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RESEARCH PAPER

Effects of lignite-based sulphur fertilizer levels on soil properties and growth of *Brassica napus*

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Abstract

Lignite and sulphur are instrumental in enhancing the growth and yield-related traits of Brassica napus, commonly known as rapeseed. This study aimed to explore the effects of lignite-based sulphur fertilizers on Brassica napus production. Spanning two consecutive seasons, the experiment included treatments with a control group, three levels of elemental sulphur (30, 40, and 50 kg ha^{-1}), and three levels of lignite-based sulphur fertilizer (30, 40, and 50 kg ha^{-1}). Employing a randomized complete block design with four replications, the study revealed that applying lignite-based sulphur fertilizer at a rate of 50 kg ha^{-1} led to significant improvements in various growth parameters, such as plant height, primary and secondary branches per plant, pods per plant, pod length, seeds per pod, biological yield, seed yield, thousand seed weight, and oil yield. Notably, substantially higher seed and oil yields were achieved with the application of 50 kg ha^{-1} of lignite-based sulphur fertilizer. In semi-arid climates, to maximize rapeseed yield, yield components, and quality, it is advisable to utilize lignite-based sulphur fertilizer at a rate of 50 kg ha^{-1}.

Keywords

Lignite, Elemental sulphur, Lignite-based sulphur fertilizer, *Brassica napus*

Introduction

Lignite is an organic material that contains between 50–70% carbon and has a strong capacity to reduce environmental stresses like salt and drought stress (Rehman et al. 2017). It is composed of naturally compressed peat and has the appearance of a soft, combustible, dark rock. It also includes substantial levels of humic and fulvic acid. It is utilized as a supplement when heavy metal stress is present and as a source of organic material to improve the fertility of degraded soils (Rehman et al. 2017). As compared to other organic compounds, it resists mineralization and breakdown better. It is mined in large quantities and is found abundantly globally (Rehman et al. 2017). Plant productivity and soil fertility are closely related, so it is important to pay attention to soil amendments to identify possible signs of improvement (Gerke 2022). By enhancing the soil's carbon pool, several soil additives, such as the use of biochar, straw mulching, animal slurry, and organic fertilizers, can improve soil fertility (Hamid et al. 2020).

Sulphur is a secondary macronutrient and is ranked as the fourth main element after nitrogen, phosphorus, and potassium in crop plants (Shah et al. 2022). It has a key role in oilseed crops for their nutrition and yield. By taking part in various plants metabolic processes, it contributes to their growth and development activities (Narayan et al. 2022). It plays significant functional roles in enzymes, vitamins, lipids, and other plant parts in addition to being essential for the synthesis of amino acids. As a limiting factor it cannot reach its full potential and it affects development processes (Shah et al. 2022). The greater production and quality of oilseed crops are attainable when they have access to the optimal level of sulphur (Raza et al. 2018; Mehmood et al. 2021). It enhances the uptake of crucial nutrients such as nitrogen (N), phosphorus (P), and potassium (K). Furthermore, additional research has demonstrated that sulphur enhances seed yield, oil content, and protein content (Raza et al. 2018). Sulphur in the form of fertilizer applied to soil acts as a slow-release fertilizer that requires rain to help distribution in the soil (Kulczycki 2021).

Agriculture is the backbone of Pakistan's economy and contributes 22.9% of gross domestic production (GDP). It plays a unique role in fostering the economic growth and development of the nation. The agriculture sector in Pakistan involves 37.4% of labour forces that produce their food and ensure the availability of food for the nation (GOP 2023). Edible oil production in Pakistan is insufficient to meet the growing needs of the fast-growing population as per capita consumption of edible oil is standing currently at 24 kg (Imran et al. 2023). Pakistan spends a huge amount of money on importing edible oil, which depletes its foreign exchange reserves. The total amount of edible oil available in Pakistan during 2022–2023 (July-March) was 3.177 million tonnes, only 15.6% of the nation's total demand is met by local production. To fulfil the need for edible oil in Pakistan, 2.754 million tonnes (costs Rs. 826.482 billion) was being imported into the country (GOP 2023; Qiu et al. 2023).

Most human food is made up of the oil derived from these crops, which is also a significant source of healthy fatty acids (Ahmad et al. 2021). Traditional oilseed crops are rapeseed mustard, groundnut, linseed, and sesame while canola, sunflower, soybean, and safflower are non-traditional oilseed crops (Ijaz et al. 2019). *Brassica* napus L., belonging to the Brassica genus and Brassicaceae family, represents a promising oilseed crop with significant potential for edible oil production. Its seeds comprise approximately 20% protein (Stolte et al. 2022) and boast an average oil content ranging from 40% to 50% (Cartea et al. 2019; Sabbahi et al. 2023). The extracted oil from *Brassica napus* L. consists of 7% saturated fats and 61% unsaturated fats, comprising 13% linoleic acid, 8–9% linolenic acid, and 12% oleic acid (Cartea et al. 2019). *Brassica napus* is used for food (vegetable oil) and non-food (biodiesel and livestock meal) purposes. Vegetable oil is used for cooking, baking, frying, sauteing, salad dressings and marinating at home, restaurants, and food processing plants. It also has non-food usages like biofuel, renewable diesel, aquaculture, and bio-plastics. The meal obtained from pressing and extraction of *Brassica napus* has high-value nutrition for livestock and pet feed and fertilizer (GOP 2023). Keeping in view the significance of oil seed crops, a study was planned to evaluate the potential role of lignite-based sulphur fertilizer on soil conditions and oil seed production.

Materials and methods

Preparation of lignite-based sulphur fertilizer

Granular lignite-based sulphur fertilizer was utilized for the experiment. For the synthesis of granular fertilizer, 1:1 of lignite and elemental sulphur was utilized. Using a spatula, equal amounts of elemental sulphur and lignite were combined. Then 20 g of starch was added and swirled until 200 mL of distilled water that had been heated had thickened enough to be sticky. The starch solution was then added, and a mixture of lignite and elemental sulphur was well-blended. Granules of the thickened substance were produced using a sieve (1 mm size). Granules were dried in an oven and divided according to size. Three sieves of size 1 mm, 2 mm and 3 mm were used for its uniformity and then fertilizer was ready for use. For the authenticity of the synthesized product, the following characterization tests were conducted.

Characterization of lignite-based sulphur fertilizer

The lignite-based sulphur fertilizer underwent characterization through X-ray diffraction (XRD), Fourier transform infrared (FTIR), and elemental analysis to ascertain its organic carbon and sulphur content. XRD analysis entailed determining the crystallographic structure of the fertilizer sample using a computer-controlled X-ray diffractometer. The functional groups within the fertilizer were identified via a Thermo Scientific Nicolet 380 IR spectrometer (Model: FT/IR-6600typeA) utilizing the traditional KBr pellet method. Lignite-based sulphur fertilizer was used in powder form, pressed into pellets in an evacuated die under 10 MPa for 2 mins. The sample was analyzed at ambient temperature with the scan range of 500–4000 cm^{-1} at the resolution of 8 cm^{-1}.

The organic carbon in the lignite-based sulphur fertilizer was determined by digestion of fertilizer 5 g sample in crucibles at 550 °C for 6 hours in a muffle furnace. Crucibles were weighed freshly (W1) and placed in the oven for 4 hours (W2). The samples were kept in a desiccator for cooling and weighed (W3). The formula described by Paez et al. (2016) was employed to quantify the organic carbon content in the fertilizer.

$$\text{Ash (\%)} = \frac{W_3 - W_2}{W_2 - W_1} \times 100$$

$$\text{Organic Matter (\%)} = 100 - \text{ash (100)}$$

$$\text{Organic Carbon (\%)} = \frac{\text{Organic matter value}}{1.724}$$

The sulphur content in the lignite-based sulphur fertilizer was determined through precipitation, followed by heating in a muffle furnace at 800 °C for one hour, and subsequent cooling in a desiccator. To initiate precipitation, 4 g of the sample was dissolved in 250 mL of distilled water, filtered, and then 20 mL of the filtered solution was transferred to a beaker containing 100 mL of distilled water. Next, 2 mL of HCl was added to the beaker, and the solution was boiled for 5 minutes. Following this, 50 mL of $BaCl_2$ solution was added, and the solution was boiled again for 5 minutes. The boiled solution was then placed in a water bath for 1 hour at 80 °C, covered with a glass lid. Afterward, the solution was filtered to isolate the precipitates. The precipitates were washed out and placed filter paper in crucibles (pre heated at 800 °C) and weighed (W1). The crucibles were placed in a muffle furnace at 800 °C for 1 hour and weighed (W2) after cooling in a desiccator. The method outlined by Horwitz and Latimer (2005) was utilized to ascertain the sulphur content in the fertilizer.

$$\text{Sulphur (\%)} = \frac{W_2 - W_1 \times 250 \times 32 \times 100}{\text{Weight of sample} \times 20\text{ mL} \times 233}$$

Field experiment

Field experiments were conducted at PMAS-Arid Agriculture University Rawalpindi, University Research Farm, Koont, Punjab, Pakistan with a randomized complete block design to explore the effects of lignite-based sulphur fertilizer on yield and quality of brassica and soil properties. There were seven treatments having control, elemental sulphur concentrations (30, 40, and 50 kg ha^{-1}) and three concentrations of lignite-based sulphur fertilizer (30, 40 and 50 kg ha^{-1}) applied on *Brassica napus* (Variety: NARC Sarsoon) with four replications. The final seedbed was prepared by two ploughing with one planking. During the final seedbed preparation, phosphorus, and nitrogen, in the form of DAP and urea, were applied at a ratio of 90:60 kg ha^{-1}. The individual plot size measured 5 m × 2.7 m, with six rows of plants spaced 45 cm apart. The plant-to-plant distance was maintained at 15 cm after thinning at the two-leaf stage. Supplemental sulphur and lignite-based sulphur fertilizer were applied at the time of sowing in their respective treatments. All the other cultural practices were kept constant. The fertilizer was used for the first time but lignite and lignite combinations with other materials and elemental sulphur were used in preliminary studies (Paramashivam et al. 2016; Farhangi-Abriz and Nikpour-Rashidabad 2017; Kulczycki 2021).

Data collection

Soil analysis

Soil moisture content was determined using the oven dry method at depths of 0–15 cm and 15–30 cm across all study areas. To assess soil pH, 20 g of soil was placed in a 100 mL beaker, and 40 mL of distilled water was added. The suspension was then shaken for about 30 minutes. The pH was then evaluated by soaking the electrodes of the pH meter in the suspension and pH was measured (Mclean 1982). To assess the electrical conductivity of the soil, 20 g of soil was placed in a 100 mL beaker, and 40 mL of distilled water was added. The contents were then shaken for about 30 minutes. The electrical conductivity was then measured by submerging the electrodes of the EC meter into the suspension and EC was measured (Richard 1954). To study the soil texture, 40 g of soil was combined with 40 mL of 5% sodium hexametaphosphate in a beaker. After a brief period of resting, 150 mL of distilled water was added, and the liquid was then transferred to a cup for soil dispersion. It was well mixed before being poured into a calibrated cylinder, hitting the mark. A hydrometer reading for the suspension's silt and clay concentration was obtained after 40 seconds of mixing with a plunger. The plunger was used once more, and the clay reading was noted after two hours. Sand, silt, and clay percentages were plotted on a texture triangle to define the texture class (Gee and Bauder 1986). The content of mineral nitrogen (ammonium nitrogen and nitrate nitrogen) was determined by the ABDTA method (Aziz et al. 2019). For phosphorus and potassium determination, 1 g of soil was extracted with 0.01 M calcium chloride solution and exposed to a spectrophotometer and flame photometer. Soil organic carbon was determined using the Walkley-Black method (Walkley 1947). Sulphur content in soil was determined by turbidimetric method and a spectrophotometer was used to determine the values (Wall et al. 1980).

Crop Data

Agronomic parameters, including plant height, were evaluated by randomly selecting 10 plants from each treatment at the maturity stage and measuring them with a meter rod. The number of primary and secondary branches per plant, as well as pods per plant, were counted from these selected plants at maturity. Pod length and seeds per pod were determined by selecting 50 pods from each treatment. For biological yield determination, two central rows, each 2 meters in length, were harvested, and the harvested material was sun-dried for 7 days to measure seed yield. Thousand seed weights were calculated using a seed counter machine on three separate seed lots from each sample. The harvest index was calculated by dividing the seed yield by the biological yield and then multiplying by 100. Oil yield was determined by multiplying the oil content by the seed yield and dividing by 100.

Chlorophyll content was measured by using a Spade meter from 5 leaves randomly from each treatment just before flower initiation. Relative water content was determined by picking 5 leaves randomly from each treatment just before flower initiation, observing fresh weight and submerging in distilled water for 72 hours and turgid weight was calculated. Then leaves were oven-dried at 65 °C until constant dry weight was gained and a formula was used to determine relative water content.

Statistical analysis

The collected data underwent statistical analysis using the computer software Statistix 8.1. To compare means, the Duncan's Multiple Range test (DMRT) was employed at a significance level of 5% (Montgomery 2017).

Results

Fertilizer characterization

The elemental composition of the lignite-based sulphur fertilizer was characterized to determine its organic carbon and sulphur content. Organic carbon was quantified using the digestion method, yielding a value of 36.36%, while the sulphur content was found to be 48.67%. X-ray diffraction analysis was conducted to examine the crystallographic structure of the fertilizer. The XRD pattern of the lignite-based sulphur fertilizer, depicted in Fig. 1, illustrates the diffracted beam intensity as a function of the Bragg angle (2θ), facilitating analysis of the crystal structure and morphology (Behazin et al. 2016; Baysal et al. 2016). Sharp peaks in the pattern indicate the presence of various inorganic components, notably crystalline forms of SiO_2 and CaO (Liu et al. 2012). Notably, a distinct sharp peak at 23.125° for lignite-based sulphur fertilizer signifies the presence of microcrystalline carbon, akin to graphite crystals. The presence of amorphous carbon structures and unorganized layers of microcrystalline structures, characterized by varying degrees of maturity, contributes to the low crystallinity observed in the lignite-based sulphur fertilizer. This is attributed to the presence of aliphatic carbon structures, including lipid chains and alicyclic compounds, within the fertilizer. In the XRD pattern 2θ = 24.9 indicated the presence of kaolinite in lignite-based sulphur fertilizer (Xu et al. 2023). In XRD pattern with extremely sharp and high-intensity diffraction peaks at 2θ = 15.39°, 23.12°, 25.89°, 26.74°, 27.73°, 28.73°, and 29.014° showed correspondence to different minerals.

Fourier Transform Infrared spectroscopy was conducted to evaluate the presence of functional groups in the lignite-based sulphur fertilizer. The analysis was carried out at ambient temperature, scanning within the range of 450–4000 cm^{-1} at a resolution of 8 cm^{-1}. The resulting FTIR spectrum is illustrated in Fig. 2. For a semi-quantitative assessment of functional groups in the fertilizer samples, encompassing aromatic structures (700–900 cm^{-1}), oxygen-containing structures (1000–1800 cm^{-1}), aliphatic structures (2800–3000 cm^{-1}), and hydroxyl structures (3200–3600 cm^{-1}), the spectrum was divided into four absorbance bands (He et al. 2017).

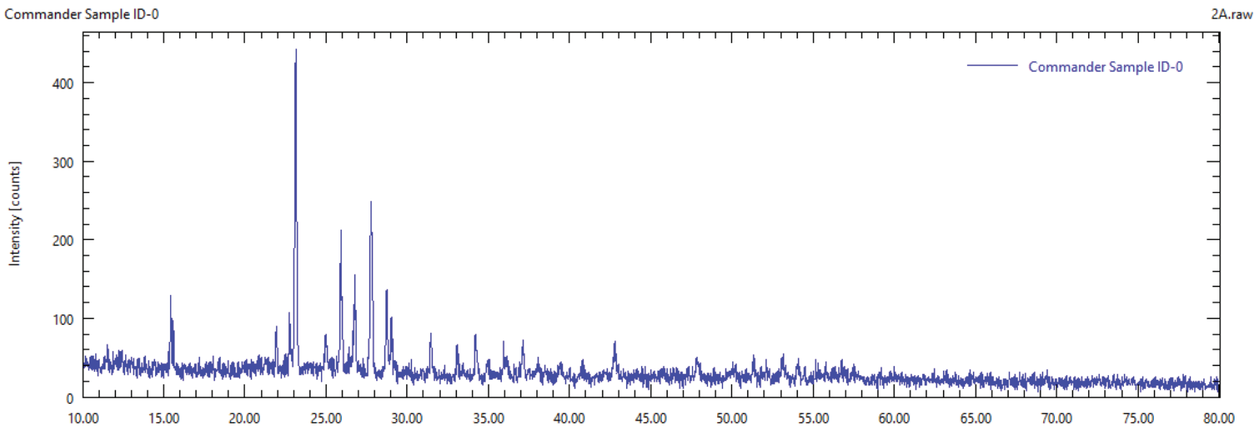

Figure 1. X-Ray Diffraction of lignite-based Sulphur fertilizer.

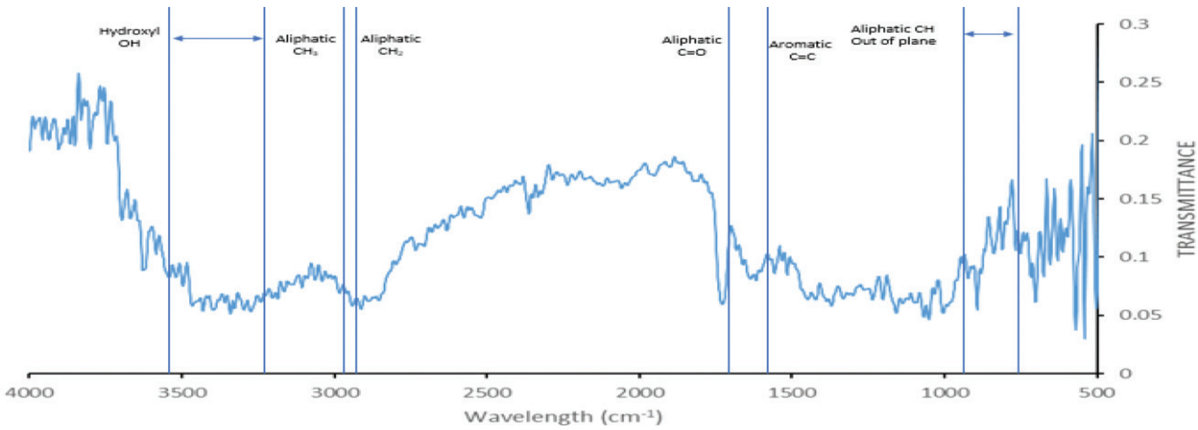

Figure 2. FTIR Analysis of lignite-based Sulphur fertilizer.

Soil analysis

The randomly collected samples from the experimental site were analysed during both years (2021–22 and 2022–23) before sowing and after harvesting as represented in Table 1. Soil texture was found sandy loam as there was a main source found sand and followed by silt and clay. Lignite based sulphur fertilizer positively affected the soil organic carbon and sulphur content which were focus. Variations in values showed the effect of lignite-based sulphur fertilizer on soil properties.

Agronomic parameters

Investigated results revealed that lignite-based sulphur fertilizer significantly affects the agronomic and yield attributes as represented in Table 2. During a two-year study, a linear increase in agronomic and yield attributes was recorded by lignite-based sulphur fertilizer. Plant height was measured highest (137.1 cm) with 50 kg lignite-based sulphur fertilizer application and lowest (118.1 cm) in control during the first year. During the second year, the highest plant height (188.3 cm) was recorded from a plot treated

Table 1. Physico-chemical properties of the experimental site during 2021–22 and 2022–23.

Determinations	Units	2021–22				2022–23			
		Before Sowing		After Harvesting		Before Sowing		After Harvesting	
		0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Sand	%	72.3	71.6	71.5	71.8	75.2	74.3	75.5	74.1
Silt	%	15.5	15.7	15.1	16.2	15.3	15.9	15.5	16.4
Clay	%	9.1	9.6	8.7	9.3	9.5	9.8	9.3	9.5
Soil Moisture Content	%	18.8	20.8	6.4	7.5	9.9	8.7	9.3	14.9
pH	-	8.3	8.2	8.4	8.3	7.8	7.7	8.01	8
EC	dS/m	0.81	0.79	0.82	0.81	1.3	1.04	1.37	1.11
N_{min}	ppm	5.6	5.4	5.7	5.6	5.21	4.88	5.42	5.01
P available	ppm	6.1	5.9	6.2	6	5.99	5.62	6.14	5.88
K available	ppm	167	161	170	165	96.1	82.7	101.3	80.1
Organic Carbon	g/100g	3.35	3.29	3.39	3.34	2.99	2.71	3.53	3.48
Sulphur	mg/kg	11.2	10.7	11.3	10.9	5.22	6.57	7.73	8.06

Table 2. Plant height (PH), primary branches plant^{-1} (PB), secondary branches plant^{-1} (SB), pods plant^{-1} (PP), seeds pod^{-1} (SP), pod length (PL), thousand seed weight (TSW), biological yield (BY), seed yield (SY), harvest index (HI), and oil yield (OY) as influenced by lignite-based sulphur fertilizer.

Treatments	PH (cm)	PB	SB	PP	SP	PL (cm)	TSW (g)	BY (kg ha^{-1})	SY (kg ha^{-1})	HI (%)	OY (kg ha^{-1})
Year 1											
Control	118.1 ± 1.18 i	3.0 ± 0.03 de	1.8 ± 0.02 i	106.8 ± 1.90 e	16 ± 0.77 j	5.1 ± 0.32 j	3.8 ± 0.61 h	5074 ± 6.01 j	844 ± 3.33 l	16.7 ± 1.90 c	350.9 ± 2.33 k
Elemental sulphur @ 30 kg ha^{-1}	121.4 ± 1.21 hi	3.1 ± 0.03 de	2 ± 0.02 i	109.3 ± 1.89 e	16.9 ± 0.78 hij	5.9 ± 0.33 hi	4.1 ± 0.63 g	5463 ± 6.33 ij	1004.2 ± 3.98 k	18.4 ± 2.11 abc	418.9 ± 2.39 j
Elemental sulphur @ 40 kg ha^{-1}	122.6 ± 1.10 hi	2.9 ± 0.03 e	2.85 ± 0.03 gh	117.8 ± 1.21 e	17.7 ± 0.78 gh	6.5 ± 0.36 fg	4.4 ± 0.60 f	5954 ± 6.68 hi	1131.2 ± 4.01 j	19.0 ± 2.17 ab	474.6 ± 2.91 i
Elemental sulphur @ 50 kg ha^{-1}	124.6 ± 1.11 hi	3.0 ± 0.03 de	3.15 ± 0.04 fgh	130.2 ± 1.96 e	18.2 ± 0.79 fg	6.8 ± 0.36 ef	4.8 ± 0.66 de	6546 ± 6.11 gh	1238.4 ± 3.77 hi	18.9 ± 2.16 ab	523.2 ± 3.10 hi
Lignite based sulphur fertilizer @ 30 kg ha^{-1}	127.7 ± 1.07 gh	3.1 ± 0.03 de	2.7 ± 0.03 h	132.47 ± 1.99 e	18.9 ± 0.74 def	6.9 ± 0.37 de	5.0 ± 0.67 cd	7303 ± 6.88 fg	1396.1 ± 4.11 fg	19.2 ± 2.17 a	602.4 ± 3.23 g
Lignite based sulphur fertilizer @ 40 kg ha^{-1}	134 ± 1.19 fg	3.9 ± 0.05 cd	3.7 ± 0.05 def	170.13 ± 2.06 d	19.8 ± 0.71 bcd	7.3 ± 0.32 cd	5.2 ± 0.67 bc	8138 ± 7.11 ef	1562.6 ± 4.45 de	19.2 ± 2.16 a	674.8 ± 3.01 f
Lignite based sulphur fertilizer @ 50 kg ha^{-1}	137.1 ± 1.04 f	3.9 ± 0.05 cd	4.0 ± 0.05 bcd	189.08 ± 2.31 d	20.5 ± 0.75 b	8.1 ± 0.40 ab	5.5 ± 0.69 a	9185 ± 7.51 cd	1738 ± 4.67 c	19.1 ± 2.15 ab	761.8 ± 3.31 de
Year 2											
Control	153.8 ± e	4.7 ± 0.06 bc	3.4 ± 0.05 efg	281.7 ± 2.58 bc	16.5 ± 0.71 ij	5.8 ± 0.36 i	3.9 ± 0.57 gh	6597 ± 5.99 gh	1152.1 ± 3.12 ij	17.8 ± 2.11 abc	576.3 ± 2.89 gh
Elemental sulphur @ 30 kg ha^{-1}	163.2 ± d	4.7 ± 0.06 bc	3.5 ± 0.05 ef	273.93 ± 2.51 c	17.5 ± 0.78 ghi	6.3 ± 0.38 gh	4.4 ± 0.60 f	7700 ± 6.09 ef	1336 ± 3.67 gh	17.4 ± 2.07 abc	674.7 ± 2.97 f
Elemental sulphur @ 40 kg ha^{-1}	164.9 ± d	4.9 ± 0.06 abc	3.9 ± 0.06 cde	281.12 ± 2.67 bc	18.5 ± 0.79 efg	6.7 ± 0.33 efg	4.6 ± 0.62 ef	8538 ± 6.51 de	1460 ± 3.71 ef	17.1 ± 1.99 bc	726.5 ± 3.07 ef
Elemental sulphur @ 50 kg ha^{-1}	171 ± cd	5 ± 0.06 ab	4.0 ± 0.06 bcd	311.9 ± 2.69 ab	18.9 ± 0.82 def	6.9 ± 0.39 de	4.9 ± 0.67 de	9190 ± 6.87 cd	1592.9 ± 3.89 d	17.3 ± 2.03 abc	791.5 ± 3.09 d
Lignite based sulphur fertilizer @ 30 kg ha^{-1}	176.4 ± bc	5.3 ± 0.07 ab	4.3 ± 0.06 abc	318.3 ± 2.88 a	19.3 ± 0.85 cde	7.4 ± 0.35 cd	5.0 ± 0.67 bcd	9902 ± 6.11 bc	1753.4 ± 4.27 c	17.7 ± 2.06 abc	870.9 ± 3.43 c
Lignite based sulphur fertilizer @ 40 kg ha^{-1}	182.5 ± ab	5.6 ± 0.07 ab	4.5 ± 0.07 ab	322.45 ± 2.91 a	20.2 ± 0.82 bc	7.7 ± 0.31 bc	5.3 ± 0.68 b	10390 ± 7.01 b	1894.6 ± 4.88 b	18.3 ± 2.12 abc	931.6 ± 3.51 b
Lignite based sulphur fertilizer @ 50 kg ha^{-1}	188.3 ± a	5.8 ± 0.07 a	4.6 ± 0.07 a	331.68 ± 2.96 a	21.6 ± 0.87 a	8.4 ± 0.33 a	5.7 ± 0.65 a	11611 ± 6.93 a	2055.8 ± 4.97 a	17.7 ± 2.16 abc	1025.4 ± 3.77 a
LSD for Treatment × Year	9.16	0.94	0.57	32.61	1.02	0.43	0.25	860.28	104.53	1.96	55.43

The values represent the averages (±SE) of four independent replicates followed by different letters within columns are significantly different at $P \leq 0.05$, according to Duncan's Multiple Range test.

with 50 kg ha^{-1} lignite-based sulphur fertilizer and the lowest plant height (153.8 cm) was measured from the control. Second-year study confirmed the increment of plant height in *Brassica napus* by using lignite-based sulphur @ 50 kg ha^{-1}. The maximum number of primary branches plant^{-1} (3.9) were produced in plots treated with 50 kg ha^{-1} lignite-based sulphur and the minimum (3.0) produced in plots treated with elemental sulphur @ 40 kg ha^{-1} in the first year. During the second year the maximum number of primary branches plant^{-1} (5.8) was produced with lignite-based sulphur fertilizer @ 50 kg ha^{-1} and a minimum number of primary branches plant^{-1} was recorded from the control. Overall primary branches plant^{-1} were increased in the second year and confirmed this increment with use of 50 kg ha^{-1} lignite-based sulphur fertilizer. The maximum number of secondary branches plant^{-1} (4.0) was observed in plots treated with 50 kg ha^{-1} lignite-based sulphur fertilizer and a minimum (1.8) were recorded from the control in the first year. During the second year, the number of secondary branches plant^{-1} were highest (4.6) in plots applied with 50 kg ha^{-1} lignite-based sulphur fertilizer while the lowest were observed from control. The second-year study confirmed the increment in the number of secondary branches per plant with the use of lignite-based sulphur fertilizer @ 50 kg ha^{-1}. The maximum number of pods plant^{-1} (189.1) was recorded in lignite-based sulphur fertilizer @ 50 kg ha^{-1} and the minimum (106.8) was recorded in control in the first year. During the second year, the maximum pods per plant (331.7) were observed in plots treated with 50 kg ha^{-1} lignite-based sulphur fertilizer and the minimum (281.7) was observed in control. Second-year study confirmed the substantial effect in the increment of pods per plant by using 50 kg ha^{-1} lignite-based sulphur fertilizer. The maximum number of seeds pod^{-1} (20.5) was recorded in plots treated with lignite base sulphur fertilizer and a minimum (16.0) was observed in control in the first year. While in the second year, maximum number of seeds per pod (21.6) were recorded in lignite-based sulphur fertilizer @ 50 kg ha^{-1} and minimum seeds per pod (16.5) were recorded in control. The increase in the number of seeds per pod was confirmed in second year by using the lignite-based sulphur fertilizer at the rate of 50 kg ha^{-1}. The tallest pod (8.1 cm) was measured in plots treated with lignite-based sulphur fertilizer @ 50 kg ha^{-1} and shortest pod (5.1 cm) was recorded in control in first year. While in second year, tallest pod (8.4 cm) was observed in plots applied with 50 kg ha^{-1} lignite-based sulphur fertilizer and shortest pod (5.8 cm) was measured in control. The study confirmed the increment in pod length by using lignite-based sulphur fertilizer @ 50 kg ha^{-1}.

Thousand seed weight was measured by taking three lots of seeds from each treatment and averaged. The highest thousand seed weight (5.54 g) was recorded from plots treated with 50 kg ha^{-1} lignite-based sulphur fertilizer and the lowest thousand seed weight (3.8 g) was observed in control in the first year. In the second year, the highest thousand seed weight (5.7 g) was recorded from the application of lignite-based sulphur fertilizer and the lowest seed weight was recorded from control. The second-year experiment confirmed that yield attributes were also affected significantly by lignite-based sulphur fertilizer application. The biological yield (9185 kg ha^{-1}) was recorded highest in plots treated with 50 kg ha^{-1} lignite-based sulphur fertilizer and lowest (5074 kg ha^{-1}) in control in the first year. In the second year of the experiment, the plots treated with 50 kg ha^{-1} of lignite-based sulphur fertilizer had the maximum biological output (11611 kg ha^{-1}), whereas the control group had the lowest biological yield (6597 kg ha^{-1}). The use of lignite-based sulphur fertilizer at a rate of 50 kg ha^{-1} was found to increase the biological yield in *Brassica napus* in the second year of the study. The maximum seed yield (1738 kg ha^{-1}) was recorded in plots treated with lignite-based sulphur fertilizer and the minimum seed yield (844 kg ha^{-1}) was observed in control in first year. During the second year, the maximum seed yield (2055 kg ha^{-1}) was observed in plots applied with 50 kg ha^{-1} lignite-based sulphur fertilizer while the minimum seed yield (1152 kg ha^{-1}) was recorded in control. The significant increase in seed yield in the second year is confirmed by using lignite-based sulphur fertilizer @ 50 kg ha^{-1}.

Harvest index is the ratio of biological yield and seed yield. The harvest index was recorded highest (19.1%) in plots treated with 50 kg ha^{-1} lignite-based sulphur fertilizer and the lowest (16.7%) was recorded in control in first year. During the second year, the harvest index was decreased as compared to first year. While the maximum harvest index (18.3%) was recorded in plots treated with 40 kg ha^{-1} lignite-based sulphur fertilizer and the minimum harvest index (17.1%) was recorded with the application of elemental sulphur @ 40 kg ha^{-1}. In the first year, the total harvest index was substantial as compared to the second year. The oil yield was recorded highest (761.8 kg ha^{-1}) in plots treated with 50 kg ha^{-1} lignite-based sulphur fertilizer and the minimum oil yield (350.9 kg ha^{-1}) was recorded in first year. In the second year, the highest oil yield (1025.4 kg ha^{-1}) was observed in plots applied with lignite-based sulphur fertilizer @ 50 kg ha^{-1} and the lowest oil yield (576.3 kg ha^{-1}) was observed in control.

The data regarding chlorophyll content showed an increment in both years. The highest chlorophyll content (36.3) was found in plots treated with lignite-based sulphur fertilizer @ 50 kg ha^{-1} and the lowest chlorophyll content (28.6) was recorded from control in the first year. During second year, maximum chlorophyll content (43.4) was measured from plots treated with 40 kgha^{-1} lignite-based sulphur fertilizer while minimum chlorophyll content (38.9, 38.7) was found in control and plots treated with elemental sulphur @ 30 kg ha^{-1} respectively (Table 3). The relative water content was found highest (73.5%) in plots treated with lignite-based sulphur fertilizer @ 40 kg ha^{-1} and the lowest (67.9%) was recorded in plots treated with 40 kg ha^{-1} elemental sulphur in the first year. During the second year, maximum relative water content (89.8%) was found in plots treated with 40 kg ha^{-1} lignite-based sulphur fertilizer application while minimum (81.9%) was recorded from the control (Table 3).

Table 3. Physiological parameters i.e., chlorophyll content (CLC), and relative water content (RWC) as effected by lignite-based sulphur fertilizer.

Treatments	CLC (Spade-units)	RWC (%)
Year 1		
Control	28.64 ± 0.87 c	70.78 ± 1.11 ef
Elemental sulphur @ 30 kg ha^{-1}	29.83 ± 0.91 bc	75.24 ± 1.22 bcdef
Elemental sulphur @ 40 kg ha^{-1}	29.25 ± 0.92 c	67.99 ± 1.17 f
Elemental sulphur @ 50 kg ha^{-1}	31.26 ± 0.96 bc	67.96 ± 1.01 f
Lignite based sulphur fertilizer @ 30 kg ha^{-1}	29.91 ± 0.88 bc	69.38 ± 1.02 f
Lignite based sulphur fertilizer @ 40 kg ha^{-1}	31.66 ± 0.97 bc	73.50 ± 1.16 cdef
Lignite based sulphur fertilizer @ 50 kg ha^{-1}	36.31 ± 1.03 abc	73.15 ± 1.13 def
Year 2		
Control	38.92 ± 1.11 ab	81.90 ± 1.10 abcde
Elemental sulphur @ 30 kg ha^{-1}	38.74 ± 0.98 ab	83.82 ± 1.21 abcd
Elemental sulphur @ 40 kg ha^{-1}	42.94 ± 1.15 a	86.61 ± 1.17 ab
Elemental sulphur @ 50 kg ha^{-1}	37.31 ± 1.04 abc	85.31 ± 1.06 abc
Lignite based sulphur fertilizer @ 30 kg ha^{-1}	41.68 ± 1.01 a	82.92 ± 1.02 abcd
Lignite based sulphur fertilizer @ 40 kg ha^{-1}	43.40 ± 1.17 a	89.84 ± 1.27 a
Lignite based sulphur fertilizer @ 50 kg ha^{-1}	42.25 ± 1.07 a	83.80 ± 1.21 abcd
LSD for Treatment × Year	9.45	11.87

The values represent the averages (±SE) of four independent replicates followed by different letters within columns are significantly different at P ≤ 0.05, according to Duncan's Multiple Range test.

Discussions

The vegetative development of the crop is frequently indicated by factors such as plant height and the count of primary and secondary branches per plant (Al-Taey et al. 2019; Al-Tawaha et al. 2020; Zhang et al. 2023a). This enhancement may be attributed to sulphur's role in facilitating protein synthesis, enzyme activation, and chlorophyll production (Imran et al. 2021a; Li et al. 2022). The application of lignite notably influenced plant height and the number of primary and secondary branches per plant, with these parameters exhibiting an increase corresponding to higher lignite application rates. The reason for this was that lignite encourages vegetative growth. The study by Imran et al. (2023), which explained that increased application of lignite-produced humic acid may retard the height, supports this experiment by improving vegetative in rapeseed (*Brassica napus* L.) at a moderate amount.

Differences in pods plant^{-1} different levels of fertilizer were significant and higher pods plant^{-1} (331.7) was observed where lignite-based sulphur fertilizer @ 50 kg ha^{-1} applied as compared to control (281.7). This could be attributed to the role of lignite-based sulphur fertilizer in fertilization rates, where the presence of sulphur enhances photosynthetic activity, leading to increased production of proteins and carbohydrates essential for plant growth and development. Consequently, this may result in a higher number of pods per plant (Imran et al. 2020). Imran et al. (2021b) and Ruan (2014) reported the same results regarding pods plant^{-1} by using lignite-derived humic acid in combination with sulphur. Seeds pod^{-1} is an important yield-increasing component. The results regarding seeds pod^{-1} agree with Imran et al. (2023) who reported the increase in seeds per pod in *Brassica napus* by using the sulphur and humic acid in combination form. It may be the reason that lignite-based sulphur fertilizer plays an important role in increasing the fertilization rate which ultimately increases the seeds per pod. Data regarding pod length showed substantial results. It might be due to the reason that lignite-based sulphur fertilizers play an important role in fertilization rate and the presence of sulphur increases photosynthetic activity to enhance the protein and carbohydrates crucial for the growth and development of plant resulting in increased pod length (Imran et al. 2020; Yang et al. 2024a).

The total biomass produced above ground is referred to as the biological yield. Using lignite-based sulphur fertilizer greatly boosted biological yield, and it was observed that applying 50 kg ha^{-1} of sulphur fertilizer created greater biological yield. According to Imran et al. (2023), the fertilizer's sulphur aids in the development of protein and chlorophyll, which supports photosynthesis in plants and the synthesis of starch, protein, vitamins, lipids, and other essential substances. Additionally, lignite increases biological yield. It might be because lignite promotes the growth of roots, improves vegetative growth, increases branching and flowering, and eventually raises the plant's total biomass (Imran et al. 2023). The sulphur present in the fertilizer plays an important role in protein synthesis and increases crop production. The application of sulphur fertilizer based on lignite produced a higher yield than the control. This could be because fertilizer made of lignite and sulphur speeds up fertilization, increasing seed yield. Imran et al. (2023) reported unfavourable outcomes and concluded that the application of lignite does not effect on seed output. However, the combination of sulphur and lignite exhibits positive effects on seed yield, with the highest recorded seed yield (2055.8 kg ha^{-1}) observed with the application of 50 kg ha^{-1} of lignite-based sulphur fertilizer. These findings are consistent with those reported by Imran et al. (2023).

Thousand seed weight was notably influenced by the application of lignite-based sulphur fertilizer, with higher weights observed particularly at the rate of 50 kg ha^{-1}. This suggests a promising potential for achieving both high thousand seed weight and enhanced oil productivity. The fertilizer contains more than 48% sulphur which helps in cell division and yield enhancement. The results agreed with Dubey et al. (2013) and lignite-based sulphur fertilizer substantially affected the thousand seed weight. The highest value of harvest index (18.3%) was recorded from plots treated with lignite-based sulphur fertilizer @ 40 kg ha^{-1} which was statistically similar with plots receiving 50, 30 kg ha^{-1} lignite-based sulphur fertilizer while the minimum value of harvest index (17.8%) was recorded in control. Lignite-based sulphur fertilizer enhanced the seed yield. This may be due to the reason that lignite-based sulphur fertilizer helps to increase biological yield and seed yield (Naveed et al. 2015; Zhang et al. 2023b; Yang et al. 2024b). This study is against with finding of Imran et al. (2023) who recorded the increase in harvest index with an increase in sulphur and lignite-derived humic acid application. A significant increase in oil yield was recorded in the second year contrasted to the first year by using lignite-based sulphur fertilizer. A second-year study found that applying lignite-based sulphur fertilizer could boost oil yield and that plots treated with the fertilizer at a rate of 50 kg ha^{-1} produced higher oil yields. Sulphur is also a part of lignite and lignite-based sulphur fertilizer contains 48.74% sulphur which has positive effects on seed yield and oil yield as sulphur helps in photosynthetic formation, protein formation and enzymatic activities ultimately resulting in increased seed and oil yield (Yi et al. 2022; Imran et al. 2023; Liu et al. 2023).

Conclusions

Elemental sulphur and lignite were successfully combined to make fertilizer (lignite-based sulphur fertilizer). The response of rapeseed (*Brassica napus L.*) was significantly positive to fertilizer application. Using the lignite-based sulphur fertilizer at a rate of 50 kg ha^{-1} resulted in significantly higher seed production, thousand seed weight, seeds pod^{-1}, and oil production. To achieve edible oil self-sufficiency and support the yellow revolution in Pakistan, it may be inferred that rapeseed brassica should be treated with lignite-based sulphur at a rate of 50 kg ha^{-1}. This will increase the yield, yield components, and quality of *Brassica napus* under the Pothohar region. Now additional work is necessary to study the effect of lignite-based sulphur fertilizer on rapeseed and other field crops under irrigated areas.

Author Contribution

ABDUL MANAF and QAISER HUSSAIN designed the study. AZMAT ALI NOSHER, SEHRISH ANWAR and RANA NOMAN ANWAR performed the experiments. LAIBA MUKHTAR helped in data curation and analysis of data. SALEH H. SALMEN and MOHAMMAD JAVED ANSARI collected literature reviews and helped in writing the original draft of the article. YAMIN BIBI and ABDUL QAYYUM provided technical expertise to improve the article and helped in funding acquisition. All authors reviewed and edited the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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