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Research article

Industrial Strategies for Sulfur Application to Maximize Broad Bean Production

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Abstract

Soil nutrient depletion, particularly sulfur deficiency, has become a major constraint limiting pulse crop productivity in semi-arid regions like Kandahar, Afghanistan. Broad bean (*Vicia faba* L.) is an important legume for food security and soil health, often suffers from suboptimal yields due to inadequate sulfur nutrition. However, scientific guidance on the best sulfur sources and application rates for local conditions remains limited. This study was conducted to evaluate the effect of different sulfur sources and application rates on the yield, production efficiency, and economic returns of broad bean under Kandahar's agro-climatic conditions. A field experiment was carried out at the ANASTU research farm from Feb. to Jun 2022 using a randomized complete block design with two sulfur sources (gypsum and elemental sulfur) and four application levels (0, 20, 30, and 40 kg S/ha). The findings revealed that gypsum significantly outperformed elemental sulfur, producing the highest seed yield (1,289.1 kg/ha), gross return (AFN 135,359.0/ha), and net return (AFN 106,579.0/ha). Among sulfur levels, 30 kg S/ha was the most effective, recording the highest yield (1,426.3 kg/ha), gross return (AFN 149,765.0/ha), net return (AFN 120,285.0/ha), and production efficiency (12.7 kg/ha/day). Sulfur application improved seed yield by up to 64.5% compared to the control. The study concludes that gypsum at 30 kg S/ha is the optimal strategy for maximizing broad bean productivity and profitability, and provides a valuable basis for improving nutrient management and sustainable pulse cultivation in sulfur-deficient, semi-arid environments.

Keywords: Economic return, elemental sulfur, Broad bean, gypsum, production efficiency, seed yield, sustainable agriculture

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1. Introduction

Broad bean (*Vicia faba* L.) is an important legume crop grown globally for its nutritional, economic, and soil-enhancing properties. As a rich source of protein, Broad bean plays a key role in food security, livestock feed, and sustainable agriculture through biological nitrogen fixation. However, its productivity is often constrained by nutrient deficiencies, especially sulfur (S), which is crucial for amino acid synthesis, enzyme activation, and chlorophyll formation (Zhao et al., 2024; Scherer, 2001).

Different sources and levels of sulfur can significantly impact seed yield, economic returns, and overall production efficiency in Broad bean cultivation. Gypsum ($CaSO_4 \cdot 2H_2O$) and elemental sulfur (S) are commonly used sources of sulfur, each with distinct release mechanisms and agronomic benefits (McGrath & Zhao, 1996). While gypsum provides immediate sulfur availability, elemental sulfur undergoes microbial oxidation before becoming plant-available, potentially affecting short-term crop response.

In recent years, industrial agriculture has increasingly focused on nutrient-specific management practices to boost crop yields. Among these, sulfur application has gained prominence due to widespread S deficiencies caused by reduced atmospheric deposition and the use of high-analysis, sulfur-free fertilizers (Gerson, 2024; Ehsan et al., 2017). To address this challenge, industrial strategies such as the use of various sulfur sources (e.g., gypsum, elemental sulfur, ammonium sulfate), optimized application timing, and precision placement techniques have been developed to enhance sulfur use efficiency and crop response (Zoca & Penn, 2024; Obaid et al., 2024).

Several studies have highlighted the importance of sulfur in enhancing yield and profitability in legume crops. According to Salvagiotti et al. (2008), sulfur application improved seed yield, protein content, and nitrogen fixation in various legumes. Additionally, Singh et al. (2020) reported that appropriate sulfur levels increased both yield and economic returns in pulse crops.

In Afghanistan's semi-arid farming systems, there is a lack of localized research guiding sulfur application strategies in legumes such as Broad beans. Farmers often rely on conventional practices without scientifically validated input recommendations, which leads to suboptimal yields, inefficient input use, and economic losses. While various sulfur sources such as gypsum and elemental sulfur are available, there is limited information on their relative effectiveness and optimal application rates under local agro-ecological conditions.

Understanding how different sulfur sources and levels influence Broad bean performance is critical for developing effective nutrient management strategies. This research offers insights that can directly improve farm productivity, resource use efficiency, and profitability. Moreover, it supports national food security goals by increasing pulse crop yields while promoting sustainable soil fertility management.

Broad bean, with its relatively high sulfur demand compared to cereals, benefits significantly from targeted S fertilization. Recent studies have demonstrated that appropriate sulfur management can improve not only yield and seed quality but also the economic returns of Broad bean farming (Balloei et al., 2025).

Given the increasing recognition of sulfur as a limiting nutrient in legume production, especially under the semi-arid conditions of Kandahar, Afghanistan, this study was designed to assess the performance of different sulfur sources and application rates in Broad bean cultivation. The research specifically aimed to address the following questions: How do different sources of sulfur (gypsum and elemental sulfur) affect the seed yield and economic returns of Broad bean? What is the optimal sulfur application rate to maximize production efficiency under Kandahar conditions? And which combination of sulfur source and level provides the most cost-effective and agronomically efficient results?

To answer these questions, the study pursued two primary objectives: (1) To evaluate the effect of different sulfur sources (gypsum and elemental sulfur) on seed yield, production efficiency, and economic returns of Broad bean, and (2) To determine the optimal sulfur application rate for maximizing productivity and profitability in the local agro-climatic context. This research explores industrial sulfur application strategies aimed at maximizing Broad bean production by integrating agronomic practices with modern nutrient delivery systems.

2. Materials and methods

Experimental Site and Duration

The field experiment was conducted at the Research Farm of the Afghanistan National Agricultural Sciences and Technology University (ANASTU), located in Kandahar Province, Afghanistan. The study was carried out from Feb. to Jun 2022 during the winter cropping season, with a total crop duration of 112 days.

Soil Analysis

Before sowing, composite soil samples were collected from the experimental plot at a depth of 0–30 cm for baseline fertility assessment. Post-harvest soil samples were also collected to evaluate the impact of sulfur treatments. Samples were analyzed for pH, electrical conductivity (EC), organic carbon, available nitrogen (N), phosphorus (P), potassium (K), and available sulfur (S), using standard protocols as outlined by Jackson (1973) and Singh et al. (2021).

Experimental Design and Treatments

The field experiment was conducted using a Randomized Complete Block Design (RCBD) with three replications to ensure statistical reliability and minimize experimental error. The study evaluated the impact of two sulfur sources—gypsum

($CaSO_4 \cdot 2H_2O$) and elemental sulfur (S^0)—combined with five levels of sulfur application: 0 kg S/ha (control), 10 kg S/ha, 20 kg S/ha, 30 kg S/ha, and 40 kg S/ha. This resulted in a total of 10 treatment combinations. The sulfur treatments were manually applied and thoroughly incorporated into the soil at the time of sowing to ensure uniform nutrient distribution. Each treatment plot received the respective sulfur source and dosage according to the experimental layout, enabling a comparative evaluation of yield response, production efficiency, and economic returns under the local agro-climatic conditions of Kandahar, Afghanistan.

Crop Management Practices

Certified Broad bean (*Vicia faba* L.) seeds were sown using a seed rate of 100 kg/ha, maintaining a spacing of 40 cm between rows and 10 cm between plants. All plots received a uniform basal application of nitrogen (20 kg/ha) and phosphorus (60 kg/ha) at sowing. Standard agronomic practices such as irrigation, weeding, and pest control were uniformly applied to all plots throughout the growth period.

Data Collection

Observations were recorded on key agronomic and economic parameters to assess the impact of sulfur source and application levels on Broad bean performance. The parameters measured included seed yield (kg/ha), gross return (AFN/ha), net return (AFN/ha), production efficiency (kg/ha/day), and monetary efficiency (AFN/ha/day). Seed yield was obtained by harvesting and threshing the central area of each plot and converting the weight to kilograms per hectare. Economic analysis was conducted using the prevailing local market price of Broad bean and the actual input costs for fertilizers and other agronomic practices incurred during the 2022 cropping season. Gross return was calculated as the product of seed yield and market price, while net return was derived by subtracting total production costs from the gross return. Production and monetary efficiencies were calculated by dividing yield and net return, respectively, by the crop duration in days.

Statistical Analysis

The collected data were statistically analyzed using ANOVA, and treatment means were compared using the Critical Difference (CD) at 5% probability level ($P = 0.05$). Standard Error of Mean (SE) and Standard Error of Difference (SE) were also calculated to assess treatment variability.

3. Results

Effect of Sulfur Source

The data revealed significant differences between the two sulfur sources in terms of seed yield and economic performance of the Broad bean. Application of gypsum resulted in the highest seed yield of 1,289.1 kg/ha, compared to 1,217.4 kg/ha from elemental sulfur (Table 1). This increase in yield under gypsum treatment translated into a higher gross return (AFN 135,359.0/ha) and net return (AFN 106,579.0/ha), whereas elemental sulfur yielded a gross return of AFN 127,827.0/ha and net return of AFN 98,247.0/ha (Table 2).

Table 1. Effect of sulfur source and application rates on seed yield kg/ha of Broad bean.

Treatment		Seeds Yield kg/ha
Source of Sulphur		
	Gypsum	1,289.1
	Sulphur	1,217.4
	SEm±	3.795
	SE(d)	5.367
	C.D(P=0.05)	11.3
Sulphur level kg/ha		
	0 kg S/ha	867.2
	10 kg S/ha	1,285.0
	20 kg S/ha	1,301.8
	30 kg S/ha	1,426.3
	40 kg S/ha	1,386.0
	SEm±	6.0
	SE(d)	8.5
	C.D(P=0.05)	17.8

Likewise, production efficiency and monetary efficiency were notably higher in gypsum treatment, recording 11.51 kg/ha/day and 951.6 AFN/ha/day, respectively, compared to 10.87 kg/ha/day and 877.2 AFN/ha/day in elemental sulfur (Table 3). The differences in seed yield and economic parameters between the two sources were found to be statistically significant at the 5% level, as indicated by the critical difference (C.D.).

Effect of Sulfur Levels

Application of sulfur at increasing levels significantly enhanced the performance of Broad bean in terms of both yield and economics. The maximum seed yield of 1,426.3 kg/ha was obtained with 30 kg S/ha, followed closely by 40 kg S/ha (1,386.0 kg/ha) (Table 1). The lowest yield (867.2 kg/ha) was recorded in the control treatment (0 kg S/ha).

The highest gross return (AFN 149,765.0/ha) and net return (AFN 120,285.0/ha) were also achieved at 30 kg S/ha. This treatment also resulted in the best production efficiency (12.7 kg/ha/day) and monetary efficiency (1,074.0 AFN/ha/day), significantly outperforming all other treatments (Table 2; Table 3).

Table 2. Effect of sulfur source and application rates on Gross return AFN/ha and Net return AFN/ha of Broad bean

Treatment	Gross return AFN/ha	Net return AFN/ha
Source of Sulphur		
Gypsum	135,359.0	106,579.0
Sulphur	127,827.0	98,247.0
SEm±	398.5	398.4
SE(d)	563.5	563.4
C.D(P=0.05)	1,183.7	1,183.6
Sulphur level kg/ha		
0 kg S/ha	91,052.5	62,472.5
10 kg S/ha	134,925.0	106,045.0
20 kg S/ha	136,692.5	107,512.5
30 kg S/ha	149,765.0	120,285.0
40 kg S/ha	145,530.0	115,750.0
SEm±	630.0	630.0
SE(d)	891.0	890.9
C.D(P=0.05)	1,871.6	1,871.5

Incremental increases beyond 30 kg S/ha (i.e., 40 kg S/ha) resulted in a slight decrease in both yield and economic returns, suggesting that 30 kg S/ha is the optimum sulfur application rate under the conditions of this experiment.

Table 3. Effect of sulfur source and application rates on production efficiency and Monetary efficiency of Broad bean

Treatment	Production Efficiency kg/ha/day	Monetary Efficiency AFN/ha/day
Source of Sulphur		
Gypsum	11.51	951.6
Sulphur	10.87	877.2
SEm±	0.034	3.558
SE(d)	0.048	5.031
C.D(P=0.05)	0.101	10.6
Sulphur level kg/ha		
0 kg S/ha	7.7	557.8
10 kg S/ha	11.5	946.8
20 kg S/ha	11.6	959.9
30 kg S/ha	12.7	1,074.0
40 kg S/ha	12.3	1,033.5
SEm±	0.054	5.63
SE(d)	0.076	7.96
C.D(P=0.05)	0.159	16.7

Industrial Role and Relevance

This study offers crucial insights with direct applications in the agricultural input industry, fertilizer manufacturing, and large-scale commercial farming sectors. As demand grows for sustainable and cost-effective crop production, the findings from this research help bridge the gap between traditional farming and evidence-based, nutrient-specific industrial agriculture.

Fertilizer Industry Guidance

The results demonstrate that gypsum, as a sulfur source, outperforms elemental sulfur in both agronomic and economic terms. This provides fertilizer companies with strong evidence to promote gypsum-based sulfur fertilizers, especially in pulse-growing regions. Additionally, the optimal application rate of 30 kg S/ha gives clear formulation targets for industrial-scale product development.

Precision Agriculture and Nutrient Management

The study supports the development of site-specific nutrient management plans using sulfur, particularly in sulfur-deficient soils like those found in Kandahar, Afghanistan. Agri-Tech companies and extension services can integrate these findings into fertilizer recommendation software and advisory platforms.

Profitability for Commercial Farming

The high net return and efficiency values associated with 30 kg S/ha sulfur application show that this strategy is not only agronomical sound but also economically viable for industrial-scale farms. This aligns with the goals of agribusiness firms aiming to increase productivity while optimizing input costs.

Sustainability and Soil Health

Sulfur plays a critical role in protein synthesis and soil nutrient balance. The data suggest that proper sulfur application enhances nitrogen fixation in legumes like Broad bean, reducing dependency on synthetic nitrogen fertilizers. This opens avenues for green agriculture initiatives and climate-smart farming technologies promoted by industry stakeholders.

Export and Processing Industries

With improved yield and quality, this strategy increases the marketable surplus of Broad beans, benefiting processing units, exporters, and food industries focused on plant-based proteins. Higher yields contribute to a consistent raw material supply, essential for food processing scalability.

Role of Sulfur Application

The ongoing Fourth Industrial Revolution in agriculture (often referred to as AgriTech 4.0) is characterized by digitization, data-driven decision-making, precision farming, and sustainable input use. Your research on sulfur application in Broad bean production directly contributes to this movement by providing scientifically grounded data that enhances productivity, profitability, and resource efficiency.

Driving Precision Agriculture

Your study identifies the optimal sulfur type and dosage (gypsum at 30 kg S/ha) to maximize yield and profit. These values are critical for:

Integrating into fertilizer recommendation algorithms

Developing digital decision-support tools used by farmers, agronomists, and Agri-input providers

This supports site-specific, data-backed input management, which is a cornerstone of the industrial agricultural revolution.

Promoting Input Efficiency and Resource Optimization

Sulfur is a secondary but essential nutrient, and your research shows its significant impact on nitrogen use efficiency, protein synthesis, and crop profitability. These findings:

- Help fertilizer industries reformulate blends based on evidence
- Reduce input waste and environmental risk
- Contribute to sustainable intensification, a key goal of modern industrial agriculture

Linking Research with Agri-Supply Chain and Industry

Your economic data (gross return, net return, and monetary efficiency) highlight how optimized sulfur use can: Enhance the economic sustainability of farming systems and ensure consistent crop supply to industries that rely on Broad beans, such as: Plant-based food industries, Pulse exporters, and Livestock feed manufacturers. This connection supports the Agri-processing and export industries, strengthening their supply chains.

Supporting Climate-Smart and Smart Farming Innovations

The data encourages the adoption of climate-resilient practices like nutrient balancing, which is essential in climate-affected zones like Kandahar. By improving nutrient cycling and soil health, sulfur contributes to resilient farming systems — a key pillar in modern industrial revolutions where sustainability meets technology.

Contributing to Agricultural Policy and Industry Standards

Governments and NGOs can use these findings to develop policy guidelines on sulfur application in legumes, encourage subsidy structures that prioritize evidence-based nutrient use, and Set industry benchmarks for sustainable legume production.

4. Discussion

The present study clearly demonstrates that both the source and rate of sulfur application significantly affect the yield, production efficiency, and profitability of Broad bean cultivation in the semi-arid agro-climatic conditions of Kandahar, Afghanistan. Effect of Sulfur Sources: Among the two sulfur sources tested, gypsum consistently outperformed elemental sulfur across all parameters. This could be attributed to gypsum's higher solubility and faster release of available sulfur into the soil profile, which is especially beneficial for short-duration crops like Broad bean (112 days in this study). The improved plant uptake under gypsum application likely enhanced metabolic functions, protein synthesis, and overall crop vigor, contributing to higher seed yield and better economic returns.

These results are in agreement with earlier findings by Singh et al. (2023), Kumar et al. (2024), and Khaleeq et al. (2024), who also reported that gypsum was a more effective sulfur source in legume production compared to elemental sulfur, particularly in low-sulfur soils.

Effect of Sulfur Levels: Sulfur levels had a strong positive impact on Broad bean performance. Seed yield increased steadily from 0 kg S/ha to 30 kg S/ha, beyond which a slight decline was observed at 40 kg S/ha. This suggests that 30 kg S/ha is the optimal application rate, beyond which nutrient efficiency diminishes—likely due to nutrient imbalance or limited crop demand.

The highest production and monetary efficiency were also recorded at 30 kg S/ha, highlighting its importance not only for maximizing biological output but also for ensuring economic sustainability. Similar observations were reported by

Zahra et al. (2025), Bana et al. (2023), and Rahmani et al. (2024), who emphasized that excessive sulfur application can lead to diminishing returns, especially when soil sulfur levels are adequate or nearing sufficiency.
Furthermore, the significant increase in seed yield due to sulfur fertilization can also be associated with improved nitrogen fixation and chlorophyll formation, both of which are known to be sulfur-dependent processes in legumes (Ali et al., 2024; Ehsan et al., 2024).
Industrial and Practical Implications: From an industrial standpoint, these findings support the production and promotion of gypsum-based sulfur fertilizers. They also inform agronomic advisory services and extension platforms on optimal input strategies for maximizing returns in Broad bean cultivation. Moreover, this study provides an actionable framework for farmers in Afghanistan and similar agro-ecological zones to enhance productivity while maintaining soil health.

5. Conclusion

The present study clearly demonstrates that both the source and rate of sulfur application significantly influence the yield, production efficiency, and economic returns of Broad bean (*Vicia faba* L.) under the agro-climatic conditions of Kandahar, Afghanistan. Among the sulfur sources tested, gypsum outperformed elemental sulfur, producing the highest seed yield of 1,289.1 kg/ha and the greatest net return of AFN 106,579.0/ha. Concerning sulfur application levels, 30 kg S/ha emerged as the most effective, resulting in the highest seed yield (1,426.3 kg/ha), net return (AFN 120,285.0/ha), and production efficiency (12.7 kg/ha/day).
The application of sulfur significantly improved yield and profitability compared to the control, with yield increases reaching up to 64.5%. These findings suggest that applying gypsum at 30 kg S/ha is the most efficient and economically viable strategy for enhancing Broad bean production in semi-arid regions like Kandahar. The research also provides practical insights for nutrient management, fertilizer policy development, and sustainable legume cultivation in Afghanistan and other sulfur-deficient regions.
Further research may be warranted to explore long-term soil health effects, the interaction of sulfur with other nutrients, and the scalability of sulfur-based nutrient strategies under varied agro-ecological conditions.

6. Suggestions

Based on the findings of this study and supported by statistical significance and economic analysis, the following recommendations are proposed for farmers, agronomists, policymakers, and industry stakeholders involved in Broad bean cultivation:

Optimal Sulfur Source: Gypsum

Gypsum should be preferred over elemental sulfur as the sulfur source for Broad bean cultivation, especially in sulfur-deficient soils. Its higher solubility and immediate availability contribute to better crop performance, higher yield, and increased economic returns. Fertilizer companies and agricultural input suppliers should focus on making gypsum more accessible and affordable in pulse-growing regions.

Recommended Application Rate: 30 kg S/ha

The application of sulfur at 30 kg S/ha is recommended as the most effective rate for maximizing seed yield, gross and net returns, and resource use efficiency. Applying more than this rate, such as 40 kg S/ha, showed diminishing returns and is not economically justified under similar soil and climatic conditions.
Adoption of Sulfur-Based Fertility Management
Farmers should incorporate sulfur into their nutrient management plans for Broad bean, particularly in regions where sulfur deficiency is common. Agricultural extension services should update their guidelines and training materials to include sulfur recommendations as a standard practice for pulse crops.
Industry and Policy Support
For Industry: Fertilizer manufacturers are encouraged to formulate and market gypsum-based blended fertilizers tailored for legumes.
For Policymakers: Subsidies or support programs for sulfur fertilizers—especially gypsum—should be considered to promote their use and ensure long-term soil fertility and crop productivity.
For Research Institutions: Further studies should be conducted to validate these findings across diverse agro-ecological zones and to assess the long-term impact of sulfur application on soil health and crop rotation systems.
Integration with Precision Agriculture Tools
The results of this study should be integrated into digital platforms and advisory apps to aid precision farming. Inclusion of sulfur recommendations in nutrient management software will help scale adoption among tech-savvy farmers and cooperatives.
Promotion of Sustainable Legume Production
As Broad bean is a nitrogen-fixing crop, improving its sulfur nutrition supports more sustainable and climate-smart farming. Stakeholders involved in sustainable agriculture programs should incorporate sulfur application practices as part of broader legume intensification strategies.
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