolerance, enhancing metabolic efficiency, and stimulating hormonal activity throughout these critical phases. By integrating these interventions during the initial and later growth phases, treatment A6 achieved persistent enhancements in root length and dry weight, surpassing other treatments lacking such comprehensive techniques.

Length of Siliqua and Number of Seeds per Siliqua

Gypsum (S1) consistently resulted in the most extended siliqua length of 5.41 cm and the maximum number of seeds per siliqua (average of 13.3), among the different sulphur sources shown in Table 4. The exceptional performance can be attributed to the abundant sulphate ions supplied by gypsum, which might have played a vital role in essential physiological processes such as siliqua production, elongation, and seed setting. The performance of bentonite sulphur (S2) was moderate. In contrast, elemental sulphur (S3), due to its slower oxidation and consequent sulphate release, resulted in the shortest siliqua length and the lowest quantity of seeds per siliqua.

Agrochemical treatments have an additional impact on these characteristics. The use of a treatment that combines hydrogel along with SA at both the blooming and pod formation stages (A6) resulted in the longest siliqua, with an average length of 5.42 cm, and the maximum number of seeds per siliqua, with an average of 13.7 seeds. This combination is likely to have boosted the plant's ability to retain moisture, which is vital in semi-arid circumstances. It also strengthened the plant's ability to tolerate stress, resulting in better development of siliqua (seed pod) and generation of seeds. In contrast, the control treatment with limited irrigation (A7) exhibited the smallest siliqua and the lowest number of seeds per siliqua, highlighting the negative effect of water stress on these reproductive characteristics.

Sulphur is an essential component of some amino acids and is involved in protein synthesis. Moreover, sufficient amounts of sulphur promote effective photosynthesis, increased siliqua length, and seed count by boosting chlorophyll synthesis, enzyme activation, and protein synthesis, accelerating biomass production and producing higher yields (Nagaram 2020). In this study, as influenced by different sulphur sources, gypsum application showed superior growth and yield. Further, sufficient S availability promotes a better seed set, maximizing yield attributes (Parmar *et al.* 2018). Therefore, a lack of S might result in smaller and poorer-set seeds, ultimately lowering output. The different sources of S vary in sulphate sulphur forms and thus differ in their availability, such as gypsum or ammonium sulphate, which contain sulphate forms readily available for plant uptake. In contrast, elemental S must be oxidized to sulphate before plants can utilize it. However, elemental sulphur tends to be immobile in the soil and does not leach easily, unlike sulphate forms (Kaiser 2013). The superior performance of treatments involving gypsum application may stem from the immediate availability of S, which is crucial during the vegetative phase. Additionally, gypsum promotes the formation of reproductive structures in plants by enhancing sink capacity and facilitating the efficient transfer of photo-assimilates from source to sink within the plant (Rameeh *et al.* 2021).

The higher effectiveness of treatment A6 (hydrogel @ 2.5 kg/ha + salicylic acid @ 150 ppm at 50% flowering and 50% pod formation) can be attributed to its systematic and stage-targeted methodology. Hydrogel maintained uniform soil moisture, essential for reproductive growth, whereas salicylic acid improved hormonal equilibrium, stress resilience, and enzymatic functions during blooming and pod development. The cumulative effects led to elongated siliqua and an increased seed count per siliqua relative to alternative treatments. Conversely, treatments such as A1, A2, and A3 utilizing single applications of hydrogel or salicylic acid yielded limited advantages but were devoid of the synergistic impact observed in dual-stage interventions. Treatments A4 and A5, which involved combined applications at a single stage, exhibited superior performance compared to individual treatments; however, they were less successful than A6 due to the restricted support length. Restricted irrigation (A7) showed the least effective performance owing to moisture stress. Consequently, A6 exceeded other treatments by enhancing growth at each critical phase.

Therefore, it can be affirmed that the inclusion of innovative approaches, *viz.*, application of superabsorbent polymer-hydrogel and stress-mitigators, such as SA, in the present study have proven to be promising alternatives to improve growth and yield under restricted irrigations. As mentioned, hydrogels can hold much water, stabilizing soil moisture during droughts. SA activates the plants' defensive mechanisms, helping them overcome stress and improve resilience and productivity under stress (Meena *et al.* 2020). Additionally, it has been documented that the inhibition of ethylene synthesis under stress conditions, possibly due to foliar spray, influences proline metabolism and photosynthesis, ultimately leading to superior growth of rapeseed (Liu *et al.* 2022).

Table 4. Effect of Superabsorbent Polymer and Salicylic Acid and Different Sulphur Sources onLength of Siliqua and Number of Seeds per Siliqua of *Gobhi* sarson's (*Brassica napus* L.*)*

Treatments	**Length of Siliqua**			**No. of Seeds per Siliqua**		
	2021	2022	Pooled	2021	2022	Pooled
Sources of Sulphur						
S1: Gypsum	5.37^{a}	5.46^{a}	5.41^{a}	13.3^{a}	13.3^{a}	13.3^{a}
S2: Bentonite Sulphur	5.15^{b}	5.22^{b}	5.19^{b}	12.7^{b}	12.9^{b}	12.8^{b}
S3: Elemental Sulphur	4.34^{c}	4.38^{c}	4.36^{c}	11.3^{c}	11.4^{c}	11.4^{c}
CD (*p* = 0.05)	0.04	0.04	0.04	0.07	0.06	0.07
Agrochemicals						
A0: Control (Irrigation as per requirement)	5.21^{b}	5.26^{b}	5.24^{b}	13.2^{b}	13.3^{b}	13.2^{b}
A1: Hydrogel @ 2.5 kg/ha at basal dose	4.96^{e}	5.01^{e}	4.98^{e}	12.2^{e}	12.5^{e}	12.3^{e}
A2: Salicylic acid @ 150 ppm at 50% flowering	4.76^{g}	4.88^{g}	4.82^{g}	11.9^{g}	12.0^{g}	11.9^{g}
A3: Salicylic acid @ 150 ppm at 50% pod formation	4.82^{f}	4.92^{f}	4.87^{f}	12.0^{f}	12.2^{f}	12.1^{f}
A4: Hydrogel @ 2.5 kg/ha + salicylic acid @ 150 ppm at 50% flowering	5.11^{c}	5.21^{c}	5.16^{c}	12.8^{c}	12.9^{c}	12.8^{c}
A5: Hydrogel @ 2.5 kg/ha + salicylic acid @ 150 ppm at 50% pod formation	5.05^{d}	5.11^{d}	5.08^{d}	12.7^{d}	12.7^{d}	12.7^{d}
A6: Hydrogel @ 2.5 kg/ha + salicylic acid @ 150 ppm at 50% flowering + at 50% pod formation	5.39^{a}	5.44^{a}	5.42^{a}	13.6^{a}	13.7^{a}	13.7^{a}
A7: Control (Restricted irrigation)	4.29^{h}	4.35^{h}	4.32^{h}	11.0^{h}	11.2^{h}	11.1^{h}
CD (*p* = 0.05)	0.04	0.03	0.03	0.06	0.06	0.05

Seed Yield

In 2021 and 2022, *Brassica napus* seed yield varied with the treatment, showing that S-sources and agrochemicals had a significant impact, as shown in Table 5. Gypsum (S1) consistently produced the highest seed production among various S-sources, with a pooled average of 20.1 q/ha, demonstrating its ability to provide a balanced supply of essential nutrients including sulphur and calcium required for plant growth. With a pooled output of 18.1 q/ha, Bentonite-S (S2) was effective but slower to release than gypsum. Elemental-S (S3) yielded the least at 14.1 q/ha, perhaps because it required microbial oxidation to become plant-accessible. Hydrogel and SA at flowering and pod formation under treatment A6 yielded the highest seed yield of 20.3 q/h. Hydrogel's moisture retention and salicylic acid's stress tolerance may have enhanced yields by improving various physiological and biochemical processes, thereby establishing a better source-to-sink relationship. The control treatment with appropriate irrigation (A0) yielded 19.3 q/ha, showing the importance of water supply. The restricted irrigation control (A7) yielded the least at 14.0 q/ha, demonstrating how water stress affects seed output. Treatment A6 (hydrogel at 2.5 kg/ha with salicylic acid at 150 ppm during 50% flowering and 50% pod formation) attained the maximum seed production owing to its synergistic methodology. Hydrogel maintained uniform soil moisture, essential for nutrient absorption and seed growth, whereas salicylic acid enhanced physiological efficiency, stress resilience, and hormonal equilibrium throughout two pivotal growth phases. This dual-stage application enhanced reproductive efficiency, yielding greater seed production than treatments involving single or less optimized interventions.

Table 5. Effect of Superabsorbent Polymer and Salicylic Acid and Different Sulphur Sources on Seed Yield

Treatments	**Seed Yield**		
	2021	2022	Pooled
Sources of Sulphur			
S1: Gypsum	19.9^a	20.3^a	20.1^a
S2: Bentonite Sulphur	18.0^b	18.2^b	18.1^b
S3: Elemental Sulphur	14.1^c	14.2^c	14.1^c
CD ($p = 0.05$)	0.43	0.47	0.44
Agrochemicals			
A0: Control (Irrigation as per requirement)	19.1^b	19.6^b	19.3^b
A1: Hydrogel @ 2.5 kg/ha at basal dose	16.6^d	16.9^e	16.7^d
A2: Salicylic acid @ 150 ppm at 50% flowering	15.4^f	15.7^g	15.6^f
A3: Salicylic acid @ 150 ppm at 50% podformation	16.1^e	16.2^f	16.1^e
A4: Hydrogel @ 2.5 kg/ha + salicylic acid @ 150 ppm at 50% flowering	18.3^c	18.5^d	18.4^c
A5: Hydrogel @ 2.5 kg/ha + salicylic acid @150 ppm at 50% pod formation	18.9^b	19.0^c	19.0^b
A6: Hydrogel @ 2.5 kg/ha + salicylic acid @150 ppm at 50% flowering + at 50% pod formation	20.2^a	20.5^a	20.3^a
A7: Control (Restricted irrigation).	13.9^g	14.1^h	14.0^g
CD ($p = 0.05$)	0.41	0.42	0.40

Table 6 presents the correlation coefficients between various variables across two years (2021 to 2022 and 2022 to 2023), including seed yield (SY), root dry weight (RDW), root length (RL), number of siliquae (NOS), and length of siliquae (LOS). There was a significant positive correlation between SY and NOS and LOS in both years, with values of 0.98 and 0.97 in 2021 to 2022 and 0.97 and 0.96 in 2022 to 2023, respectively. This emphasizes that a larger SA was closely connected with increased NOS and LOS.

In addition, a significant correlation was observed between RDW and SY, with a value of 0.88 in both years. This demonstrates the association between root biomass and yield, which indicates that more root biomass was associated with better yields. This is because a well-developed root system improves the plant’s capacity to absorb water and nutrients more efficiently, both of which are necessary for optimal growth and the production of seeds.

In 2021 to 2022 and 2022 to 2023, the values of SY and RL were 0.78 and 0.71, respectively, indicating a moderate correlation between the two variables. In the same way, RL exhibited moderate correlations between RDW and NOS over both years. This suggests that although RL affects these variables, its influence is less significant than other parameters. Root-related attributes RDW and RL exhibited weak but still significant correlations with the production of seeds. At the same time, variables such as NOS and LOS showed the most robust relationships with SY. This highlights the importance of targeting both reproductive and root factors in breeding and cultivation strategies to maximize seed production.

Table 6. Pearson's Correlation Matrix for Root and Yield Parameters in the year 2022 to 2023

Year	2021 to 2022					2022 to 2023				
Variables	SY	RDW	RL	NOS	LOS	SY	RDW	RL	NOS	LOS
SY	1.00	0.88	0.78	0.98	0.97	1.00	0.88	0.71	0.97	0.96
RDW	0.88	1.00	0.73	0.88	0.85	0.88	1.00	0.72	0.89	0.87
RL	0.78	0.73	1.00	0.82	0.78	0.71	0.72	1.00	0.72	0.70
NOS	0.98	0.88	0.82	1.00	0.98	0.97	0.89	0.72	1.00	0.98
LOS	0.97	0.85	0.78	0.98	1.00	0.96	0.87	0.70	0.98	1.00

CONCLUSIONS

Sulphur is crucial for oil quality, but many Indian soils are deficient, resulting in poor oil quality and productivity. The experiment's findings show the vital importance of sulphur sources and agrochemical treatments in boosting root growth and overall plant performance.

1. Plant growth and soil health benefit most from gypsum's sulphur. Among the sulphur treatments, gypsum showed the highest effectiveness, leading to a seed yield of 20.1 q/ha, outperforming bentonite sulphur (18.1 q/ha) and elemental sulphur (14.1 q/ha). Gypsum provides readily available sulphur and promotes root elongation and biomass accumulation, improving plant water and nutrient access. Good soil structure improves aeration and drainage, especially in heavy clays. Gypsum adds calcium without affecting pH, improving soil health. It displaces sodium ions to lower soil salinity and enhances root development. Gypsum outperformed bentonite and elemental sulphur for controlled irrigation crops like Gobhi Sarson.
2. To address water stress conditions, hydrogel as an absorbent and salicylic acid as a stress mitigator during flowering and siliqua formation can alleviate moisture stress and enhance growth and yield. The combined application of hydrogel (2.5 kg/ha) and salicylic acid (150 ppm) at flowering and pod formation (treatment A6) resulted in the highest seed yield of 20.3 q/ha. This approach alleviated moisture stress, boosted siliqua length (5.42 cm), and improved seed number per siliqua (13.7). Furthermore, understanding the mechanisms behind these treatments can improve crop resilience.

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