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Optimizing Soybean Yield Through Integrated Agronomic Management

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Abstract This study examines the role of Integrated Agronomic Management (IAM) in optimizing soybean (*Glycine max* L.) yield and sustainability through a combination of strategic agricultural practices. Recognizing the dual importance of soybean as a major protein and oil source and as a soil-enhancing crop, IAM integrates chemical fertilizers, organic manures, microbial inoculants, efficient irrigation, and advanced planting techniques. Findings from multiple studies reveal that IAM approaches improve nutrient management, water-use efficiency, weed and pest control, and climate resilience in soybean cultivation. Key practices, such as combining organic amendments with inorganic fertilizers, adopting optimal row spacing and seeding rates, and utilizing targeted irrigation techniques, are shown to enhance soybean productivity while minimizing environmental impacts. Through case studies, this research highlights the economic and ecological benefits of IAM, including yield increases, improved soil health, and reduced greenhouse gas emissions, underscoring the potential of IAM to address global food security challenges sustainably. Future research should continue exploring IAM strategies that adapt to climate variability and optimize genetic selection for yield improvements in diverse ecological contexts.

Keywords Integrated agronomic management; Soybean yield; Nutrient management; Water-use efficiency; Sustainable agriculture

1 Introduction

Integrated Agronomic Management (IAM) in soybean cultivation involves the strategic combination of various agricultural practices to enhance crop productivity and sustainability. This approach includes the use of chemical fertilizers, organic manures, microbial inoculants, and advanced seeding systems, among others, to optimize the growth conditions and yield of soybean crops. IAM aims to address the multifaceted challenges faced by soybean farmers by leveraging the synergistic effects of different agronomic practices.

Soybean (*Glycine max* L.) is a critical crop in global agriculture due to its dual role as a major source of dietary protein and oil, and as a crop that enhances soil fertility through nitrogen fixation. It is the world's most widely grown legume, providing essential nutrients and serving as a key ingredient in animal feed and various industrial products (Ainsworth et al., 2012; Wang et al., 2022). The crop's ability to fix atmospheric nitrogen through symbiosis with rhizobia bacteria makes it invaluable for sustainable agricultural practices, reducing the need for synthetic nitrogen fertilizers and improving soil health (Ngosong et al., 2022).

Despite its importance, optimizing soybean yield remains a significant challenge due to various biotic and abiotic factors. Soil nutrient deficiencies, particularly in phosphorus and nitrogen, are major constraints that limit soybean productivity (Zhang et al., 2021; Ngosong et al., 2022). Traditional breeding methods have improved yield under high-input conditions but often fail to maintain yield stability under nutrient-limited environments. Additionally, the environmental impact of excessive chemical fertilizer use, such as greenhouse gas emissions and soil degradation, necessitates the development of more sustainable agronomic practices (Langeroodi et al., 2019; Lohar and Hase, 2022). The transition to conservation and no-tillage systems, while beneficial for soil health, can also pose challenges in terms of early plant establishment and yield consistency (Adamič et al., 2021).

The study is to evaluate the effectiveness of comprehensive agronomic management practices in optimizing soybean yield. This study will integrate recent research findings on the use of fertilizers, organic fertilizers, microbial inoculants, and advanced seeding systems to promote soybean growth, yield, and quality. By exploring the interactions between these measures and their impact on soybean performance, this article aims to provide a comprehensive perspective on the best strategies for achieving sustainable soybean cultivation. The research scope covers field trial analysis conducted in different agricultural ecological regions, highlighting the potential of integrated agronomic management in addressing soybean yield optimization challenges and promoting global food security.

2 Soil Health and Nutrient Management

2.1 Soil composition and its impact on soybean growth

Soil composition plays a critical role in determining the growth and yield of soybean. The presence of organic matter, such as Farmyard Manure (FYM), significantly enhances soil health by increasing organic carbon content and improving nutrient availability. For instance, the application of FYM along with NPK fertilizers has been shown to increase soybean yield by 5.9% compared to NPK alone, highlighting the importance of organic amendments in soil composition (Sikka et al., 2013). Additionally, the use of Composted Sewage Sludge (CSS) in naturally infertile soils has been found to increase soil micronutrient concentrations and improve soybean yield by up to 20% compared to conventional fertilization methods (Prates et al., 2020). These findings underscore the necessity of maintaining a balanced soil composition to optimize soybean growth.

2.2 Nutrient requirements of soybean

Soybean plants have specific nutrient requirements that must be met to achieve optimal growth and yield. Nitrogen (N), phosphorus (P), and potassium (K) are the primary macronutrients essential for soybean development. Integrated nutrient management practices, such as the combined use of organic and inorganic fertilizers, have been shown to significantly enhance nutrient uptake and soybean yield. For example, the integrated use of FYM and micronutrients like boron and iron with inorganic NPK fertilizers can replace up to 10 kg N, 30 kg P_2O_5, and 20 kg K_2O per hectare, thereby improving yield attributes such as pods per plant and seed weight (Chaturvedi et al., 2012). Moreover, foliar application of macro- and micronutrients, including zinc and boron, at the pod initiation stage has been found to increase seed yield by up to 37.8% compared to no foliar nutrition (Dass et al., 2022). These practices ensure that soybean plants receive the necessary nutrients for optimal growth.

2.3 Fertilizer application techniques for optimal growth

Effective fertilizer application techniques are crucial for maximizing soybean yield and maintaining soil health. The integration of organic and inorganic fertilizers has been shown to improve soil functionality and soybean production. For instance, the use of straw mulch combined with nitrogen fertilizer enhances soil enzyme activities and nutrient availability, leading to a 75% increase in grain yield over a three-year period (Akhtar et al., 2019) (Table 1). Additionally, no-till farming practices, coupled with appropriate phosphorus fertilization, have been found to improve phosphorus uptake and utilization efficiency, resulting in higher soybean yields (Chauke et al., 2022). The application of Composted Sewage Sludge (CSS) using whole area or between-row methods has also been demonstrated to increase soybean yield by up to 67% compared to control treatments (Prates et al., 2020). These techniques highlight the importance of adopting integrated and sustainable fertilizer application methods to achieve optimal soybean growth and yield.

3 Water Management and Irrigation Practices

3.1 Water needs of soybean throughout growth stages

Soybean plants have varying water requirements throughout their growth stages, which significantly impact their yield and overall health. During the vegetative stage, adequate water is essential for establishing a robust plant structure, while the reproductive stage demands consistent moisture to support pod development and seed filling. Research indicates that supplemental irrigation during the reproductive stage (R1-R8) positively affects soybean growth and development, leading to higher dry matter and leaf area index compared to rainfed conditions (Montoya et al., 2017). Additionally, water stress at critical growth stages such as early flowering (R1) to beginning pod development (R3) can reduce seed yields by 9-13%, with more severe stress extending to R4.5 resulting in up to a 46% yield reduction. Therefore, understanding and managing water needs at each growth stage is crucial for optimizing soybean yield.

Table 1 Changes in soil carbon pools under different mulching treatments during 2015-2017 (Adopted from Akhtar et al., 2019)

Year	Treatment	SOC ($g\cdot kg^{-1}$)		DOC ($g\cdot kg^{-1}$)		LOC ($g\cdot kg^{-1}$)	
		0~0.2 m	0.2~0.4 m	0~0.2 m	0.2~0.4 m	0~0.2 m	0.2~0.4 m
2015	CK	11.5 ± 0.72	7.6 ± 1.13	3.57 ± 0.08	3.02 ± 0.04	1.91 ± 0.08	1.30 ± 0.08
	N	14.4 ± 0.86	9.2 ± 0.67	4.39 ± 0.05	3.68 ± 0.01	3.03 ± 0.03	1.87 ± 0.32
	S	11.7 ± 1.01	8.8 ± 1.82	4.12 ± 0.07	3.43 ± 0.12	2.09 ± 0.28	1.63 ± 0.13
	S + N	14.9 ± 0.83	11.3 ± 0.87	5.10 ± 0.02	4.36 ± 0.02	4.19 ± 0.51	3.82 ± 0.09
2016	CK	12.2 ± 0.48	6.6 ± 0.54	3.50 ± 0.04	3.09 ± 0.01	1.83 ± 0.03	1.33 ± 0.03
	N	13.5 ± 0.24	9.1 ± 0.62	4.43 ± 0.03	3.73 ± 0.03	2.45 ± 0.03	1.92 ± 0.08
	S	12.3 ± 0.59	9.0 ± 0.36	4.16 ± 0.05	3.49 ± 0.01	2.40 ± 0.01	1.57 ± 0.03
	S + N	14.6 ± 0.55	10.1 ± 0.37	5.24 ± 0.04	4.40 ± 0.01	4.83 ± 0.04	3.88 ± 0.09
2017	CK	10.0 ± 0.16	5.6 ± 0.11	3.56 ± 0.05	3.17 ± 0.03	2.01 ± 0.06	1.40 ± 0.01
	N	14.2 ± 0.18	9.0 ± 0.28	4.46 ± 0.02	3.85 ± 0.04	2.50 ± 0.10	1.91 ± 0.01
	S	13.0 ± 0.31	8.9 ± 0.59	4.21 ± 0.03	3.51 ± 0.01	2.41 ± 0.01	1.71 ± 0.10
	S + N	14.8 ± 0.40	9.4 ± 0.60	5.32 ± 0.01	4.50 ± 0.04	5.07 ± 0.04	4.00 ± 0.11

3.2 Irrigation techniques for water-use efficiency

Efficient irrigation techniques are vital for maximizing water use efficiency (WUE) in soybean cultivation. Surface and subsurface drip irrigation methods have been shown to enhance water productivity and yield. Subsurface drip irrigation (SSDI) uses approximately 90 mm less water than surface drip irrigation (SDI) without reducing yield, making it a more efficient option (Aydinsakir et al., 2021). Moreover, regulated deficit irrigation, where water supply is controlled to induce moderate water deficits at specific growth stages, can improve agronomic characteristics and yield, particularly when applied during the vegetative stage (Nunes et al., 2016). Another study highlights that a single irrigation at different reproductive stages (R4, R5, or R6) can increase yield by approximately 20% compared to non-irrigated conditions, although the improvements may not always justify the practice (Sweeney et al., 2003). These findings underscore the importance of selecting appropriate irrigation techniques to enhance WUE and sustain soybean productivity.

3.3 Managing drought stress in soybean cultivation

Drought stress poses a significant challenge to soybean cultivation, necessitating strategies to mitigate its impact. High-yielding soybean varieties exhibit physiological and photochemical adjustments to cope with mild drought conditions, such as enhancing photoprotective defenses and increasing intrinsic water use efficiency (Buezo et al., 2018). Additionally, stomatal responses during drought can improve leaf-scale and field-scale water use efficiencies, suggesting that increasing transpiration efficiency at the leaf scale can enhance agronomic water use efficiency at the field scale (Gorthi et al., 2019). In regions with limited water resources, deficit irrigation at selected growth stages can help avoid crop stress at critical times, thereby maintaining yield and quality (Sweeney et al., 2003). Furthermore, foliar application of macro- and micronutrients has been shown to improve productivity, economic returns, and resource-use efficiency in semi-arid climates, providing an additional strategy to manage drought stress (Dass et al., 2022). These approaches highlight the need for integrated water management practices to sustain soybean yield under drought conditions.

4 Weed Management and Control Practices

4.1 Common weeds in soybean fields

Soybean fields are often plagued by a variety of weed species that compete for resources, leading to significant yield losses. Common weeds include *Euphorbia davidii* Subils, which has been shown to significantly impact soybean crops in Argentina (Molinari et al., 2022) (Figure 1). Other prevalent weeds include species that emerge late in the season, which can be particularly problematic as they compete with the crop during critical growth periods (Datta et al., 2017). Effective identification and understanding of these common weeds are crucial for developing targeted management strategies.

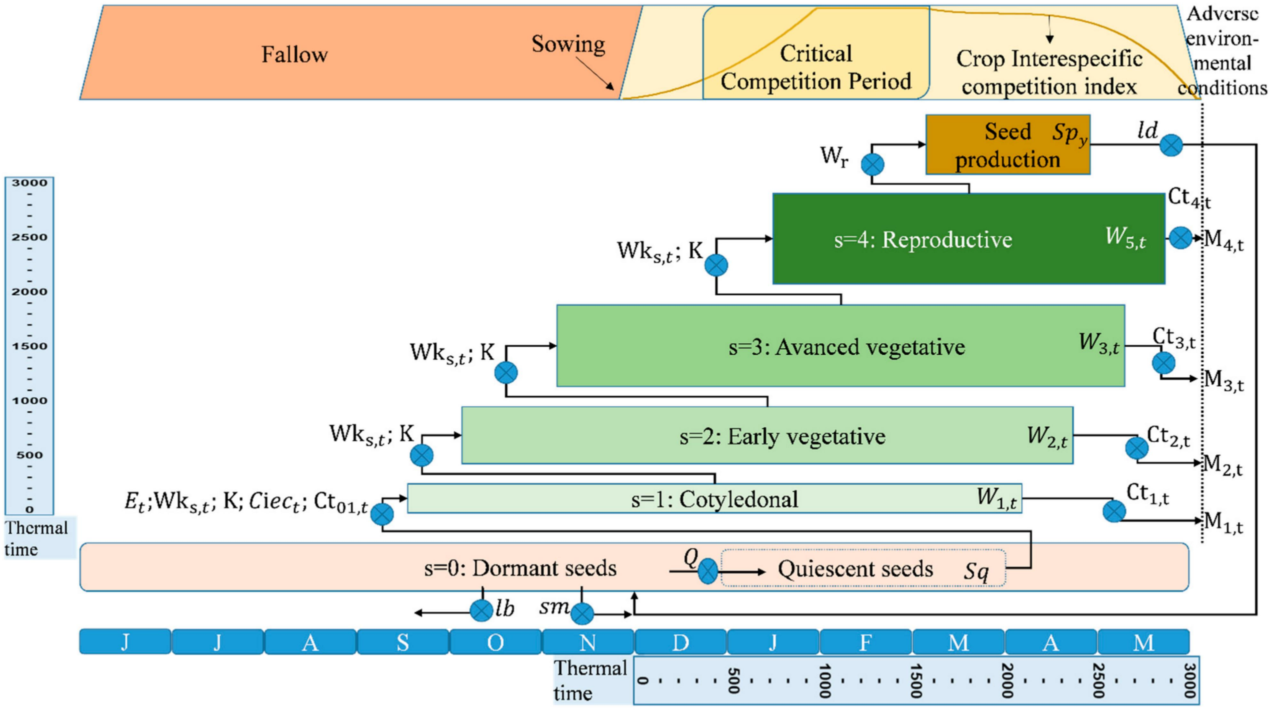

Figure 1 General diagram showing the key elements of the simulation model, displaying how *E. davidii* competes with soybean over a crop season (Adopted from Molinari et al., 2022)

Image caption: On the left, a thermal time scale used to guide the weed life-cycle development is shown. A thermal and chronological time scale for crop-growth development is displayed at the base of the diagram. At the top, the fallow and crop cycle are schematized, including the most important indexes. The weed life cycle is represented in a simple way by the most representative stages (Ws,t): dormant and quiescent seeds in the seed bank; cotyledonal (cotyledons); early vegetative (2 to 4 true leaves); advanced vegetative (6 true leaves to branching); and reproductive (flowering and fruiting) (Adopted from Molinari et al., 2022)

4.2 Integrated weed management approaches

Integrated Weed Management (IWM) combines multiple strategies to control weed populations while minimizing environmental impact and maintaining crop yield. Key components of IWM in soybean include Cultural practices: Adjusting row spacing and seeding rates can enhance crop competitiveness against weeds. Narrow row spacing and higher seeding densities promote early canopy closure, which suppresses weed growth by limiting light availability (Datta et al., 2017; Arsenijevic et al., 2021). Mechanical control: Techniques such as rotary hoeing and between-row cultivation can reduce weed biomass significantly. These methods can be combined with reduced herbicide applications to maintain effective weed control while minimizing chemical inputs. Chemical control: The use of pre-emergence (PRE) herbicides, such as flumioxazin, metribuzin, and pyroxasulfone, can delay weed emergence and reduce competition. However, the timing and selection of herbicides must be carefully managed to avoid negative impacts on crop yield (Sikka et al., 2013). Cover crops: Interseeding cover crops after soybean establishment can provide additional weed suppression. However, it is essential to select cover crops that do not compete with the soybean itself (Datta et al., 2017). Decision support Systems: Simulation models can aid in evaluating different IWM strategies by predicting outcomes such as crop yield, weed competition, and economic returns. These models help in making informed decisions about the most effective and sustainable weed management practices (Molinari et al., 2022).

4.3 Effects of weed competition on soybean yield

Weed competition is a major limiting factor for soybean yield. Studies have shown that weed infestation can lead to yield losses ranging from 53% to 56% if not managed appropriately (Daramola, 2020). The critical period for weed competition in soybean is between 14 and 42 Days After Sowing (DAS). During this period, weeds must be controlled to prevent significant yield losses. Delayed weed management beyond this critical period results in a steady decline in growth and yield, with each day of delay causing yield losses of 32~37 kg·ha^{-1} (Table 2).

Table 2 Soybean growth response to different period of weed interference in 2016 and 2017 (Adopted from Daramola, 2020)

Weed interference	Crop vigor score		Canopy height (cm)		Number of branches		Number of leaves		Leaf area index		Dry weight (g·plant^{-1})		Crop growth rate	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
WI_{14}	6.4 a	7.4 a	96.5 a	95.0 a	8.0 a	7.6 a	32.0 a	27.6 a	2.8 a	2.7 a	36.4 a	36.2 a	0.5 a	0.4 a
WI_{28}	5.9 b	6.2 c	90.0 b	89.5 b	7.1 b	7.2 b	23.4 b	20.0 b	2.4 b	2.1 c	33.6 b	33.3 b	0.4 b	0.3 b
WI_{42}	5.5 c	5.4 d	81.9 c	80.9 c	6.5 c	6.9 c	18.7 c	20.3 b	2.1 c	1.9 d	30.8 c	30.1 c	0.3 c	0.2 c
WI_{56}	5.4 c	5.8 d	80.6 c	80.4 c	6.5 c	6.7 c	18.1 c	16.2 c	2.1 c	1.9 d	30.1 c	30.6 c	0.3 c	0.2 c
WI_{har}	5.2 c	5.6 d	80.0 c	77.2 c	6.4 c	6.9 c	19.9 c	16.1 c	2.0 c	1.9 d	29.5 c	28.8 c	0.3 c	0.2 c
WF_{14}	5.3 c	5.6 d	82.9 c	80.0 c	6.5 c	6.6 c	19.3 c	17.8 c	2.0 2	2.0 c	29.9 c	29.5 c	0.3 c	0.2 c
WF_{28}	5.8 d	7.0 b	90.8 b	88.0 b	7.1 b	7.1 b	25.7 b	21.3 b	2.5 b	2.4 b	32.4 b	33.2 b	0.4 b	0.3 b
WF_{42}	6.5 a	7.4 a	100.7 a	91.0 a	7.7 a	7.5 a	31.2 a	28.8 a	2.8 a	2.7 a	34.9 a	34.9 a	0.5 a	0.4 a
WF_{56}	6.2 a	7.8 a	101.6 a	94.0 a	7.9 a	7.5 a	34.6 a	28.3 a	2.9 a	2.8 a	36.4 a	36.6 a	0.5 a	0.4 a
WF_{har}	6.6 a	7.6 a	102.3 a	100.0 a	8.0 a	7.5 a	34.6 a	30.2 a	3.0 a	2.9 a	36.4 a	36.0 a	0.5 a	0.4 a
SE±($p<0.05$)	0.32	0.43	5.82	5.74	0.43	0.37	4.3	3.6	0.23	0.18	2.2	2.6	0.06	0.06

Moreover, integrated weed management practices have been shown to reduce weed biomass and density effectively, thereby enhancing soybean yield. For instance, the use of a combination of herbicides and mechanical weeding can maintain weed biomass below critical levels, ensuring higher crop productivity (Jadhav, 2013; Snyder et al., 2016). Additionally, early planting and narrow row spacing can expedite canopy closure, further reducing the competitive advantage of weeds (Datta et al., 2017; Arsenijevic et al., 2021).

5 Pest and Disease Management

5.1 Major pests affecting soybean yield

Soybean crops are susceptible to a variety of pests that can significantly impact yield. Among the most detrimental pests are stink bugs, which have become a major concern in regions like the Neotropics, where they account for up to 60% of insecticide applications (Bueno et al., 2023). Other notable pests include soil pests such as Coleoptera larvae and dipterans like *Delia platura*, which can cause substantial damage to the crop (Mureșanu et al., 2020). Additionally, aphids and leaf-eating insects such as *Vanessa cardui* and *Autographa gamma* are prevalent and can lead to significant yield losses if not managed effectively (Wang et al., 2000).

5.2 Disease management strategies

Effective disease management in soybean cultivation involves a combination of chemical and non-chemical strategies. Chemical control measures, including the use of fungicides, are commonly employed to manage diseases such as downy mildew (*Peronospora manshurica*) and bacterial blight (*Pseudomonas glycinae*) (Mureșanu et al., 2020). However, there is a growing emphasis on integrated disease management approaches that combine cultural practices, such as crop rotation and resistant cultivars, with reduced chemical applications to minimize environmental impact (Khan et al., 2019). For instance, the use of pre-emergence herbicides in conjunction with early planting and narrow row spacing has been shown to enhance canopy closure and reduce disease incidence (Arsenijevic et al., 2021).

5.3 Role of biocontrol in pest and disease management

Biological control (biocontrol) plays a crucial role in the integrated pest management (IPM) of soybean crops. Conservation Biological Control (CBC) strategies, which focus on preserving natural enemies of pests, have been effective in maintaining pest populations below economic threshold levels. For example, reducing insecticide use and prioritizing biopesticides can enhance the presence of natural enemies, thereby reducing the need for chemical interventions. Augmentative Biological Control (ABC) programs, involving the mass release of biocontrol agents, have also shown promise in managing pest populations. Despite the challenges in large-scale application, integrating biocontrol with other management practices can lead to sustainable pest and disease management in soybean cultivation (Khan et al., 2019; Bueno et al., 2023).

6 Planting Techniques and Row Spacing

6.1 Optimum plant density for yield maximization

Optimizing plant density is crucial for maximizing soybean yield. High plant density can enhance canopy light interception and dry matter accumulation, leading to increased productivity. For instance, a study demonstrated that higher planting density (2.7 × 10^5 plants·ha^{-1}) significantly increased canopy light interception and dry matter accumulation, resulting in a 22.8% yield increase compared to normal planting density (Xu et al., 2021). Similarly, another research indicated that a seeding rate of 457 000 seeds·ha^{-1} combined with narrow row spacing improved yield by 26% and provided a substantial profit margin over conventional practices (Schmitz and Kandel, 2021). However, the response to plant density can vary with cultivar and environmental conditions, as observed in a study from Japan where narrow intra-row spacing increased yield in some cultivars but not others due to factors like leaf area index and lodging susceptibility (Kumagai, 2020).

6.2 Row spacing and its impact on light utilization

Row spacing is a critical factor influencing light utilization and, consequently, soybean yield. Narrow row spacing tends to expedite canopy closure, which enhances light interception and reduces weed competition. For example, early planted soybeans with narrow row spacing (38 cm) reached 90% green canopy cover faster and yielded more compared to wider row spacing (Arsenijevic et al., 2021). Another study found that narrow row spacing (30 cm) increased yield by 302 kg·ha^{-1} compared to wider spacing (76 cm). Additionally, uniform plant distribution within rows can further improve light interception and yield. Research showed that uniform plant spacing increased canopy light interception and dry matter accumulation, leading to a 9.5% yield increase over non-uniform spacing (Xu et al., 2021). However, the benefits of narrow row spacing can be influenced by other factors such as soil conditions and management practices (Masino et al., 2018).

6.3 Planting date and sowing depth considerations

The timing of planting and sowing depth are pivotal in determining soybean yield. Early planting generally results in higher yields due to extended growing periods and better utilization of environmental resources. Studies have shown that planting soybeans earlier in the season (late April) can significantly increase yield compared to standard planting times (late May) (Arsenijevic et al., 2021). For instance, early planting combined with narrow row spacing and high seeding rates improved yield by 26% in North Dakota (Schmitz and Kandel, 2021). Additionally, the interaction between planting date and cultivar maturity is crucial. Delayed planting shortens the growing period, reducing radiation and growing degree day accumulation, which negatively impacts yield. Therefore, planting before 20 May is recommended to maximize yield potential (Kessler et al., 2020). Sowing depth, although not extensively covered in the provided studies, should be optimized to ensure proper seedling emergence and establishment, which are critical for achieving high yields.

7 Genetic and Biological Enhancements

7.1 Role of genotype selection in agronomic optimization

Genotype selection plays a crucial role in optimizing agronomic performance and yield in soybean cultivation. The genetic architecture of soybean yield and key agronomic traits has been extensively studied, revealing significant marker-trait associations that can be leveraged for breeding programs. For instance, a Nested Association Mapping (NAM) population study identified 23 significant marker-trait associations for yield, demonstrating the value of expanding the genetic base of US soybean breeding (Diers et al., 2018). Additionally, genome-wide association studies (GWAS) have identified numerous Single Nucleotide Polymorphisms (SNPs) associated with traits such as maturity, plant height, and seed weight, which contribute to yield improvement (Ravelombola et al., 2021). These findings underscore the importance of selecting genotypes with desirable traits to enhance soybean yield.

7.2 Biological inoculants for soybean growth

Biological inoculants, particularly those involving symbiotic relationships with nitrogen-fixing bacteria, are vital for improving soybean growth and yield. The use of *Bradyrhizobium* spp. and *Azospirillum brasilense* as inoculants has shown significant benefits. For example, co-inoculation with these bacteria increased nodule number, dry weight, and grain nitrogen content, leading to a 47% increase in pods per plant and a 12% increase in yield compared to single inoculation methods (Brignoli et al., 2023). Furthermore, improvements in Biological Nitrogen Fixation (BNF) through the selection of effective bradyrhizobia strains and advanced inoculation techniques can significantly enhance soybean production. These biological enhancements are essential for sustainable soybean cultivation, especially in low-nitrogen soils.

7.3 Potential of marker-assisted selection in yield improvement

Marker-assisted selection (MAS) has shown great potential in improving soybean yield by enabling the precise selection of desirable traits. Context-specific MAS (CSM) has been particularly effective, allowing for the detection of yield quantitative trait loci (QTL) within specific genetic and environmental contexts. This approach has led to statistically significant yield gains of up to 5.8% in selected subline haplotypes (Sebastian et al., 2010). Additionally, genomic selection (GS) using advanced models such as ridge regression Best Linear Unbiased Predictor (rrBLUP) has demonstrated high accuracy in selecting agronomic traits, further enhancing yield potential (Ravelombola et al., 2021). The integration of MAS and GS in breeding programs can accelerate genetic improvement and optimize soybean yield.

8 Climate Resilience and Adaptation Strategies

8.1 Impact of climate change on soybean yield

Climate change poses significant challenges to soybean yield, with varying impacts depending on the region and specific climatic factors. In Southern Brazil, future climate scenarios predict increased temperatures and elevated atmospheric CO_2 levels, which can affect soybean yields. Studies using crop-model ensembles have shown that without adaptation, soybean yields are likely to decrease due to increased temperature stress and altered precipitation patterns (Battisti et al., 2018). Similarly, in Northern Ghana, climate change is projected to reduce soybean productivity by 3% to 13.5%, although elevated CO_2 levels could potentially offset these negative impacts, leading to increased productivity in some scenarios (MacCarthy et al., 2022). In the Southeastern United States, future climate scenarios predict a decrease in soybean yields by 1% to 13% due to temperature and moisture stresses (Lychuk et al., 2017). These findings highlight the critical need for effective adaptation strategies to mitigate the adverse effects of climate change on soybean production.

8.2 Agronomic adaptations for climate variability

Agronomic adaptations are essential to enhance soybean resilience to climate variability. In Southern Brazil, optimal sowing dates, cultivar maturity groups, and planting densities have been identified as key strategies to improve soybean yields under future climate scenarios. For instance, sowing soybean on October 15 and using cultivar maturity group 7.8 with a planting density of 50 plants/m^2 resulted in higher yields across different climate scenarios (Battisti et al., 2018). In Northeast China, delaying sowing dates and selecting appropriate cultivars have been shown to mitigate the negative effects of climate change on maize yields, suggesting similar strategies could be effective for soybean (Zhang et al., 2020a). Additionally, in the U.S. Corn Belt, adapting planting dates and varieties has been found to increase crop yields and maintain soil organic carbon levels, thereby enhancing agroecosystem resilience (Zhang et al., 2020b). These adaptive practices demonstrate the importance of optimizing genotype-environment-management interactions to sustain soybean production under changing climatic conditions.

8.3 Role of conservation agriculture in climate resilience

Conservation agriculture plays a crucial role in building climate resilience for soybean production. Practices such as crop diversification, reduced tillage, and improved water management can enhance soil health and water use efficiency, thereby increasing crop resilience to climate stressors. In Madhya Pradesh, India, intercropping soybean with cotton and adopting irrigation strategies like drip and sprinkler systems have been shown to improve grain yield and water productivity, making these practices viable options for farmers to achieve optimal productivity under varying climatic conditions (Rao et al., 2023). Furthermore, the application of biochar and irrigation in the Southeastern United States has been found to increase future corn yields, suggesting that similar practices could benefit soybean production by improving soil structure and moisture retention (Lychuk et al., 2017). Conservation agriculture practices not only mitigate the impacts of climate change but also contribute to sustainable agricultural systems by enhancing soil fertility and reducing environmental degradation.

9 Case Study: Successful Agronomic Practices in a High-Yield Soybean Farm

9.1 Background of the case study farm

The case study farm is located in the fertile region of Arlington, Wisconsin, known for its conducive environment for soybean cultivation. The farm has been operational for over two decades, focusing on sustainable and high-yield agronomic practices. The farm's management has consistently aimed to integrate advanced agronomic techniques to optimize soybean yield and maintain soil health.

9.2 Agronomic management techniques implemented

The farm implemented a series of integrated agronomic management practices to enhance soybean yield. Key techniques included Early planting and row spacing: The farm adopted early planting (late April) and narrow row spacing (38 cm) to expedite canopy closure, which was found to significantly increase yield compared to standard planting times and wider row spacing. Tillage practices: Conventional tillage was preferred over no-till systems, as it resulted in higher yields by improving soil conditions and reducing weed competition (Arsenijevic et al., 2021). Nutrient management: The farm utilized a combination of inorganic fertilizers and organic amendments such as Farmyard Manure (FYM) and compost. This integrated nutrient management approach improved nutrient uptake and soil health, leading to increased yields (Sikka et al., 2013; Chirde et al., 2020). Weed and pest control: A pre-emergence herbicide program was employed to manage weeds effectively, ensuring minimal competition for resources during the critical early growth stages of the soybean plants. Additionally, biocide spraying was used to control pests and diseases, further protecting the crop and enhancing yield (Vugt et al., 2016). Inoculation and plant population: The use of *Bradyrhizobium japonicum* inoculants and increased plant populations were key strategies. These practices improved nitrogen fixation and overall plant health, contributing to higher yields (Ronner et al., 2016; Vugt et al., 2016).

9.3 Yield outcomes and lessons learned

The implementation of these integrated agronomic practices led to significant improvements in soybean yield. Key outcomes included Yield Increase: Early planting and narrow row spacing resulted in a yield increase of 188 to 902 $kg \cdot ha^{-1}$ compared to standard practices (Arsenijevic et al., 2021). The use of integrated nutrient management, including FYM and compost, further boosted yields by up to 5.9% over conventional fertilizer use alone (Sikka et al., 2013; Chirde et al., 2020). Economic Benefits: The combination of inoculation, increased plant population, and optimal nutrient management resulted in substantial economic gains. For instance, the participatory research in Malawi demonstrated an average profit increase of US\$222 ha^{-1} with these practices (Vugt et al., 2016). Soil Health Improvement: The inclusion of organic amendments such as FYM and compost not only enhanced yield but also improved soil organic carbon content and nutrient availability, ensuring long-term soil health (Sikka et al., 2013). Environmental Sustainability: The farm's practices also contributed to environmental sustainability by reducing greenhouse gas emissions through no-tillage and residue management strategies, while maintaining high yields (Langeroodi et al., 2019).

10 Conclusion and Future Directions

The integration of various agronomic management practices has shown significant potential in optimizing soybean yield. The application of Farmyard Manure (FYM) in combination with NPK fertilizers consistently improved soybean yield and nutrient uptake compared to the use of NPK alone, with an increase of up to 10.8% in yield. Additionally, the use of wheat straw mulch and precise direct seeding techniques have been effective in enhancing soil moisture, reducing soil temperature, and subsequently increasing soybean yield by 24.7%. Early planting and narrow row spacing were found to expedite canopy closure and improve yield, while conventional tillage outperformed no-till systems in terms of yield. Integrated production systems involving the use of sunflower and *Paiaguas palisadegrass* biomass also demonstrated improved soybean yields and soil health. Sustainable management practices, such as no-tillage with residue retention, were effective in reducing greenhouse gas emissions while maintaining yield.

Future research should focus on the following areas to further optimize soybean yield through integrated agronomic management. Long-term Impact Studies: Investigate the long-term effects of integrated nutrient management, including the use of organic amendments like FYM, on soil health and soybean productivity. Climate Resilience: Develop and evaluate agronomic practices that enhance soybean resilience to climate variability, particularly in regions prone to extreme weather events. Weed and Pest Management: Explore integrated weed and pest management strategies that minimize chemical inputs while maintaining effective control and high yields. Biotechnological Advances: Leverage biotechnological tools to improve photosynthetic efficiency, nitrogen fixation, and carbon transport in soybean plants, aiming for substantial yield gains. Sustainable Practices: Further assess the environmental benefits and economic viability of sustainable practices such as no-tillage, residue retention, and crop-livestock integration.

The potential for scaling integrated agronomic practices in soybean cultivation is promising, particularly in regions with diverse agro-ecological conditions. The adoption of improved soybean varieties and agronomic practices has already shown significant yield and income gains for smallholder farmers in Malawi, suggesting a scalable model for other regions. Integrated production systems, such as those involving sunflower and *Paiaguas palisadegrass*, offer sustainable solutions for enhancing soil health and yield, which can be adapted to various cropping systems globally. Additionally, the implementation of precise direct seeding and straw management practices has broad applicability in double cropping systems, particularly in areas with similar climatic conditions to China.

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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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