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Effect of Irrigation and Fertilization on Soybean Growth and Yield in Different Soil Types

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Abstract The primary goal of this study was to evaluate the effects of different irrigation and fertilization regimes on the growth and yield of soybean across various soil types. The study found that irrigation and fertilization significantly influenced soybean growth and yield. Optimal fertilization levels, particularly nitrogen, phosphorus, and potassium, were crucial for maximizing yield in arid regions under drip irrigation. Supplemental irrigation during the reproductive stage significantly improved growth and yield in temperate humid climates. Different irrigation regimes also showed varied impacts on yield and water productivity, with partial irrigation proving most effective in semi-dry conditions. Additionally, nitrogen and iron fertilization in Mediterranean-type soils enhanced growth and yield, with a notable interaction between the two nutrients. Soil type played a critical role, with sandy loam soils benefiting most from frequent irrigation. Soil compaction, irrigation, and nitrogenous fertilization collectively influenced vegetative and physiological characteristics, with proper management mitigating negative impacts. The study also highlighted the importance of irrigation intervals and combined soil and foliar fertilization for optimal yield and quality. The findings underscore the importance of tailored irrigation and fertilization strategies to enhance soybean growth and yield across different soil types. Effective management practices, including optimal fertilization and irrigation scheduling, are essential for maximizing productivity and ensuring sustainable soybean cultivation.
Keywords Soybean; Irrigation; Fertilization; Soil types; Yield; Growth; Water productivity; Nitrogen; Phosphorus; Potassium

1 Introduction

Soybean (*Glycine max* (L.) Merr.) is a crucial crop globally, primarily due to its high protein content and its role in enhancing soil fertility through nitrogen fixation. It is extensively cultivated for its seeds, which are a significant source of dietary protein and oil. The global demand for soybean continues to rise, driven by its diverse applications in food, feed, and industrial products (Ngosong et al., 2022). In Europe, the cultivation area for soybean is expanding, reflecting its growing importance in agricultural systems (Adamič and Leskovšek, 2021).

Effective irrigation and fertilization practices are vital for optimizing soybean growth and yield. These practices address soil nutrient deficiencies, which are common constraints in soybean production. The use of chemical fertilizers, while beneficial for enhancing crop productivity, can have adverse environmental impacts if not managed properly (Ngosong et al., 2022). Additionally, alternative tillage systems, such as conservation and no-tillage, influence soil structure and nutrient availability, thereby affecting soybean growth parameters and yield components (Adamič and Leskovšek, 2021). The integration of plant growth-promoting bacteria (PGPB) and arbuscular mycorrhiza fungi (AMF) with fertilization has shown promising results in improving soybean productivity and nutrient content (Ngosong et al., 2022).

Soil type plays a critical role in determining the effectiveness of irrigation and fertilization practices. Different soil types have varying capacities for water retention, nutrient availability, and microbial activity, all of which influence soybean growth and yield. Understanding these interactions is essential for developing tailored management practices that optimize soybean production across diverse agro-ecological zones (Adamič and Leskovšek, 2021; Ngosong et al., 2022). For instance, soil compaction in less intensive tillage systems can negatively impact early plant establishment and overall plant density, highlighting the need for appropriate soil management strategies (Adamič and Leskovšek, 2021).

This study explores the combined effects of irrigation and fertilization on soybean growth and yield across different soil types, aiming to provide insights on how to optimize these practices to enhance soybean productivity while minimizing environmental impacts. By examining the interactions between soil types, irrigation, and fertilization, this study seeks to contribute to the development of sustainable soybean cultivation practices that can adapt to diverse agricultural ecological conditions.

2 Irrigation and Soybean Growth

2.1 Types of irrigation methods in soybean cultivation

Soybean cultivation employs various irrigation methods to optimize water use and enhance crop yield. Common methods include sprinkler irrigation, drip irrigation, and surface irrigation. Sprinkler irrigation is widely used due to its ability to uniformly distribute water across the field, which is particularly beneficial in temperate climates with variable precipitation (Gajić et al., 2018). Drip irrigation, on the other hand, is highly efficient in water-scarce regions as it delivers water directly to the root zone, minimizing evaporation losses and improving water use efficiency (Chomsang et al., 2021). Surface irrigation, though less efficient, is still practiced in some areas due to its simplicity and lower initial costs.

2.2 Water requirements for soybean growth

Soybean plants have specific water requirements that vary across different growth stages. Adequate water supply is crucial during the reproductive stages (R1-R8) to ensure optimal growth and yield. Studies have shown that supplemental irrigation during these stages can significantly enhance total dry matter and leaf area index, leading to higher grain yields (Montoya et al., 2017). The crop coefficients (Kc) used to estimate actual evapotranspiration (ETa) can be generalized for different regions, aiding in the efficient planning of irrigation schedules.

2.3 Impact of water stress and over-irrigation on soybean yield

Water stress at critical growth stages can severely impact soybean yield. For instance, drought stress during the early flowering to pod development stages (R1-R4) can reduce seed yields by up to 46% (Eck et al., 1987). Similarly, over-irrigation can lead to reduced water use efficiency and increased susceptibility to diseases. A study found that maintaining soil moisture at 75% of the maximum soil water holding capacity resulted in better yield outcomes compared to both higher and lower moisture levels (Gebre and Earl, 2021). Over-irrigation not only wastes water but also negatively affects the harvest index and overall productivity (Gajić et al., 2018).

2.4 Adaptation strategies for optimizing irrigation

To optimize irrigation in soybean cultivation, several adaptation strategies can be employed. One effective approach is the use of deficit irrigation, where water is applied at critical growth stages to avoid stress during the most sensitive periods (Sweeney et al., 2003). Additionally, integrating potassium fertilization with irrigation can improve plant water status and physiological responses, thereby enhancing yield under water-deficit conditions (El-Mageed et al., 2017). The use of plant growth-promoting microbes (PGPMs) and nanoparticles (Si-ZnNPs) has also shown promise in mitigating the adverse effects of water stress and salinity, leading to improved growth and productivity (Osman et al., 2021) (Figure 1). These strategies collectively help in achieving sustainable water management and maximizing soybean yield.

3 Fertilization and Soybean Growth

3.1 Nutrient requirements for soybean growth

Soybean growth and development require a balanced supply of both macronutrients and micronutrients. Key macronutrients include nitrogen (N), phosphorus (P), and potassium (K), which are essential for various physiological processes. Nitrogen is crucial for protein synthesis and overall plant growth, phosphorus is vital for energy transfer and root development, and potassium plays a significant role in water regulation and enzyme activation (Basal and Szabó, 2020; Li et al., 2022). Micronutrients such as zinc (Zn), boron (B), manganese (Mn), and iron (Fe) are also critical, albeit required in smaller quantities. These micronutrients are involved in enzyme function, chlorophyll production, and reproductive development (Gaspar et al., 2018; Silva et al., 2019; Dass et al., 2022).

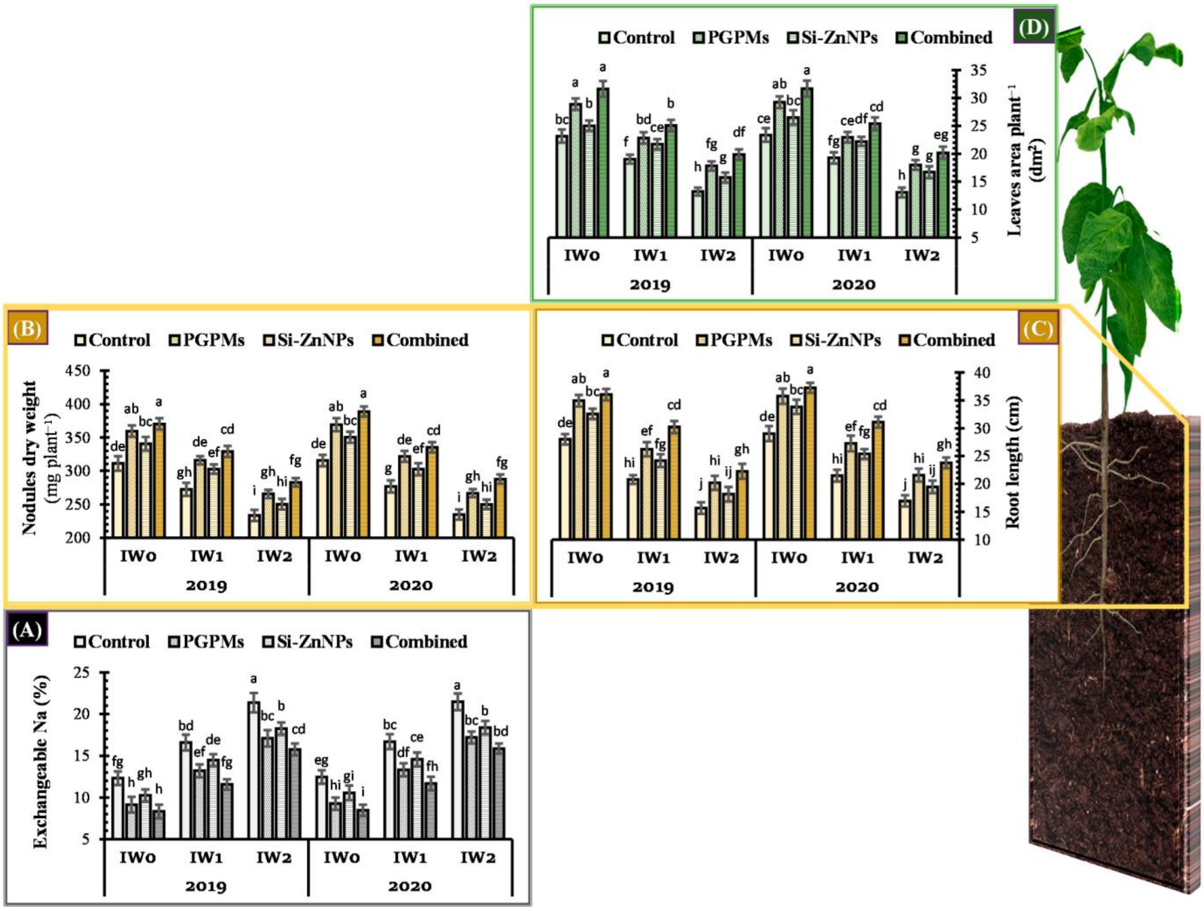

Figure 1 Influence of application of PGPMs, Si-ZnNPs and their combination on (A) the percentage of exchangeable Na in the soil, and (B) nodules dry weight, (C) root length, and (D) total leaves area of soybean plant grown in salt-affected soil with different levels of watering intervals (IW_0; 11 days, IW_1; 15 days, and IW_2; 19 days) during the successive 2019 and 2020 growing seasons. The data presented as means ± SD. Means labeled with the same lower-case letter are not significantly different according to Duncan's Multiple Range Test (Adopted from Osman et al., 2021)

3.2 Effect of fertilization on soybean yield

Different types of fertilizers have varying impacts on soybean yield. Nitrogen fertilizers, when applied correctly, can significantly enhance yield, especially under drought conditions (Basal and Szabó, 2020). Phosphorus and potassium fertilizers also contribute to yield improvement by influencing the harvest index and biomass, respectively (Li et al., 2022). Foliar applications of micronutrients such as Zn, B, and Fe have shown to improve pod formation and seed yield, particularly in semi-arid climates (Çalişkan et al., 2008; Dass et al., 2022). However, the response to micronutrient fertilization can vary based on environmental conditions and soil properties (Gaspar et al., 2018).

3.3 Soil fertility and nutrient management

Soil fertility plays a crucial role in determining the efficiency of fertilizer use and the subsequent growth of soybean. Fertile soils with balanced pH and adequate organic matter content enhance nutrient availability and uptake by plants. For instance, soils with high organic matter and balanced pH levels (6.0-7.0) generally have sufficient micronutrient availability, reducing the need for additional fertilization (Gaspar et al., 2018). Long-term fertilization practices, coupled with rhizobium inoculation, have been shown to improve soil fertility and microbial diversity, which in turn promotes higher soybean yields (Wei et al., 2023). Effective nutrient management strategies, including the use of organic amendments like farmyard manure (FYM) and micronutrients, can maintain soil fertility and support sustainable soybean production (Chaturvedi et al., 2012).

3.4 Challenges of over-fertilization

Over-fertilization poses significant challenges to soil health and the environment. Excessive application of nitrogen fertilizers can lead to nutrient imbalances, reduced plant growth, and lower yields, particularly in the absence of drought conditions (Basal and Szabó, 2020). High rates of fertilization can also result in nutrient leaching, soil acidification, and contamination of water bodies, leading to environmental degradation (Santachiara et al., 2019). Additionally, overuse of fertilizers can disrupt soil microbial communities, reducing soil fertility and affecting long-term agricultural sustainability (Wei et al., 2023). Therefore, it is essential to adopt balanced fertilization practices and integrate organic and inorganic nutrient sources to mitigate the adverse effects of over-fertilization (Chaturvedi et al., 2012).

4 Soil Types and Soybean Growth

4.1 Overview of soil types in agricultural systems

Soybean cultivation is influenced by various soil types, including sandy, clay, and loamy soils. Sandy soils, characterized by large particles and low water retention, are often found in regions with high drainage capacity but may require frequent irrigation (Jahan et al., 2020; Suriadi et al., 2021). Clay soils, with fine particles and high water retention, can support soybean growth but may pose challenges in terms of drainage and root penetration (Hati et al., 2006; Çalişkan et al., 2008). Loamy soils, a balanced mixture of sand, silt, and clay, are considered ideal for soybean cultivation due to their optimal water retention and nutrient availability properties (Lasisi and Aluko, 2009; Arora et al., 2011).

4.2 Soil physical properties and their influence on water and nutrient retention

Soil texture significantly impacts water retention and nutrient availability. Sandy soils, due to their coarse texture, have low water retention and nutrient-holding capacity, necessitating frequent irrigation and fertilization (Jahan et al., 2020; Suriadi et al., 2021). Clay soils, with their fine texture, retain water and nutrients well but can become waterlogged, affecting root growth and nutrient uptake (Hati et al., 2006; Çalişkan et al., 2008). Loamy soils offer a balanced texture that provides adequate water retention and nutrient availability, supporting optimal soybean growth (Lasisi and Aluko, 2009; Arora et al., 2011). The addition of organic amendments like biochar can improve water retention and nutrient availability in both sandy and clay soils (Jahan et al., 2020).

4.3 Soil chemistry and its impact on soybean nutrition

Soil chemistry, including pH, organic matter content, and cation exchange capacity (CEC), plays a crucial role in soybean nutrition. Optimal soil pH for soybean growth ranges from 6.0 to 7.0, as extreme pH levels can hinder nutrient availability and uptake (Çalişkan et al., 2008). Organic matter enhances soil structure, water retention, and nutrient supply, promoting better root development and nutrient absorption (Hati et al., 2006). High CEC in soils, particularly in loamy and clay soils, improves the soil's ability to retain essential nutrients like potassium, calcium, and magnesium, which are vital for soybean growth (Lasisi and Aluko, 2009; Arora et al., 2011).

4.4 Case studies from different agro-ecological zones

Several case studies highlight the impact of soil types, irrigation, and fertilization on soybean growth. In tropical sandy loam soils, conventional tillage methods significantly improved soybean growth and yield compared to no-tillage methods (Lasisi and Aluko, 2009). In Lombok, optimal irrigation schedules varied across soil types, with sandy loam soils requiring more frequent irrigation to achieve the highest yields (Suriadi et al., 2021) (Figure 2; Table 1). The use of biochar amendments in sandy loam and clay loam soils under moisture deficit conditions improved soybean physiological and yield attributes (Jahan et al., 2020). In Western São Paulo, Brazil, cover crops and nitrogen management in sandy soils previously under degraded pastures significantly increased soybean yield (Cordeiro et al., 2021). In Mediterranean-type soils, the combination of nitrogen and iron fertilization improved soybean growth and yield, particularly in soils with high pH and bicarbonate levels (Çalişkan et al., 2008). In central India, the combined use of inorganic fertilizers and farmyard manure in Vertisols improved soil physical properties, water-use efficiency, and soybean yield (Hati et al., 2006). These studies underscore the importance of tailored irrigation and fertilization practices based on specific soil types to optimize soybean growth and yield.

Figure 2 Three experiment sites (yellow pin) of soybean at third planting session (Adopted from Suriadi et al., 2021)

Table 1 Influence of irrigation frequencies on agronomic performance of soybean at coarse sandy soil type (Selaparang site) (Adopted from Suriadi et al., 2021)

Irrigation treatments	Plant height (cm)	Biomass (t ha-1)	100 seed weight	Yield (t ha-1)
I	54.52a	1.72a	9.8a	0.55a
II	67.15b	5.99b	13.36b	1.85b
III	69.07bc	7.69c	15.04c	2.23c
IV	72.17c	8.744c	15.66c	2.68d

5 Interactions between Irrigation, Fertilization, and Soil Types

5.1 Synergistic effects of irrigation and fertilization on soybean yield

Several studies have demonstrated the synergistic effects of irrigation and fertilization on soybean yield. For instance, a study conducted in the arid regions of Northwest China found that optimized fertilization under a drip irrigation system significantly enhanced soybean yield. The study revealed that nitrogen (N) fertilizer had a more pronounced effect on grain yield compared to phosphorus (P) and potassium (K) fertilizers, with the optimal combination of N, P, and K fertilizers resulting in theoretical grain yields exceeding 7.21 tons per hectare (Li et al., 2022) (Figure 3). Similarly, research in Mediterranean-type soils showed that the combined application of nitrogen and iron fertilizers improved soybean growth and yield, with the highest seed yield achieved at 80 kg N ha^{-1} and 400 g Fe ha^{-1} (Çalişkan et al., 2008). Additionally, long-term studies have indicated that the co-application of rhizobium inoculation and phosphorus-potassium fertilization can significantly increase soybean yield and alter soil bacterial community composition, promoting sustainable agricultural practices (Wei et al., 2023).

5.2 Influence of soil type on the effectiveness of irrigation and fertilization

Soil properties play a crucial role in modulating the effectiveness of irrigation and fertilization on crop productivity. For example, in calcareous soils with high calcium carbonate content, potassium fertilization has been shown to improve soybean physiological responses and yield under water deficit conditions. Higher levels of potassium fertilizer significantly increased seed yield and improved plant water status, demonstrating the importance of soil type in determining the effectiveness of fertilization under varying irrigation regimes (El-Mageed et al., 2017). In Vertisols, the combined use of inorganic fertilizers and organic manure improved soil physical properties, root growth, and water-use efficiency, leading to higher soybean yields (Hati et al., 2006). Furthermore, studies in tropical cropping systems have highlighted that soil calcium enrichment through liming and gypsum application can enhance root growth and nitrogen-use efficiency, thereby increasing soybean yield (Souza et al., 2023).

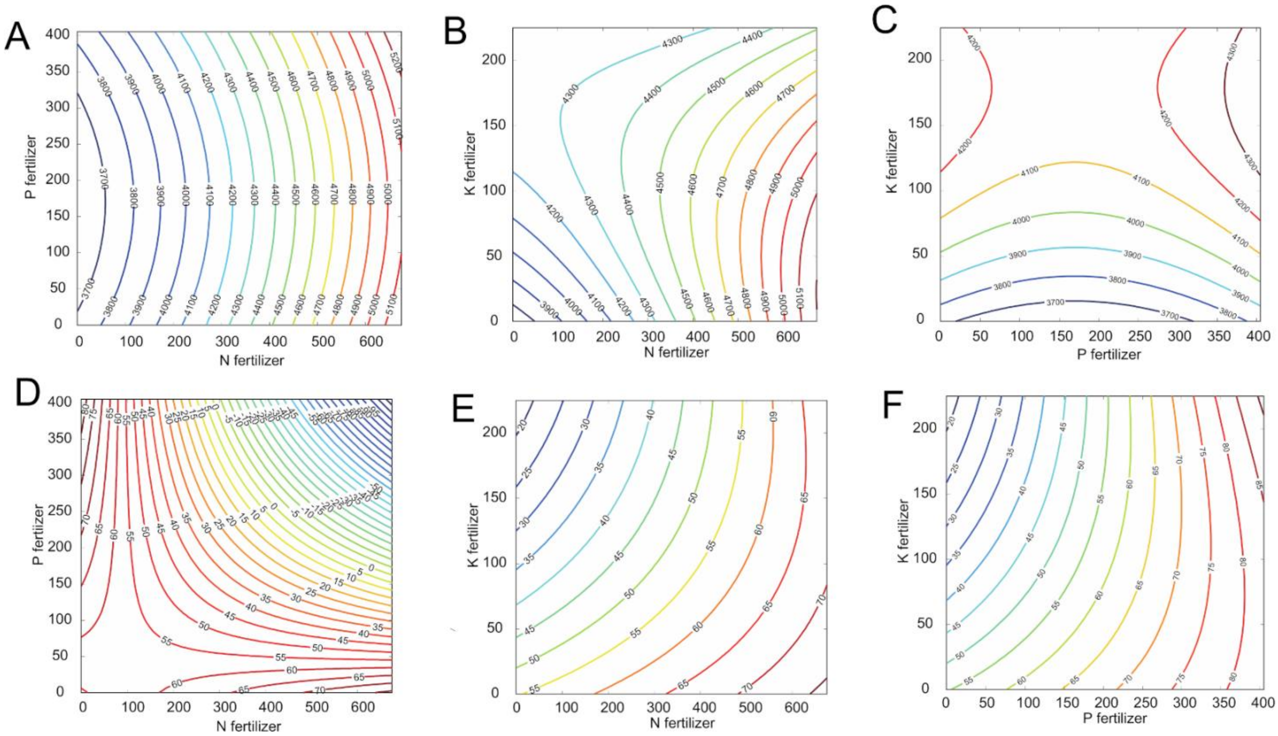

Figure 3 Effects and response surface of interaction among N, P, and K fertilizers on the grain yield (A-C) and biomass per plant (D-F) of soybean (Adopted from Li et al., 2022)

Image caption: (A) effects and response surface of N fertilizers and P fertilizer on grain yield (fixed factor = 0); (B) effects of N fertilizers and K fertilizer on grain yield (fixed factor = 0); (C) effects of P fertilizers and K fertilizer on grain yield (fixed factor = 0); (D) effects of N fertilizers and P fertilizer on biomass per plant (fixed factor = 0); (E) effects of N fertilizers and K fertilizer on biomass per plant (fixed factor = 0); (F) effects of P fertilizers and K fertilizer on biomass per plant (fixed factor = 0) (Adopted from Li et al., 2022)

5.3 Optimization strategies for different soil types

Based on the literature, several optimization strategies can be recommended for different soil types to enhance soybean yield through effective irrigation and fertilization practices:

Arid Regions: In arid regions, drip irrigation combined with optimized fertilization (particularly nitrogen) can significantly boost soybean yield. The recommended fertilization combination includes approximately 411-418 kg N ha^{-1}, 154-251 kg P_2O_5 ha^{-1}, and 118-145 kg K_2O ha^{-1} (Li et al., 2022).

Mediterranean Soils: For Mediterranean-type soils with high bicarbonate and pH, a combination of nitrogen and iron fertilization is beneficial. The optimal rates are 80 kg N ha^{-1} and 400 g Fe ha^{-1}, applied in split doses during the vegetative stages (Çalişkan et al., 2008).

Calcareous Soils: In calcareous soils, higher levels of potassium fertilizer (up to 150 kg K_2O ha^{-1}) are recommended to improve plant water status and yield under water stress conditions (El-Mageed et al., 2017).

Vertisols: The combined application of inorganic fertilizers (NPK) and organic manure (farmyard manure) is effective in Vertisols. This practice improves soil physical properties, root growth, and water-use efficiency, leading to higher yields (Hati et al., 2006).

Tropical Cropping Systems: In tropical systems, soil calcium enrichment through liming and gypsum application, along with appropriate nitrogen fertilization, can enhance root growth and overall yield. This strategy is particularly effective in integrated cropping systems where maize is double-cropped after soybeans (Souza et al., 2023).

6 Environmental and Climate Factors

6.1 Climate conditions and their impact on soybean irrigation

Climate conditions, including temperature, rainfall patterns, and overall climate variability, significantly influence soybean water requirements. In temperate regions, the amount and distribution of precipitation during the growing season are critical for soybean yield. For instance, a study conducted over three years demonstrated that different irrigation regimes significantly impacted soybean yield and water productivity, particularly under varying precipitation conditions. The study found that irrigation is essential in semi-dry and dry years when seasonal precipitation is below 300 mm, while in wet years, yields were comparable to those achieved with irrigation due to favorable precipitation distribution (Gajić et al., 2018).

In regions characterized by high annual precipitation but with periods of soil water deficit, supplemental irrigation during the reproductive stage (R1-R8) has been shown to positively affect soybean growth and yield. This is particularly important as rainfed conditions resulted in a 35% reduction in yield compared to irrigated treatments (Montoya et al., 2017). Additionally, combined heat and drought stress can drastically reduce soybean yields, with irrigation playing a crucial role in mitigating these stresses. For example, in the USA, irrigation alleviated both water and heat stresses, although dependencies on temperature and precipitation remained (Luan et al., 2021).

Elevated atmospheric CO_2 and temperature also affect soybean water use. Studies have shown that elevated CO_2 levels can enhance crop biomass and yields, potentially altering water use efficiency. However, these effects are modulated by air temperature and nitrogen management, indicating the complex interplay between climate factors and crop water requirements (Lenka et al., 2020).

6.2 Soil erosion and conservation techniques

Soil erosion and degradation are significant concerns in irrigated and fertilized soybean fields. Various conservation techniques can be employed to prevent soil degradation and maintain soil health. One effective approach is the use of plant growth-promoting microbes (PGPMs) and nanoparticles (Si-ZnNPs), which have been shown to enhance soybean growth and productivity under water deficit and salt-affected soil conditions. These treatments improve leaf potassium content, photosynthetic pigments, and relative water content, thereby reducing oxidative damage and enhancing overall plant health (Osman et al., 2021).

In addition, proper nitrogen fertilizer management is crucial in preventing soil degradation. For instance, excessive soil moisture from extreme precipitation events can lead to nitrogen loss and reduced crop yields. Field trials have demonstrated that pre-plant nitrogen fertilizer applications, combined with rescue nitrogen applications, can mitigate these effects and improve yields in subsequent soybean crops (Kaur et al., 2017).

Drip irrigation is another effective technique for preventing soil degradation in low rainfall regions. Drip irrigation helps maintain plant water status, which is critical for dry matter production and yield. Studies have shown that drip irrigation can prevent yield decreases in years with low rainfall, highlighting its importance in maintaining soil health and productivity (Chomsang et al., 2021).

7 Economic Considerations of Irrigation and Fertilization

7.1 Cost-benefit analysis of irrigation practices

The economic viability of different irrigation methods for soybean cultivation varies significantly based on regional climatic conditions and the specific irrigation practices employed. For instance, in the temperate humid climate of Salto, Uruguay, supplemental irrigation during the reproductive stage (R1-R8) was found to increase soybean yield by up to 35% compared to rainfed conditions. However, the economic benefit of this practice was contingent on soybean prices being above $350 per ton. When prices fell below this threshold or when rainfall was stable, rainfed conditions were more economically viable (Montoya et al., 2017).

In the Loess Plateau of China, a two-year study comparing drip irrigation (DI) and flood irrigation (FI) found that DI combined with 80% field capacity irrigation and 750 kg/hm^2 fertilization yielded the highest economic benefits. This combination improved soil moisture and nutrient content, leading to increased crop yields and overall profitability (Luo et al., 2023). Similarly, in Japan's low rainfall regions, drip irrigation was shown to prevent yield decreases in dry years, thereby stabilizing income for farmers (Chomsang et al., 2021).

7.2 Financial implications of fertilization strategies

Fertilization strategies also play a crucial role in the economic outcomes of soybean farming. In the arid regions of Northwest China, a study demonstrated that nitrogen (N) fertilization had a more significant impact on soybean yield compared to phosphorus (P) and potassium (K). The optimal fertilization combination for maximizing yield and quality traits was found to be 411.62~418.39 kg/ha N, 153.97~251.03 kg/ha P_2O_5, and 117.77-144.73 kg/ha K_2O. This optimized fertilization strategy not only enhanced yield but also improved the cost-efficiency of fertilizer use (Li et al., 2022).

In the Indian mid-Himalaya, long-term fertilization with a combination of farmyard manure (FYM) and recommended doses of NPK fertilizers significantly increased soybean yield under both rainfed and supplementary irrigation conditions. The highest economic returns were observed with the combined application of FYM and NPK, highlighting the cost-efficiency of integrating organic and inorganic fertilizers (Panday et al., 2018).

Moreover, in the steppe zone of Central Ciscaucasia, the application of mineral fertilizers in combination with biological nitrogen (rhizotorfin) was found to be economically feasible. The highest profitability was achieved with the application of N12P52 and pre-sowing inoculation with rhizotorfin, resulting in a profitability rate of 68.8% (Shabaldas et al., 2020).

8 Challenges and Future Perspectives

8.1 Environmental and economic constraints

Water scarcity and soil degradation are significant challenges in soybean cultivation. Water stress, often exacerbated by soil salinity, severely limits plant productivity and soil fertility, leading to reduced yields and increased oxidative damage in plants (Osman et al., 2021). Additionally, inappropriate water and fertilizer management can lead to soil degradation and groundwater pollution, further complicating sustainable agricultural practices (Yan et al., 2021). Economic considerations also play a crucial role; for instance, in regions like Uruguay, the profitability of supplemental irrigation is highly dependent on soybean market prices, making it a less viable option when prices are low or rainfall is stable (Montoya et al., 2017). Therefore, balancing the economic costs with environmental sustainability is essential for long-term agricultural success.

8.2 Technological advances in irrigation and fertilization

Technological advancements such as precision agriculture and smart irrigation systems offer promising solutions to the challenges of irrigation and fertilization. Precision agriculture techniques, including the use of soil moisture sensors and crop coefficients, can optimize water use efficiency and ensure that irrigation is applied only when necessary, thereby conserving water resources (Montoya et al., 2017). Smart irrigation systems, which can adjust water application based on real-time data, further enhance water use efficiency and crop yield (Yang et al., 2022). Additionally, the integration of plant growth-promoting microbes (PGPMs) and nanoparticles has shown potential in mitigating the adverse effects of water stress and soil salinity, thereby improving soybean growth and productivity under challenging conditions (Osman et al., 2021).

8.3 Sustainable practices for soybean cultivation

Future directions for sustainable soybean cultivation should focus on the integration of advanced irrigation and fertilization techniques with sustainable agricultural practices. The use of drip irrigation systems, combined with optimized fertilization strategies, has been shown to significantly enhance soybean yield and quality traits in arid regions (Li et al., 2022). No-till farming practices, coupled with appropriate phosphorus fertilization, can improve soil properties and phosphorus use efficiency, leading to higher soybean yields (Chauke et al., 2022). Long-term co-application of rhizobium inoculation and fertilizers not only increases soybean yield but also promotes soil microbial diversity, which is crucial for maintaining soil health and fertility (Wei et al., 2023). Therefore, adopting a holistic approach that combines technological innovations with sustainable practices is essential for the future of soybean cultivation.

9 Conclusion

The review of various studies on the effect of irrigation and fertilization on soybean growth and yield across different soil types has highlighted several critical insights. Optimal fertilization levels, particularly nitrogen (N), phosphorus (P), and potassium (K), significantly influence soybean yield, with nitrogen being the most sensitive factor in arid regions. Supplemental irrigation during the reproductive stages has been shown to enhance soybean growth and yield, especially in regions with high annual precipitation but periodic soil water deficits. The interaction between irrigation and fertilization regimes is crucial, as inappropriate management can lead to unstable yields and potential soil degradation. Different irrigation regimes, such as full irrigation and deficit irrigation, have varying impacts on yield and water productivity, with moderate irrigation often providing the best balance. Long-term fertilization combined with supplementary irrigation can significantly improve yield and water use efficiency in rainfed systems. Drip irrigation has been found to prevent yield decreases in low rainfall years, highlighting its importance in maintaining stable yields. Tailored irrigation schedules based on soil type can optimize soybean production, with sandy loam soils benefiting the most from frequent irrigation. Potassium fertilization under water deficit conditions can improve physiological responses and yield. Soil compaction, irrigation, and fertilization collectively influence vegetative and physiological characteristics, with proper management mitigating negative impacts. Finally, specific irrigation intervals and combined soil and foliar fertilization can maximize yield and quality.

The importance of tailored irrigation and fertilization practices based on soil types cannot be overstated for enhancing soybean productivity. Different soil types respond uniquely to irrigation and fertilization regimes, necessitating customized approaches to maximize yield and resource use efficiency. For instance, sandy loam soils require more frequent irrigation to achieve optimal yields, while loam and clay soils may not need as frequent watering. In arid regions, precise nitrogen fertilization is critical to achieving high yields under drip irrigation systems. In temperate regions with variable precipitation, supplemental irrigation during critical growth stages can significantly boost yields. Additionally, the combination of soil and foliar fertilization, particularly with potassium, can enhance plant water status and yield under water deficit conditions. Long-term studies have shown that integrating organic and inorganic fertilizers with appropriate irrigation schedules can sustainably improve productivity and water use efficiency in rainfed systems. Therefore, understanding the specific requirements of different soil types and adjusting irrigation and fertilization practices accordingly is essential for optimizing soybean growth and yield, ensuring sustainable agricultural practices, and enhancing overall productivity.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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