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Advances in Agronomic Practices for High-Yield Soybean Cultivation

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Abstract Soybeans are a critical crop for global food security and agricultural economies, making it essential to identify and optimize agronomic practices that enhance yield and sustainability. This review explores various strategies for improving soybean cultivation through advanced agronomic practices. We examine soil health management, including organic and inorganic fertilization, crop rotation, and sustainable practices from global case studies. Water management, including irrigation techniques and drought resistance, is discussed in the context of optimizing yield potential. The role of advanced crop management, such as planting optimization, weed control, and tillage practices, is evaluated for improving soybean productivity. Genetic improvement through breeding technologies, including marker-assisted selection and CRISPR, is explored to boost yield and disease resistance. Additionally, we assess the importance of sustainable agricultural practices like integrated pest management and precision agriculture in reducing environmental impact. The review concludes with a case study comparing agronomic practices in the United States and Argentina, illustrating the effectiveness of these strategies in boosting soybean yields. This study aims to provide a comprehensive review of current best practices and future directions for soybean cultivation, offering insights for enhancing productivity and sustainability in global agriculture.%
Keywords Soybean cultivation; Agronomic practices; Soil fertility; Water management; Genetic improvement

1 Introduction

Soybean (*Glycine max* L.) is a critical crop globally, renowned for its high protein and oil content, making it a staple in both human and animal diets. Its cultivation is pivotal not only for food security but also for its role in enhancing soil fertility through nitrogen fixation (Ngosong et al., 2022; Wang et al., 2022). The crop's adaptability to various climatic conditions and its economic significance have led to extensive research aimed at optimizing its yield and quality (Assefa et al., 2019; Sobko et al., 2020). In regions like Europe, where soybean cultivation is expanding, understanding the crop's agronomic requirements is essential for maximizing productivity (Adamič and Leskovšek, 2021).

Agronomic practices significantly influence soybean yield and quality. Traditional methods, such as the use of chemical fertilizers, have been shown to improve growth and yield but often at the expense of environmental sustainability. Recent studies have highlighted the benefits of integrating organic manures and plant growth-promoting bacteria (PGPB) with chemical fertilizers to enhance soil health and crop productivity (Lohar and Hase, 2022; Ngosong et al., 2022). Additionally, innovative approaches like the use of Fe-based nanomaterials and conservation tillage systems are being explored to further improve soybean growth and yield (Adamič and Leskovšek, 2021). The choice of seeding systems, such as drilling versus precision seeding, also plays a crucial role in determining the agronomic characteristics and yield of soybean (Sobko et al., 2020).

This study attempts to explore the impact of integrated nutrient management practices, including the use of chemical fertilizers, organic manures, and microbial inoculants, on soybean yield and soil health, discuss the effectiveness of innovative technologies such as nanomaterials and conservation tillage in enhancing soybean growth and nodulation, and provide an overview of the influence of different seeding systems on soybean agronomic traits and yield stability, while identifying key genetic and environmental factors that contribute to soybean seed composition and yield, offering insights for future breeding programs. Through these efforts, the study aims to provide a comprehensive understanding of the current best practices in soybean cultivation and their potential to achieve sustainable high yields.

2 Improvement of Soil Health and Fertility for Soybean Production

2.1 Soil fertility management for soybean cultivation

Effective soil fertility management is crucial for optimizing soybean yield and ensuring long-term soil health. Various studies have demonstrated the importance of both organic and inorganic amendments in enhancing soil fertility. For instance, long-term organic amendments, such as straw and manure, have been shown to significantly increase soil organic matter and total nitrogen, thereby improving soybean yields (Amadou et al., 2021). Additionally, the integration of biochar-based fertilizers in crop rotations has been found to enhance soil parameters and crop quality traits, further supporting sustainable soybean production (Yuan et al., 2022).

2.2 Organic and inorganic fertilization practices

The combination of organic and inorganic fertilization practices has been widely studied for its benefits on soybean yield and soil health. Research indicates that the application of manure combined with chemical fertilizers can significantly improve nitrogen use efficiency and soil fertility, leading to higher crop yields (Hua et al., 2020). Similarly, the use of composted sewage sludge has been shown to enhance soybean production and agronomic performance in naturally infertile soils, such as those in the Cerrado region of Brazil (Prates et al., 2020). These findings highlight the potential of integrated fertilization practices in promoting sustainable soybean cultivation.

2.3 Crop rotation and its benefits on soybean yield

Crop rotation is a well-established practice that offers numerous benefits for soybean yield and soil health. Studies have shown that diversified crop rotations, such as corn-soybean sequences, can significantly increase crop yields compared to monocultures (Yuan et al., 2022). Additionally, crop rotation has been found to improve soil microbial communities and nutrient status, further enhancing soybean productivity (Wang et al., 2023). The positive effects of crop rotation on soil fertility and crop yield underscore its importance in sustainable agronomic practices.

2.4 Soil conditions and improvement needs in soybean cultivation fields

In soybean cultivation fields, soil health and fertility are critical factors that determine crop yield and quality. However, prolonged monocropping, excessive use of chemical fertilizers, and depletion of soil organic matter have led to soil degradation, acidification, and imbalances in microbial communities. These issues restrict the soil's ability to supply essential nutrients required for soybean growth, further affecting nitrogen fixation efficiency and stress resistance. Field observations in many soybean-growing regions indicate high soil compaction, low organic matter content, and suppressed rhizobial activity. In this context, adopting integrated soil improvement practices is essential. Measures such as applying organic fertilizers, returning crop residues to the field, planting green manure crops, and optimizing crop rotation systems can enhance soil nutrient content and organic matter levels. These practices not only improve soil structure and promote microbial activity but also provide a healthier soil environment for sustainable soybean production (Figure 1).

3 Water Management Strategies for High-Yield Soybeans

3.1 Efficient irrigation techniques (drip, sprinkler, and subsurface drip irrigation)

Efficient irrigation techniques are crucial for optimizing water use and enhancing soybean yield. Drip irrigation, including surface drip (SDI) and subsurface drip irrigation (SSDI), has been shown to significantly improve water productivity and yield. A study conducted in Antalya, Turkey, demonstrated that SSDI treatments used approximately 90 mm less water than SDI without any reduction in yield, indicating higher water use efficiency (Aydinsakir et al., 2021). Similarly, a meta-analysis in China found that drip fertigation, which combines drip irrigation with fertilization, led to a 26.4% increase in water productivity and a 12.0% increase in yield compared to traditional irrigation methods (Li et al., 2021).

Sprinkler irrigation is another effective technique. Research has shown that sprinkler irrigation at 80% crop evapotranspiration (ETC) significantly improved physiological performance, water productivity, and yield of soybeans compared to standard flood irrigation (Sachin et al., 2023). This method also reduced canopy temperature, which is beneficial for maintaining plant health under heat stress conditions.

Figure 1 Field situation of soybean planting (Photo credit: Yuting Zhong)

3.2 Water conservation practices in soybean production

Water conservation practices are essential for sustainable soybean production, especially in regions with limited water resources. One effective practice is the use of optimized irrigation regimes. For instance, a study in a temperate environment found that applying 65% of full irrigation (I65) produced the highest seed yield and water productivity, indicating that moderate water stress can enhance water use efficiency without compromising yield (Gajić et al., 2018).

Another conservation strategy is the integration of crop rotation and no-till farming systems. Research in São Paulo, Brazil, showed that irrigation rates of 70% and 100% of reference evapotranspiration (ETo) in conventional systems provided higher grain yields. However, the study also highlighted the potential long-term benefits of no-till systems, which can improve soil moisture retention and reduce water requirements over time (Cruz et al., 2021).

3.3 Drought resistance and management of water stress

Developing drought-resistant soybean varieties and implementing effective water stress management practices are critical for maintaining high yields under water-limited conditions. High-yielding soybean varieties have been shown to cope with mild drought by enhancing their photoprotective defenses and increasing intrinsic water use efficiency. For example, the variety N-3001 exhibited a faster transition into the reproductive stage to avoid drought periods, demonstrating a strategic adaptation to water stress (Buezo et al., 2018).

Additionally, precise irrigation management can mitigate the effects of drought. A study using the APEX model in Arkansas, USA, found that reducing irrigation by up to 20% from the original amount did not significantly reduce yields, suggesting that careful irrigation scheduling can conserve water without sacrificing productivity (Carroll et al., 2020). This approach, combined with the selection of drought-tolerant varieties, can significantly enhance the resilience of soybean crops to water stress.

Efficient irrigation techniques, water conservation practices, and the development of drought-resistant varieties are key strategies for achieving high-yield soybean cultivation. Drip and sprinkler irrigation methods have proven effective in enhancing water productivity and yield, while optimized irrigation regimes and conservation practices can further improve water use efficiency. By integrating these strategies, soybean producers can sustainably manage water resources and maintain high yields even under challenging environmental conditions.

4 Advanced Crop Management and Field Practices

4.1 Planting time and density optimization

Optimizing planting time and density is crucial for maximizing soybean yield (Figure 2). Early planting has been shown to expedite canopy closure and increase yield. For instance, early planted soybeans reached 90% green canopy cover (T90) faster and yielded more compared to standard planting times. Additionally, narrow-row spacing can further expedite canopy closure, although it may not significantly impact yield compared to wider rows (Arsenijevic et al., 2021). These findings suggest that early planting and optimal row spacing are effective strategies for enhancing soybean growth and yield.

Figure 2 Sowing density of soybeans (Photo credit: Yuting Zhong)

4.2 Weed control and integrated pest management (IPM)

Effective weed control is essential for high-yield soybean cultivation. Integrated pest management (IPM) strategies, which include the use of cover crops and reduced reliance on chemical herbicides, have shown promise. Cover crops like cereal rye can significantly suppress weed biomass and improve soybean yields (Vincent-Caboud et al., 2019a). Moreover, conservation practices such as no-till farming and cover cropping can enhance biological pest control by supporting populations of arthropod predators, reducing the need for insecticides (Rowen et al., 2022). These practices not only control weeds but also contribute to sustainable farming by improving soil health and reducing chemical inputs.

4.3 Tillage vs no-till farming for soybean crops

The choice between tillage and no-till farming has significant implications for soybean yield and soil health. No-till systems, especially when combined with cover crops, can reduce soil erosion, improve soil structure, and enhance water retention (Figure 3) (Islam et al., 2015; Silva et al., 2022). However, the success of no-till systems depends on effective cover crop management. For example, no-till systems with herbicide-based cover crop termination produced the highest soybean yields, while herbicide-free systems had lower yields due to challenges in cover crop termination timing (Halwani et al., 2019). Long-term studies have shown that no-till systems with appropriate cover crop rotations can sustain high soybean yields and improve soil quality.

Figure 3 Long-term no-till maize-soybean (soya) strip row farming practice located in Dunnville, Ontario, Canada (Adopted from Islam et al., 2015)

Image caption: Left, alternate maize and soybean strips. Right, experimental site in June 2013 demonstrates that crops are grown in twin rows and retain crop residues on the soil surface. The maize and soybean strips shown here were planted with alternate crop in 2012. In 2013, planting was done exactly on the previous cropping rows (Adopted from Islam et al., 2015)

4.4 Cover cropping and its role in enhancing soybean growth

Cover cropping plays a vital role in enhancing soybean growth by improving soil health and suppressing weeds. Cover crops like cereal rye and sunn hemp have been shown to increase soybean yield and provide greater water stability to the plants (Silva and Vereecke, 2019; Silva et al., 2022). The biomass produced by cover crops acts as mulch, reducing weed pressure and conserving soil moisture (Vincent-Caboud et al., 2019a). However, the effectiveness of cover crops can vary based on species, environmental conditions, and management practices. For instance, cover crop-based rotational tillage systems have been effective in organic farming, although challenges remain in maximizing soybean yields due to delayed planting and early growth. Future research should focus on optimizing cover crop species and management practices to enhance their benefits for soybean cultivation (Vincent-Caboud et al., 2019b; Han et al., 2022).

Advanced crop management and field practices, including optimized planting time and density, integrated pest management, no-till farming, and cover cropping, are essential for high-yield soybean cultivation. These practices not only improve soybean yield but also contribute to sustainable farming by enhancing soil health and reducing chemical inputs. Continued research and refinement of these practices will be crucial for meeting the growing demand for soybeans while maintaining environmental sustainability.

5 Genetic Improvement for High-Yield Soybean Cultivation

5.1 Genetic selection for yield and disease resistance

Genetic selection has been pivotal in enhancing soybean yield and disease resistance. Studies have shown that significant marker-trait associations for yield and other agronomic traits can be identified through genome-wide association studies (GWAS) and genomic selection (GS). For instance, a study involving 250 soybean accessions identified SNP markers significantly associated with yield, maturity, plant height, and seed weight, which can be utilized in marker-assisted selection (MAS) and GS to improve these traits (Ravelombola et al., 2021).

Additionally, the development of nested association mapping (NAM) populations has revealed significant marker-trait associations, demonstrating the value of expanding the genetic base of soybean breeding (Diers et al., 2018). These genetic advancements are crucial for developing high-yield, disease-resistant soybean cultivars (Hong and Huang, 2024).

5.2 Role of biotechnology in enhancing soybean productivity

Biotechnology plays a significant role in enhancing soybean productivity by introducing traits such as insect resistance and herbicide tolerance. These biotech traits indirectly contribute to yield improvement by reducing losses due to pests and weeds (Ramachandra et al., 2015). Moreover, the integration of high-throughput phenotyping technologies, such as UAV-based multispectral imaging, has improved the accuracy of selecting high-yield soybean varieties. This technology allows for the efficient selection of superior genotypes based on image-derived secondary traits, which has been shown to outperform traditional breeder selections (Zhou et al., 2022). These biotechnological advancements are essential for meeting the increasing global demand for soybean.

5.3 Marker-assisted selection (MAS) in soybean breeding

Marker-assisted selection (MAS) has revolutionized soybean breeding by enabling the precise selection of desirable traits. MAS involves the use of molecular markers linked to specific traits, allowing for the efficient selection of high-yield and stress-resistant varieties. For example, MAS has been successfully used to stack multiple stress resistance genes in rice, demonstrating its potential for similar applications in soybean (Ludwików et al., 2015). Additionally, the identification of SNP markers associated with key agronomic traits through GWAS provides valuable resources for MAS in soybean breeding programs (Diers et al., 2018; Ravelombola et al., 2021). The integration of MAS with genomic selection further enhances the efficiency and accuracy of breeding efforts.

5.4 CRISPR and genetic modification for yield enhancement

CRISPR and other genetic modification techniques offer promising avenues for yield enhancement in soybean. These technologies allow for precise genome editing to introduce or modify traits that contribute to higher yield and stress tolerance. For instance, the loss-of-function of the GIGANTEA gene in soybean has been shown to enhance salt tolerance and early maturity, providing a target for molecular breeding (Dong et al., 2022). Additionally, the development of genomic resources and advanced breeding techniques, such as speed breeding and machine learning, further supports the application of CRISPR in soybean improvement (Thudi et al., 2020). These cutting-edge technologies hold significant potential for achieving substantial yield gains in soybean cultivation.

The genetic improvement of soybean for high yield and disease resistance has made significant strides through the application of advanced molecular techniques and biotechnological innovations. Genetic selection, biotechnology, MAS, and CRISPR-based genetic modification are all contributing to the development of superior soybean cultivars. These advancements are essential for meeting the growing global demand for soybean and ensuring sustainable agricultural practices.

6 Sustainable Agricultural Practices for Soybean Cultivation

6.1 Integrated pest management (IPM) and its role in sustainable soybean farming

Integrated Pest Management (IPM) is a cornerstone of sustainable soybean farming, offering a balanced approach to pest control that minimizes environmental impact while maintaining or enhancing crop yields. IPM strategies incorporate a variety of pest control methods, including biological control, cultural practices, and the judicious use of chemical pesticides based on economic thresholds. For instance, the adoption of IPM in Brazil has significantly reduced pesticide applications from six to approximately two per season, demonstrating both economic and environmental benefits (Bortolotto et al., 2015; Bueno et al., 2023). Additionally, IPM practices have been shown to conserve beneficial insects such as pollinators, which are crucial for crop productivity. A study in the Midwestern United States revealed that IPM could reduce insecticide use by 95% while increasing crop yields through enhanced pollination by wild bees (Pecenka et al., 2021). These findings underscore the potential of IPM to achieve sustainable pest management in soybean cultivation.

6.2 Reducing environmental impact through precision agriculture

Precision agriculture (PA) leverages advanced technologies such as satellite imagery, drone surveillance, and soil sensors to optimize resource use and reduce the environmental footprint of farming activities (Nemade et al., 2023). By enabling precise application of inputs like water, fertilizers, and pesticides, PA minimizes waste and mitigates adverse environmental impacts. For example, integrating PA with IPM can enhance pest management efficiency and reduce chemical usage, thereby promoting ecological balance (Bueno et al., 2020). The use of precision tools allows for targeted interventions, ensuring that resources are applied only where needed, which not only conserves inputs but also reduces greenhouse gas emissions associated with over-application (Langeroodi et al., 2019). This synergy between PA and IPM represents a promising avenue for sustainable soybean cultivation, as it combines technological innovation with ecological principles to achieve high yields with minimal environmental impact.

6.3 Climate-smart agriculture approaches

Climate-smart agriculture (CSA) encompasses a range of practices designed to increase agricultural productivity, enhance resilience to climate change, and reduce greenhouse gas emissions (Sekabira et al., 2023). In the context of soybean cultivation, CSA practices include the use of no-tillage systems, residue management, and optimized nitrogen fertilization. Field experiments in Iran demonstrated that no-tillage combined with wheat residue mulch and moderate nitrogen application significantly reduced CO_2 and N_2O emissions while maintaining soybean yields (Langeroodi et al., 2019). These practices not only mitigate climate change by lowering greenhouse gas emissions but also improve soil health and water retention, contributing to long-term agricultural sustainability. Additionally, CSA approaches often incorporate IPM and PA techniques to further enhance resilience and productivity, making them integral to the future of sustainable soybean farming (Kebe et al., 2023). By adopting CSA practices, farmers can better adapt to changing climatic conditions while ensuring food security and environmental conservation.

7 Impact of Agronomic Practices on Soybean Yield: A Case Study

7.1 Case study: analysis of agronomic practices in the united states and Argentina

Agronomic practices significantly influence soybean yield, with various strategies being implemented across different regions to optimize production. In the United States, integrated agronomic and weed management practices, such as early planting, narrow row spacing, and conventional tillage, have been shown to enhance soybean canopy development and yield. Early planting, in particular, resulted in a yield increase of 188 to 902 $kg \cdot ha^{-1}$ compared to standard planting times (Arsenijevic et al., 2021). Additionally, the use of preemergence herbicides, although slightly delaying canopy closure, did not negatively impact yield, highlighting the importance of weed management in maintaining high productivity.

In Argentina, the focus has been on understanding the environmental impacts of soybean cultivation, particularly greenhouse gas (GHG) emissions and energy efficiencies. Studies have shown that the Pampean region exhibits higher GHG and energy efficiencies compared to the extra-Pampean region, primarily due to differences in climate and precipitation (Arrieta et al., 2018). This regional analysis underscores the need for tailored agronomic practices that consider local environmental conditions to optimize yield and sustainability.

7.2 Comparative yield data pre- and post-implementation of agronomic strategies

The implementation of advanced agronomic practices has led to notable improvements in soybean yield. For instance, in Brazil, co-inoculation of soybean with *Azospirillum brasilense* and *Bradyrhizobium* spp. has been shown to increase grain yield by 3.2% compared to single inoculation methods (Barbosa et al., 2021). Similarly, the use of composted sewage sludge (CSS) as a fertilizer in the Cerrado region of Brazil resulted in a 12 to 20% increase in soybean yield compared to conventional fertilization methods (Prates et al., 2020).

In Malawi, the adoption of improved soybean varieties and agronomic practices (ISVAPs) has led to a 61% yield gain and a 53% income gain for adopters compared to non-adopters (Tufa et al., 2019). This significant increase in yield highlights the potential benefits of adopting advanced agronomic practices in smallholder farming systems.

7.3 Lessons learned and future directions

The case studies from the United States, Argentina, Brazil, and Malawi provide valuable insights into the impact of agronomic practices on soybean yield. Key lessons learned include early planting and narrow row spacing, which are effective strategies for enhancing soybean yield by promoting faster canopy closure and reducing competition with weeds (Arsenijevic et al., 2021). Additionally, co-inoculation with beneficial bacteria such as *Azospirillum brasilense* and *Bradyrhizobium* spp. can improve root mass, nodule number, and grain yield, particularly in regions with specific soil and climatic conditions (Barbosa et al., 2021). The use of organic fertilizers, such as composted sewage sludge, also plays a role in sustainably increasing soybean yield in infertile soils, offering an alternative to conventional mineral fertilizers (Prates et al., 2020). Furthermore, agronomic practices must be tailored to local environmental conditions to optimize yield and sustainability, as evidenced by the Pampean region in Argentina, where favorable climatic conditions lead to higher GHG and energy efficiencies.

Future research should focus on further refining these practices to enhance their effectiveness and adaptability across different regions. Additionally, there is a need for continued efforts to improve the availability and quality of inoculants and organic fertilizers to support sustainable soybean production. By integrating these advanced agronomic strategies, farmers can achieve higher yields and contribute to the overall sustainability of soybean cultivation.

8 Concluding Remarks

Recent studies have highlighted several agronomic practices that significantly enhance soybean yield. The adoption of no-till strip row farming, which involves growing maize and soybeans in alternate strips and rotating them yearly, has shown a remarkable 75% increase in maize yield, suggesting potential benefits for soybean as well. Foliar application of macro- and micronutrients, particularly chelated zinc, has been demonstrated to improve soybean productivity, economic returns, and resource-use efficiency in semi-arid climates. Co-inoculation of soybean with *Azospirillum brasilense* and *Bradyrhizobium* spp. has also been found to increase root mass, nodule number, and grain yield, contributing to sustainable soybean production. Additionally, the use of composted sewage sludge as a fertilizer in naturally infertile soils has resulted in significant yield increases, highlighting the potential of organic fertilizers in enhancing soybean production.

Despite these advancements, several challenges remain in soybean production. Weather volatility continues to be a major factor affecting yield variability, as demonstrated by the significant impact of weather conditions on soybean yield in drained paddy fields. The need for sustainable nutrient management practices is critical, particularly in regions with semi-arid climates where inadequate nutrient management poses a significant challenge. Furthermore, the integration of weed management practices with agronomic practices is essential to ensure timely canopy closure and optimal yield, as delayed canopy development due to weed competition can significantly reduce yields. The environmental impact of soybean cultivation, particularly greenhouse gas emissions, also presents a challenge that requires the development of agronomic practices that mitigate these emissions while maintaining yield.

Research and innovation play a crucial role in addressing the challenges of sustainable soybean farming. The development and dissemination of improved soybean varieties and agronomic practices have been shown to significantly enhance productivity and income for smallholder farmers. The integration of technology, such as precision agriculture tools, sensor-based monitoring systems, and AI applications, has revolutionized farming by enabling precise resource management and data-driven decision-making. Additionally, the adoption of integrated production systems that utilize crop residues.

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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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