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Evaluating the Effects of Climate Change on Soybean Production and Economic Outcomes: Strategic Approaches to Ensure Global Food Security

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ABSTRACT

Climate change poses a major challenge to global agricultural systems, with the soybean sector being particularly vulnerable to environmental fluctuations, which can negatively affect both the quantity and quality of production. This study aims to analyze the impact of climate change on the efficiency and overall economic losses in soybean production systems and to explore appropriate adaptation strategies to ensure the sector's contribution to meeting global food demand. The study employs a qualitative descriptive research approach, focusing on assessing the effects of climate change on efficiency and economic losses in soybean production to safeguard global food security. The results revealed a clear relationship between climate stressors, economic losses, and reduced productivity and efficiency in the soybean sector, especially in regions with limited adaptive capacity. However, the adoption of climate-smart practices, such as using heat-resistant cultivars, improving water and nutrient management, and applying sustainable agricultural techniques, produced positive outcomes for both environmental and economic sustainability. To ensure global food security, it is imperative to implement integrated adaptation strategies that encompass investment in research and technology, policy support for sustainable practices, and capacity building for farmers. Furthermore, international cooperation will be essential to strengthen the resilience of soybean production systems in the context of

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climate change. Of particular significance is the application of the Integrated Framework for Soybean Resilience and Strategic Adaptation to Climate Change, which ensures that soybean production can withstand climatic variability while maintaining long-term food security and economic stability.

Keywords: Agricultural Technologies; Climate Change; Food Security; Sustainability; Soybean Production

1. Introduction

Global food supply is heavily reliant on a limited number of staple crops, approximately 15 in total, with soybean (*Glycine max*) being among the most prominent. It holds the sixth position in global production volume and ranks fourth in terms of cultivated land area [1,2]. Commonly referred to as the "king of beans," soybean plays a vital role in both human and animal nutrition, while also contributing significantly to the ecological balance of soils due to its biological nitrogen fixation and diverse applications [3,4]. Rich in protein and essential nutrients, soybean is a key component in strategies aimed at achieving global food security [5]. Historically cultivated in central China around 5000 years ago, soybean production has seen a fifteen-fold increase and has geographically shifted to dominate in countries like the United States, Brazil, and Argentina, which collectively produce approximately 80% of the global supply [6].

Climate patterns across the globe are undergoing rapid and unpredictable changes, both at present and in the foreseeable future. The excessive release and accumulation of greenhouse gases, namely nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4), have been identified as primary drivers of these shifts. As outlined in the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), these changes are expected to disrupt various environmental parameters, including temperature, precipitation, humidity, and atmospheric CO_2 concentrations. Such disruptions are likely to reduce water availability and negatively impact both crop and livestock productivity, thereby posing a direct threat to global food security. Projections suggest that by the end of the 21st century, the global average temperature could rise by 0.3 ℃ to 4.8 ℃, while CO_2 levels in the atmosphere may climb from the current 420 ppm to as high as 935 ppm [7,8]. Furthermore, recent studies forecast a potential decline in annual rainfall by 15% to 30%, along with an expansion of arid zones into areas traditionally classified as temperate, primarily due to rising temperatures and reduced precipitation developments that may have "severe" consequences in the near future [9]. Within this evolving climatic context, key stressors such as elevated temperatures and CO_2 levels are anticipated to directly influence plant viability and agricultural yields. As a result, understanding the potential environmental and climatic effects on soybean growth and productivity under varying future scenarios has become increasingly critical [10].

Agriculture is widely recognized as one of the most climate-sensitive and vulnerable sectors globally [11]. Consequently, evaluating the economic consequences of climate change on agricultural systems has become imperative. To achieve this, researchers typically employ three primary methodological approaches: crop simulation models, Ricardian analysis, and statistical modeling techniques. Crop simulation models are designed to explore the interactions between arable land, prevailing climatic conditions, and available agricultural technologies. These models are particularly useful for assessing potential improvements in harvesting strategies at localized scales, although they require comprehensive datasets for accurate predictions. The Ricardian approach, on the other hand, focuses on long-term agricultural adaptation by examining how climatic variables and other external factors affect land value and farmer profitability. Statistical modeling serves as the third method, utilizing techniques such as ordinary least squares on time-series or cross-sectional data to estimate yield sensitivity. This approach accounts for a variety of influencing factors, including technological advancements, soil conditions, and climatic disturbances [12]. Moreover, some researchers have integrated crop models with broader climate modeling frameworks namely the Global Climate Model (GCM) which offer a more comprehensive assessment of climate change impacts on agricultural productivity across different regions [13].

This study emphasizes the critical role of dairy production in ensuring global food security, while addressing the substantial challenges posed by climate change to this sector. It further examines practical and strategic solutions aimed at enhancing resilience, promoting sustainable productivity, and minimizing economic losses within dairy systems. To provide a comprehensive understanding of these issues, the research is guided by four central questions, seamlessly integrated into the analysis: the first examines the critical role of soybean in strengthening global food security and promoting economic sustainability; the second investigates how environmental factors significantly affect the resilience and productivity of soybean production; the third assesses the impacts of climate change on soybean yields, market prices, and the broader economy; and the fourth evaluates proposed mitigation strategies designed to address these climate-related challenges in soybean production.

Identifying and addressing the key challenges to sustainable soybean production is crucial for ensuring long-term global food security under changing climate conditions. Rising temperatures, irregular rainfall patterns, and the increasing frequency of extreme weather events, hallmarks of climate change, pose significant risks to soybean yield, efficiency, and economic stability, often resulting in reduced productivity and compromised crop quality. Although numerous studies have examined the impacts of climate change on soybean production, most are limited to descriptive analyses or specific case studies, highlighting the need for a comprehensive approach that combines risk assessment with practical, actionable solutions. This study provides an in-depth analysis of climate-related risks affecting the soybean sector and explores strategies to enhance its resilience and sustainability over time. The study adopts an innovative approach through the development of an Integrated Framework, which not only synthesizes existing knowledge but also offers a practical tool for risk evaluation, strategic solution identification, and the enhancement of resilience and sustainability within soybean production systems. Through this framework, the study contributes valuable insights that support the global dialogue on food security. Additionally, the study emphasizes the importance of early adaptation strategies to strengthen soybean production systems, enabling them to withstand future environmental pressures, maintain productivity, and minimize economic losses, thereby ensuring the long-term sustainability of global food security.

2. Materials and Methods

This study adopts a qualitative descriptive research methodology to analyze the impact of climate change on sustainability, economic losses, and performance of soybean production for global food supply. Descriptive research, as Neuman noted, is distinguished by its ability to "present a detailed picture of a situation, social setting, or relationship" and "begin with a well-defined issue or question and endeavor to describe it accurately [14]." It also emphasizes addressing "how" and "who" questions. Furthermore, qualitative research designs, including phenomenology and grounded theory, can serve both descriptive and explanatory purposes [15]. Additionally, Lambert V.A. and Lambert C.E. advocate the use of the term "qualitative descriptive research" to prevent misclassification with other methodologies such as phenomenology, grounded theory, and ethnography [15]. Their concept of "naturalistic inquiry" emphasizes that qualitative descriptive research seeks to observe phenomena in their natural state as much as possible within the research context [15].

This study adopts a qualitative descriptive research methodology because it examines the effects of climate change on sustainability, economic losses, and performance of soybean production for global food supply, confirming its classification as qualitative descriptive research. Moreover, the study's objectives require an in-depth content analysis of both electronic and printed materials related to the phenomena under investigation [16]. According to Bowen, content analysis involves three main phases: skimming, comprehensive reading, and interpretation [16]. By segmenting extensive texts into smaller, more manageable units, content analysis facilitates the identification of core meanings [17], achieved by detecting recurring themes and patterns within the text [18].

Furthermore, following Bowen's three-phase model (skimming, comprehensive reading, and interpretation) [16], this study applies a systematic approach to analyzing electronic and printed materials. A structured review protocol was developed to enhance methodological transparency and reduce narrative bias. Inclusion criteria were based on publication date within the past five years, alongside foundational references to provide theoretical context, language (English), source type (peer-reviewed articles and credible international reports), geographical scope covering the countries with the highest global soybean production and consumption, and thematic relevance to climate change and soybean production. Sources were excluded if they were outdated, non-peer-reviewed, or unrelated to soybean production or climate issues.

Key databases such as Web of Science, Scopus, and Google Scholar were searched using compound keywords, including "climate change", "Soybean Production," "heat stress in crops," "yield," "economic losses," and "agricultural adaptation." The selected literature was coded and thematically categorized to identify patterns, trends, and key insights across different regions. This systematic content analysis enabled evidence-based interpretations, enhancing coherence between research questions and findings. This structured approach strengthens the methodological rigor of the study and allows for the formulation of relevant policy recommendations and strategic adaptation insights across diverse global contexts.

3. Results and Discussion

3.1. Soybean Plays a Vital Role in Strengthening Global Food Security and Economic Sustainability

Despite some ongoing debates about its health benefits, soybean remains a critical source of both food and oil worldwide. It plays a major role in daily edible oil consumption and meat production. Notably, only about 20% of the total soybean harvest is consumed directly by humans in products such as tofu, soy milk, and soybean oil, whereas approximately 76% serves as animal feed, and the remaining 4% is allocated for industrial uses. Soybeans are renowned for their high protein content, approximately 40%, which includes essential amino acids like lysine that are vital for human health. This makes soy and its derivatives particularly popular among vegetarians and individuals with lactose intolerance, as plant-based proteins are often regarded as healthier alternatives to those derived from animals [3,6,13].

In addition to its protein richness, soybean contains around 20% vegetable oil, positioning it as a primary raw material for edible oil production. Soybean oil is extensively utilized in food processing, cooking, and various industrial applications. The crop also serves as a vital feed ingredient in animal, poultry, livestock, and aquaculture industries due to its high protein and energy values. From an economic perspective, the cultivation and processing of soybean form an essential sector in numerous countries, providing substantial employment opportunities for agricultural workers and generating significant economic value along related industrial supply chains [4]. Voora et al. emphasize that the global soybean industry supports millions of jobs worldwide [3]. Furthermore, 76% of soybean production functions as an affordable, high-quality protein source for animal feed in meat and dairy industries, while 20% caters to edible oils and human food products, and 4% is devoted to industrial applications such as biodiesel production [6].

Global soybean production has increased dramatically, by approximately 1200% over the past few decades, primarily driven by the expansion of cultivated areas and improvements in crop yields [19]. Notably, nearly 80% of total soybean output is directed toward livestock feed and aquaculture [3]. Domestic production levels are determined by both the area under cultivation and yield per hectare; thus, analyzing these two factors separately allows for the development of more effective strategies to ensure a stable soybean supply [13]. Moreover, Argentina ranks as the world's third-largest soybean producer, following the USA and Brazil, with an annual output of 51 million tons, representing 13% of global production [20]. Meanwhile, Brazil's soybean industry has experienced significant expansion growing by 60% in the last decade—and is projected to increase production by an additional 30% by 2030 compared to 2020 levels [21].

Between 2014 and 2023, the global area under soybean cultivation grew steadily by 20.3 million hectares, reaching 139.4 million hectares (**Figure 1**). In 2023, the top 10 soybean-producing countries, Brazil, USA, Argentina, China, India, Canada, Russia, Paraguay, Bolivia, and Ukraine, accounted for over 80% of global production. Among these, Brazil, the USA, and Argentina together represented 68.6% of the total planted area as shown in **Figure 2** [22].

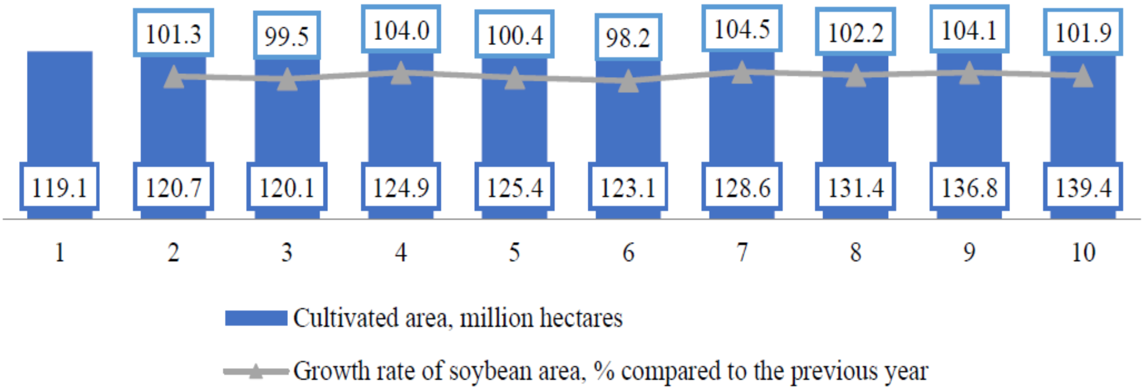

Figure 1. Dynamics of soybean acreage in the world [22].

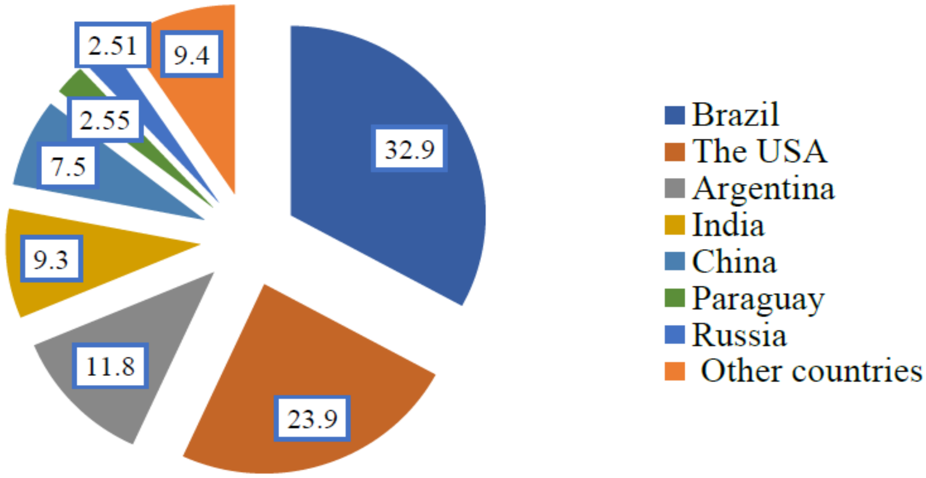

Figure 2. Structure of the global soybean planting area by country in 2023 (%) [22].

The global soybean harvest in 2023 reached 398.2 million tons, 20.1 million tons higher than in 2022. Moreover, Brazil, the USA, and Argentina remained the top three producers, contributing 156.0 million tons (39.2%), 113.3 million tons (28.5%), and 50.0 million tons (12.6%) respectively. Moreover, the average global soybean yield in 2023 was 28.6 c/ha (centner per hectare), an improvement compared to 2014. The highest yield was recorded in Turkey (41.2 c/ha), followed by the USA and Brazil with equal yields of 34.0 c/ha. According to a recent AMIS report, global soybean trade in the 2024/2025 season amounted to 421.14 million tons, representing an increase of 25.14 million tons (+5.97%) compared with 396 million tons in 2023/2024 [23]. In addition, global soybean consumption between 2014 and 2023 is illustrated in **Figure 3**. Looking ahead, demand is projected to continue its steady growth through 2030 [24]. As a key agricultural commodity, the expansion of soybean production is largely driven by rising global demand, primarily its use as feed in the livestock sector, as well as growing consumer interest in soy-based food products as a major plant-derived protein source [21].

However, the expansion of soybean cultivation to meet this increasing demand has come at an environmental cost, contributing to the loss of vital ecosystems. In terms of consumption, China ranks first with 120.5 million tons (31.5% of global demand), followed by the United States with 65.9 million tons (17.2%) and Brazil with 57.5 million tons (15.0%) [22]. Soybeans rank among the most widely traded agricultural commodities worldwide. A significant share of this trade takes place through the Chicago Board of Trade (CBOT) soybean futures market in the United States, particularly within futures contracts [3]. On a global scale, the bulk of soybean production is transported and stored in large quantities before being processed into oil and meal in industrial facilities.

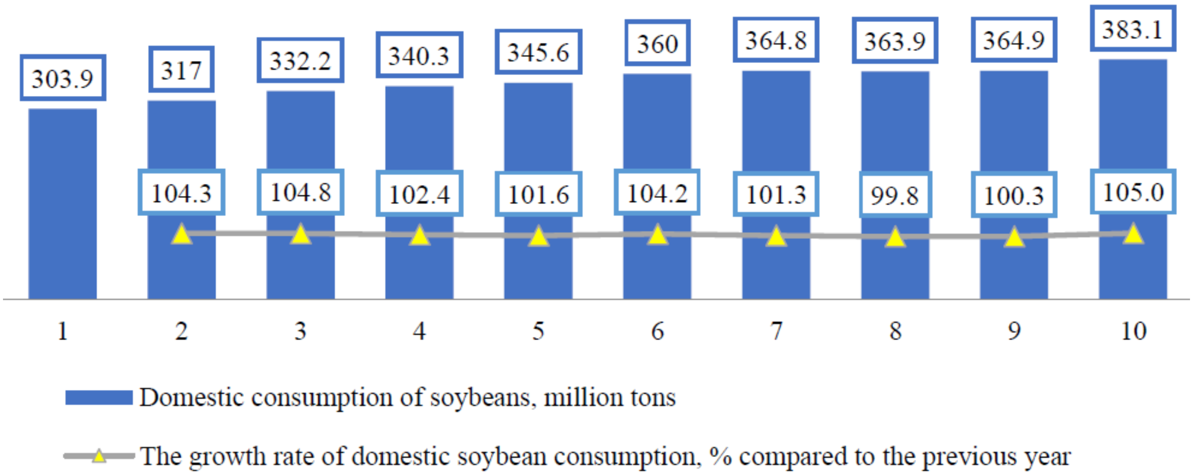

Figure 3. Dynamics of domestic soybean consumption (million tons) [22].

China stands as the largest soybean consumer globally, with consumption reaching 120.5 million tons in 2023, while domestic production accounted for only 20.8 million tons. This substantial shortfall demonstrates the country's inability to meet domestic demand independently, positioning it as a major net importer of soybeans, soybean meal, and soybean oil, despite being a leading producer as recently as 1996. Currently, about 75% of soybeans consumed in China are imported, primarily from Brazil, the United States, and Argentina, with nearly 85% of these imports allocated to animal feed. Remarkably, Brazil's soybean exports to China increased by 30% in 2020 compared with 2019 [13,22]. According to the most recent AMIS report, global soybean trade reached 60.02 million tons in 2024/2025, reflecting a modest increase of 0.58 million tons (+1%) compared to 59.44 million tons in 2023/2024 [23].

It is evident that soybean serves as a cornerstone of global food security and the associated agricultural and economic sectors, functioning as a primary source of plant-based protein and edible oils. The majority of soybean production is allocated to animal feed, supporting meat and dairy supply chains and highlighting the indirect reliance of global diets on this crop. Global soybean production has increased dramatically, exceeding 1200% over recent decades, driven by strategies to expand cultivated areas and improve yields. However, this intensive expansion poses significant environmental challenges, including biodiversity loss, land degradation, and increased carbon emissions. Additionally, Soybean productivity is influenced by environmental factors such as climate variability, soil quality, and biotic stresses, alongside global supply-demand dynamics and geopolitical conditions that affect price stability and production strategies. Addressing these challenges requires an integrated approach combining the development of stress-resistant cultivars, precision agriculture, efficient resource management, and enhanced farmer education and training, supported by national and international policies to ensure market stability and food security. Moreover, the development of climate-resilient soybean varieties and improved resource-use efficiency, coupled with transparency in products derived from soy-fed animals, represents a strategic approach to achieving sustainable production while minimizing environmental impacts. Integrated analyses of cultivated areas and yield per hectare underscore soybean's role as a model for understanding the complex interactions between agricultural production, global demand, and environmental pressures, making it a central focus for future research in climate-smart agriculture, food system planning, and global food security policy.

3.2. Environmental Factors Significantly Influence the Resilience and Productivity of Soybean Production

Soybean production faces significant climate change–related challenges, both in terms of adaptation and mitigation. The expansion of soybean cultivation contributes to deforestation, biodiversity loss, and associated greenhouse gas emissions. Rising temperatures, erratic rainfall, and increased incidence of pests and diseases driven by climate change already negatively impact soybean production systems [25]. As one of the most important crops globally in terms of food security and economic significance, soybean productivity is highly sensitive to environmental factors, including soil quality, water availability, and climatic variability. Understanding these impacts is crucial for developing effective management strategies that enhance crop resilience and ensure global food security.

3.2.1. Effects of Heat Stress in Soybean Production

Heat stress impacts not only the morphological, physiological, and yield components of soybean plants but also profoundly affects seed quality traits. For example, in soybean, protein accumulation begins roughly 10–12 days after flowering, while oil accumulation starts around 15–20 days after flowering [26]. Exposure to stress during this critical developmental window can dramatically influence seed quality [27]. Under heat stress conditions, soybean seeds generally exhibit reduced protein content accompanied by increased oil content [28]. Moreover, Seed development is an extremely temperature-sensitive process, far more vulnerable to abiotic stresses than vegetative tissues. Elevated temperatures during seed development in soybean often result in poor germination, heightened susceptibility to pathogen infection, and diminished economic value. With climate change expected to increase both the frequency and intensity of summer heatwaves, the effects of heat stress on seed development are likely to become more widespread throughout the twenty-first century [29].

The factors directly influencing soybean planting area, growth, and yield can be broadly categorized into natural factors—such as climate conditions, soil quality, fertility, and input-related factors. Among these, soybean yields are highly sensitive to climatic variability [4,13]. Temperature, in particular, is a critical environmental variable that affects every stage of soybean growth, thereby directly shaping both yield and quality. During the germination and seedling stages, optimal temperatures promote rapid and uniform seed germination. Conversely, excessively high temperatures can trigger excessive moisture loss from seeds, while low temperatures may delay germination [4]. Throughout the growing season, elevated temperatures can adversely affect yields by disrupting physiological processes such as photosynthesis, respiration, and water regulation, while also accelerating soil moisture evaporation, potentially leading to drought conditions [30]. On the other hand, extremely low temperatures can cause frost damage, compromise cellular integrity, and even result in plant death. Both temperature extremes hinder normal growth and ultimately reduce yield [4].

Maintaining appropriate temperatures is also vital for flower bud formation and the subsequent development of flowers and fruits. Temperatures that are too high or too low can reduce the number of flower buds, trigger flower drop, interfere with pollination, and negatively affect fruit set and quality. During maturation, high temperatures can shorten the growth period, further reducing both yield and quality [4]. Interestingly, Gendron St-Marseille et al. observed that climate warming could extend the growing season at higher latitudes, opening new regions for soybean cultivation. Moreover, early planting under longer daylight conditions can enhance yields by accelerating reproductive development [31].

3.2.2. Effects of Precipitation Patterns on Soybean

Precipitation plays a critical role in determining soybean yields, as this crop is highly sensitive to water availability throughout the growing season [13]. Sgroi et al. reported a direct relationship between precipitation deficits and reduced soybean yields. Drought negatively affects all growth stages, from seed germination to plant development, leading to lower yields and diminished crop quality. Dry soils limit the plant’s ability to absorb water, impair physiological functions, cause leaf wilting, stunt growth, and in some cases, even result in plant death [32]. Conversely, excessive rainfall can cause waterlogging, reducing oxygen availability to the roots and obstructing nutrient absorption. Such conditions increase the risk of root rot and pest outbreaks, disrupt normal developmental stages such as flowering and fruit formation, and ultimately reduce both yield and quality [32].

Statistical analyses reveal a strong relationship between rainfall, maximum temperature, and total soybean yield. While rainfall alone accounts for approximately

72% of yield variation, incorporating temperature into the model increases explanatory power to 91.3% [12].

3.2.3. Impacts of Climate Change on Soybean Pathogens

Climate warming heightens plant vulnerability to parasitic infections and can significantly alter host-parasite interactions, including their phenology and population dynamics. Despite this, the precise effects on these interactions and on overall crop yield remain uncertain [31]. The soybean–nematode system serves as an excellent model for investigating how climate change impacts below-ground parasites, particularly regarding their establishment, reproduction, and infection timing in response to rising soil temperatures [31]. A prime example is the soybean cyst nematode (SCN), a major pathogen originally introduced to North America from Asia, first detected in North Carolina in 1954. It quickly spread through both biotic vectors, such as humans and animals, and abiotic vectors like wind and water [31].

On the other hand, Soybean production has evolved into a complex agroecological system that is increasingly vulnerable to climate change. Rising temperatures, heat stress, and altered precipitation patterns not only reduce overall yield but also modify seed biochemical composition, including protein and oil content, thereby impacting both nutritional and economic value. From a biological perspective, the interaction between climate variability and pathogens, such as the soybean cyst nematode, forms a complex feedback loop: higher temperatures accelerate pest proliferation, weakening plant resilience and amplifying production losses. Consequently, future soybean production strategies must adopt an integrated approach that combines the development of climate-resilient cultivars, precision irrigation, and soil management to mitigate both environmental and biotic stresses. Predictive modeling of climate impacts and pathogen dynamics can inform planting schedules, the expansion of suitable cultivation areas, and priorities for breeding programs. Coupled with early warning systems for heatwaves, droughts, and pest outbreaks, these tools provide actionable insights for farmers, enhancing productivity and economic sustainability under variable climatic conditions. Ultimately, the resilience of global soybean systems will depend not only on technological innovation but also on coordinated policies that promote sustainable and climate-smart agricultural practices, underscoring soybean's role as a model for integrating food production, environmental stewardship, and global food security.

3.3. Prices and Economic Impact of Climate Change on Soybean Production

International soybean prices are strongly influenced by macroeconomic and geopolitical conditions, as well as shifts in global supply and demand. Over the past decade, price fluctuations have had a significant impact on the soybean market. One of the most important global price indicators is the Dalian Exchange Contract in China, as the country is the world's largest consumer and importer of soybeans, accounting for nearly 60% of the global market share, thereby exerting a decisive influence on international trade and pricing trends [3]. Moreover, several key factors shape global soybean prices, including: production costs and growing conditions in major producing regions; market reactions to economic shocks such as the COVID-19 pandemic and the Russia–Ukraine conflict, which drove prices upward and increased shipping, storage, and labor costs; supply and demand adjustments in response to market volatility; and competition from alternative vegetable oils such as sunflower oil. A notable challenge for producers across soybean-growing countries is the lack of premium prices for sustainable production efforts. The introduction of clear pricing mechanisms, such as premiums or minimum prices, could help shield compliant farmers from volatility, offset certification costs, and ensure greater market stability [3].

On the other hand, Foreign Agricultural Service Global Market Analysis Staff also directly shapes farmers' production decisions [3]. Expected price levels further influence farmers' choices regarding crop varieties, planting area, input intensity, and management practices, which in turn affect both yield and output. Higher soybean prices may also prompt land reallocation from other crops to soybeans in pursuit of greater profitability. However, despite rising international prices, many farmers' margins remain compressed due to escalating input costs. Typically, less than half of farm expenditures are allocated to variable inputs (seeds, fertilizers, chemicals), while the majority go toward equipment, land, and family labor, expenses that are inflexible in the short term. This financial pressure often complicates debt repayment among soybean producers [33].

Consequently, the net effect of expected soybean prices on yield depends on the balance of these opposing factors, which must be evaluated empirically [13]. Their findings indicate that while higher soybean prices tend to expand planting areas, they may also reduce per-hectare yields. Moreover, input costs, particularly fertilizer, exert a significant impact on yields; rising fertilizer prices discourage its use, thereby diminishing productivity, while seed quality directly influences soybean quality, affecting pricing and global trade competitiveness [3]. Additionally, fluctuations in energy prices strongly influence the final cost of soybeans and derived products. Political and economic disruptions often trigger sharp increases in fuel, gas, lubricants, and oil prices, alongside higher costs for spare parts and agricultural machinery maintenance, all of which add further volatility to soybean production costs [22]. In addition, farmers' education levels and planting experience exert a significant positive influence on crop yields. For example, when soybean prices rise, less-experienced farmers often expand their planting areas, resulting in lower yields per unit of the newly cultivated land and, consequently, reduced overall soybean productivity [34]. Investment in education and training for soybean producers, however, can substantially improve outcomes by enhancing their ability to safeguard rights, address production and trade challenges, and strengthen resilience [33].

The COVID-19 pandemic, compounded by Russia's invasion of Ukraine, has disrupted the supply chains for soybeans, corn, and sunflower oil in unexpected ways, leading to production declines and escalating energy costs [3,35]. The Russia–Ukraine conflict has also caused a sharp reduction in sunflower oil exports due to plant and port closures in Ukraine, increasing global demand for soybean oil and driving higher international prices. This, in turn, incentivized the expansion of soybean cultivation in countries such as Brazil [36]. At the same time, rising production costs, particularly fertilizer prices, pose challenges for Brazil, the world's leading soybean producer and exporter. The country imports approximately 85% of its fertilizer requirements, with around one-quarter sourced from Russia, and nearly 44% of Brazil's imported fertilizer applied to soybean production [37]. The soybean sector is also shaped by government policies and regulatory measures. Major producing and exporting countries employ tools such as taxation and agricultural policies to protect the economic value of the crop, support local producers, safeguard the competitiveness of domestic industries, and buffer local markets against price volatility. Nevertheless, some producing countries have imposed export restrictions in response to declining supplies and rising prices, contributing to a global food crisis and severe food insecurity in many low-income nations [3].

Climate change-related risks are escalating rapidly, particularly for highly vulnerable communities residing in diverse environments such as urban centers, rural areas, and informal settlements. The direct consequences of climate change and climate variability include extreme precipitation, heat stress, pluvial and fluvial flooding, landslides, drought, heightened aridity, and water scarcity, accompanied by widespread indirect impacts on populations, economies, and ecosystems [38]. Developing countries are expected to face particularly severe effects, as many rely heavily on agriculture for income, host large impoverished rural populations dependent on subsistence farming, and are the least financially and technically equipped to adapt to changing conditions [39]. Accordingly, effective adaptation planning to mitigate the impacts of climate change on poverty and food security requires robust methods to identify vulnerable regions at both national and local scales [40].

The United States, as one of the world's largest soybean producers and exporters, benefits in part from its globally high yields. Nonetheless, climate change threatens these yields, with direct implications for production and export availability. Projections suggest that U.S. soybean yields may decline by 3.0% by 2036 compared to 2016 levels, primarily due to more frequent extreme heat events and reduced precipitation in some counties. Incorporating these projections into a simulation model of market impacts reveals that reduced yields could decrease U.S. soybean exports by 1.17%, equivalent to USD 319 million based on 2016 export levels, assuming constant yields in other countries [41].

Hu et al. examined the effects of extreme weather events (EWEs) on soybean production in the United States, Brazil, and Argentina, as well as the resulting ripple effects on global soybean trade and China's domestic soybean market. Their findings indicate that while EWEs in a single country exert only modest impacts on global markets, simultaneous EWEs across multiple major producers can reduce global soybean output by 8.8%–17.1% and drive price increases of 9.5%–33.2%. Such disruptions could cut China's soybean imports by as much as 20.7%. These shocks also extend to downstream industries, including soybean oil, soybean meal, and the livestock sector, where higher feed costs elevate meat, poultry, and pork prices [42]. Consequently, consumer expenditures on soybeans and meat could rise by approximately USD 25.6 billion. China's soybean reserves play a pivotal role in mitigating such effects; strategic stock releases can cap soybean price increases by up to 10% and meat price increases by up to 1%, saving consumers as much as USD 5.5 billion. Looking forward, climate change is expected to intensify economic risks for soybean production globally and domestically, underscoring the necessity for measures that strengthen market resilience. These measures include fostering international cooperation to respond to EWEs, developing drought- and flood-resistant soybean varieties, expanding local storage capacity, advancing precision agriculture and modern farming practices to enhance productivity, and reducing reliance on imports through alternative feed sources. In summary, EWEs exert profound impacts on soybean production, markets, and prices, amplifying economic losses and reinforcing the urgency of effective adaptation and risk mitigation strategies [42].

Moreover, EWEs also have nuanced and complex implications for crop farmers. While such events typically reduce local yields, widespread production losses often lead to price surges. The evidence suggests that compensatory price increases frequently offset yield losses, especially where supply shocks elicit strong price responses. For instance, U.S. soybean revenues rose by over 8% in 1988 relative to normal weather years, whereas in 2012 revenues declined by no more than 4%. This highlights the importance of crop-specific and time-sensitive price responsiveness to supply disruptions. Moreover, projections indicate that if growing-season weather during 1997–2019 had mirrored the volatility expected for 2036–2065 under a moderate emissions pathway, revenue variability for corn and soybeans in median U.S. counties would have risen by more than 60%, with even stronger effects in areas outside the main Corn Belt. These findings underscore the substantial economic risks posed by climate change–induced variability in agricultural revenues [43].

Additionally, Thomasz et al. estimated the economic losses in soybean production due to severe and extreme droughts between 1970 and 2016. Using a counterfactual scenario to represent non-extreme variability, they monetized production losses based on international soybean prices. Results revealed a strong correspondence between extreme negative yield deviations and instances of severe or extreme drought. The 2008/2009 and 2011/2012 agricultural seasons recorded the steepest declines in soybean yields at the county level. Total losses during these years were valued at USD 8.046 million (in 2016 dollars), equivalent to 22% of Argentina's international reserves for that year [40]. Additionally, in China, climate change also exerts considerable influence on soybean production. For example, a 1 cm increase in precipitation during April and May alters planting area slightly expanding it by 0.233% in April but reducing it by 0.172% in May. Higher rainfall in June and July, however, significantly boosts soybean yields. Findings further show that because soybeans are shade-tolerant, rising accumulated temperatures during the growing season impede crop development and reduce yields [13].

On the other hand, global soybean prices are influenced by complex and multifaceted interactions among economic, geopolitical, and environmental factors, making the market highly volatile and sensitive to shocks. At the economic level, farmers' decisions are affected by fluctuating production costs, including rising prices for fertilizers and energy, which in turn impact the scale of cultivated land and yield per hectare. Additionally, farmers' levels of experience and agricultural education play a crucial role in enhancing productivity and maximizing returns, highlighting the need for investment in training and agricultural education to strengthen producers' capacity to adapt to price volatility and climate-related risks. On the other hand, extreme weather events (EWEs), including droughts, floods, and elevated temperatures, increase the vulnerability of the global food system by directly affecting yields and forcing markets to raise prices to compensate for supply shortages. This creates a complex economic feedback loop between local production and global markets. These dynamics indicate that heavy reliance on soybean imports in countries such as China weakens food security and exposes them to international price fluctuations.

Consequently, risk management strategies in the soybean industry must be multi-layered, encompassing the development of drought-, flood-, and heat-resistant varieties, strengthening local storage capacities, implementing precision agriculture, and improving resource-use efficiency, alongside promoting international cooperation to address simultaneous production shocks. Furthermore, predictive models for price and climate variability should be integrated with price support and subsidy policies to ensure sustainable productivity and protect farmers from excessive volatility. Ultimately, soybeans emerge as a strategic indicator of the balance between global food security and economic resilience in the face of simultaneous climatic and economic challenges, necessitating a comprehensive scientific approach to managing production, trade, and policy.

3.4. Proposed Mitigation Strategies to Address Climate Change on Soybean Production

Climate change directly impacts the soybean growing environment, including shifts in temperature, changes in precipitation patterns, growth cycles, pest and disease prevalence, as well as overall yield and quality. These challenges necessitate the adoption of strategies to adapt to and mitigate the adverse effects of climate change on soybean production. Key mitigation approaches include the development of stress-resistant soybean varieties, efficient water resource management, advanced irrigation techniques, and optimized agricultural management practices. Collectively, these strategies aim to enhance the resilience and adaptability of soybean crops under changing climatic conditions. Furthermore, Fraanje and Garnett, highlighted that the soybean sector holds significant potential to contribute to climate change mitigation, both through improved production practices and by reducing its environmental footprint [21].

3.4.1. Breeding Programs

Climate models predict that most global soybean croplands will face hotter and more humid conditions between 2050 and 2100, likely resulting in reduced yields [44]. Moreover, breeding stress-resistant soybean varieties is a crucial strategy to mitigate the impacts of climate change on soybean production, combining both traditional and modern approaches. Traditional breeding introduces stress-tolerant traits from wild species or superior cultivars into target varieties through hybridization, selection, and progeny evaluation, often enhanced by combination breeding and hybrid vigor, while molecular breeding identifies functional genes and regulatory networks associated with stress tolerance, employing tools such as marker-assisted selection, genome-wide association studies, and high-throughput screening to improve breeding efficiency. Advanced technologies, including gene-editing methods, offer novel pathways to further enhance stress resistance. Concurrently, breeders must balance stress tolerance with quality traits to ensure market competitiveness and consumer acceptance, integrating climate-relevant techniques to develop cultivars that perform effectively under environmental stresses. Cutting-edge biotechnology continues to produce soybean varieties that are more nutritious and input-efficient [44], exemplified by the identification of a drought-resistance gene in soybeans by Argentine researchers [45]. Utilizing cultivars already adapted to diverse environments allows the selection of genotypes capable of activating molecular, biochemical, and physiological responses to biotic and abiotic stresses such as drought, saline soils, and high temperatures, thereby enhancing overall tolerance [10].

In this context, the study examined the effects of high temperatures on genetically modified (GM) soybean and hybrids derived from crosses with wild soybean, focusing on their growth and reproductive capacity under heat stress. Results showed that key protein levels remained stable despite high temperatures, while some growth indicators, such as pollen germination, pod number, and seed weight, declined. Nevertheless, the hybrids maintained competitive growth similar to wild soybean, indicating the potential persistence and spread of transgenes in agricultural environments. These findings provide valuable insights for developing heat-tolerant soybean varieties and understanding the potential ecological risks associated with GM genes [46].

3.4.2. Water Resource Management and Irrigation Techniques

Water resource management and irrigation techniques play a critical role in sustaining soybean production under the challenges posed by climate change, particularly drought and altered precipitation patterns. Effective management requires careful consideration of water quantity, quality, distribution, and utilization within soybean-growing areas. Protecting water sources and ecosystems, preventing pollution, and avoiding over-extraction are essential to maintain ecological balance and ensure the sustainable availability of water, providing reliable resources for healthy soybean growth. Strategies for water resource management include increasing water supply and optimizing usage through rainwater harvesting for irrigation or groundwater replenishment, as well as implementing water prioritization systems. Such rational allocation mechanisms promote stable and sustainable farmland irrigation, thereby enhancing production efficiency and yield. Additionally, water-saving irrigation methods and soil moisture management techniques, such as drip irrigation, micro-sprinkler systems, and localized root-zone irrigation, can minimize water wastage while meeting crop requirements, noting that soybeans generally require less water than crops like rice and wheat. Complementary soil management practices, including optimized fertilization, tillage, and soil structure improvement, enhance soil water retention, reduce evaporation, and increase soybean water-use efficiency, thus supporting reliable crop growth [4,13]. Modern smart irrigation technologies further advance water efficiency by using sensors to monitor soil moisture and weather conditions in real time, adjusting irrigation volume and timing, and enabling remote system control, thereby improving automation, reducing labor costs, and conserving water. In line with these innovations, Inari Agriculture has developed engineering improvements that increase soybean yields by 20% while reducing water inputs [47].

3.4.3. Soil Protection and Sustainability

Maintaining soil fertility through crop diversification is a key climate adaptation strategy [48]. As a nitrogen-fixing crop, soybean can enhance soil fertility without relying on synthetic nitrogen fertilizers, which contribute to greenhouse gas emissions during both production and application, resulting in nitrous oxide release. Additionally, ensuring that new plantations are established on degraded lands rather than natural ecosystems is essential for sustainable land-use management [3].

Soybean represents a key model for sustainable agriculture due to its vital role in biological nitrogen fixation (BNF), which reduces dependence on synthetic nitrogen fertilizers and mitigates related emissions. Evidence from Brazil indicates that the economic value of BNF during the 2019–2020 growing season was approximately USD 15.2 billion, in addition to direct profits of about USD 914 million generated from inoculation and co-inoculation with *Bradyrhizobium* spp. and *Azospirillum brasilense*, which covered 25% of the total soybean cultivated area. These findings highlight the strategic importance of soybean in delivering substantial economic returns while simultaneously promoting environmental sustainability in the agricultural sector [49].

Early studies highlight the significant economic potential of biological nitrogen fixation (BNF) in agriculture. In the United States, one of the first assessments estimated that improvements in BNF efficiency generated an economic value of USD 1.067 billion, accompanied by a reduction of 1547 thousand tons of nitrogen fertilizers, while the total elimination of nitrogen fertilizers in major crops was associated with a value of USD 4.484 billion [50]. Approximately a decade later, the global economic benefits of BNF for legumes were estimated at USD 90 billion, with USD 8 billion accruing to the United States [51]. Additionally, a study across 19 African countries estimated the economic value of BNF at USD 203 million in 2004 [52]. These findings underscore the substantial regional and global economic significance of BNF technologies in enhancing resource efficiency and reducing reliance on synthetic fertilizers [49].

3.4.4. Pest Management

Understanding the adaptability of species to current and future pathogens, insects, and weeds, as well as changing climatic conditions, is critical for maintaining crop health and yield stability, particularly in light of increasing frequency and intensity of extreme yield fluctuations.

Although many organisms currently have limited impact under existing climatic conditions, they may pose significant challenges in the future. Therefore, developing and deploying innovative pest management tools is essential to maximize production outcomes [31].

Adjusting agricultural management practices, including modifying planting structures, optimizing cultivation techniques, and improving fertilization management, is crucial to mitigating climate change impacts on soybean production. Diverse planting structures such as crop rotation, intercropping, or mixed cropping can reduce the persistence of soil-borne pests and diseases, lower dependence on chemical pesticides, enhance soil fertility, stabilize farmland ecosystems, and support sustainable agricultural development. Additional strategies to combat climate change effects include providing soybean producer subsidies and supportive policies to encourage cultivation, stabilizing input prices, investing in soybean infrastructure, developing skilled personnel in soybean cultivation, increasing funding for soybean research, and promoting the overall sustainable development of soybean production [31].

Soybean is an economically significant crop in the United States; however, its profitability has been adversely affected by various diseases. The economic impacts of 23 common soybean diseases were assessed across 28 soybean-producing states in the U.S. over the period 1996–2016, using a dataset comprising 13,524 observations. Multiple statistical approaches were employed to estimate losses, accounting for factors such as state, year, the period before and after the discovery of soybean rust, geographic region, and zones classified by yield, harvest area, and production. These factors were found to have a significant influence on total economic losses attributable to soybean diseases [53]. Across states and years, the soybean cyst nematode, charcoal rot, and seedling diseases caused the greatest economic damage, while soybean rust, bacterial blight, and southern blight were the least economically detrimental. Notably, average losses increased by 51% in the period following the discovery of soybean rust (2004–2016) compared to the pre-discovery period (1996–2003). From 1996 to 2016, the total estimated economic loss due to soybean diseases in the U.S. amounted to USD 95.48 billion, with USD 80.89 billion occurring in the northern states and USD 14.59 billion in the southern states. Over the entire period, the average annual economic loss was approximately USD 4.55 billion, with roughly 85% of these losses concentrated in the northern U.S [53].

Regions with lower yield, harvest, and production levels experienced significantly lower economic losses from diseases compared to high-yield/production zones. This observation was further supported by a positive linear correlation between mean soybean yield loss (per state, due to all diseases over 21 years) and mean state-wide soybean production (MT), average yield (kg ha^{-1}), and harvest area (ha). These findings provide valuable insights for guiding research priorities, policy development, and educational initiatives aimed at improving soybean disease management and mitigating economic losses [53].

3.4.5. Predicting Soybean Yield Models

Producing countries with low climate impacts tend to achieve high yields while using minimal fertilizers [3]. Growers should implement targeted measures based on temperature requirements at different growth stages to maintain optimal growing environments and maximize soybean growth and yield. Traditionally, the impact of climate change on crops has been studied within agronomic disciplines, but the local-level focus of these studies limits the ability to evaluate overall economic impacts. Therefore, a unified model projecting total production is necessary to assess climate risk at a macroeconomic scale rather than at the local or farm level. While biophysical models provide the most accurate representation at local scales, statistical models can offer a more precise depiction at larger scales [12]. Long-term statistical analyses suggest that soybean yields are primarily driven by technological innovations, which form discernible trends in empirical yield series [30].

Predictive models for soybean yield include statistical models that use historical data and mathematical techniques to analyze the relationship between climate, soil, and crop growth, and ecosystem models that simulate ecological and biological processes during soybean development to forecast yield changes. Applying both approaches comprehensively enhances the accuracy and reliability of yield predictions. Data-driven prediction models offer high flexibility and precision, reflecting dynamic changes in soybean growth processes and providing valuable information for agricultural decision-making. Furthermore, technologies such as remote sensing provide essential data on growth conditions and land use, which, when combined with meteorological and geographic information system (GIS) data, can validate and optimize yield prediction models, thereby improving precision and reliability. Integrating remote sensing with other data sources establishes a comprehensive and robust foundation for monitoring and forecasting soybean yields [4].

3.4.6. Towards Soybean Sustainability

Current knowledge, combined with forthcoming scientific advances, allows humanity to maintain hope for more favorable future scenarios than those predicted in the most pessimistic outlooks [10]. In this context, a warm climate could present opportunities for northern agriculture by opening new lands for lucrative crops such as soybeans and extending the growing season in existing production areas, enabling the cultivation of late-maturing varieties with higher yields [31].

Governments should enhance awareness campaigns on climate change and adaptive measures to provide farmers with the knowledge needed to adopt climate-resilient practices in soybean production. In addition, government-supported agricultural or crop insurance policies serve as effective tools to help farmers mitigate the adverse effects of climate change, reduce price volatility, hedge risks, and maintain more stable incomes. Furthermore, producing and consuming countries could develop policies to financially incentivize soybean farmers who implement sustainable agricultural practices and demonstrate measurable results, for example through payments for environmental services such as carbon emission mitigation [3]. Finally, promoting the adoption of advanced technologies in soybean production is a crucial factor for increasing yields, reducing production costs, and improving farmers' overall profitability.

3.5. Integrated Framework for Soybean Resilience and Strategic Adaptation to Climate Change

Soybean is a critical crop that plays a key role in global food security, serving as a major source of protein and contributing significantly to agricultural economies. However, soybean production faces increasing threats due to climate change, including rising temperatures, irregular rainfall, and more frequent extreme weather events such as droughts and floods. Although numerous studies have examined the impacts of climate change on soybean, most are descriptive or limited to specific case studies. This highlights the need for an integrated framework that not only synthesizes existing knowledge but also provides a practical tool to assess risks, identify strategic solutions, and enhance resilience and sustainability in soybean production systems. The framework consists of four interconnected components that form a comprehensive model to enhance the resilience and sustainability of soybean production, namely:

3.5.1. Production Components

Production components represent the key factors that determine the capacity of soybean crops to grow and achieve high yields. These components include agronomic practices such as precision farming, balanced fertilization, and efficient irrigation management, as well as the adoption of modern technologies, including smart irrigation systems, remote sensing, and digital growth monitoring. Seed quality is also crucial, as drought- and pest-resistant varieties adapted to changing climatic conditions are essential for maintaining production stability. For example, drought-resistant soybean varieties can be used in semi-arid regions to offset yield losses caused by water scarcity, while drip irrigation systems in high-temperature areas can improve water use efficiency and increase yield. The framework allows for evaluating these production components using measurable indicators such as growth rate, crop yield, and seed quality, which facilitates identifying the most effective practices and enhancing production resilience under varying climatic conditions.

3.5.2. Environmental Factors

Environmental factors include natural conditions that directly influence soybean growth and resilience, such as temperature, rainfall, soil quality, and resource availability. The framework incorporates a risk classification system to assess the severity and frequency of environmental stressors and link them directly to production outcomes, enabling the prediction of potential yield reductions and quality losses. As a practical example, in regions experiencing frequent heatwaves, practices such as adjusting planting seasons or applying organic mulches to retain soil moisture can mitigate stress effects. Enhancing soil fertility through organic amendments or nutrient supplements can also improve soybean growth under environmental pressure. This demonstrates how environmental factors can be connected with production practices to inform data-driven preventive measures.

3.5.3. Economic Impacts

Economic impacts are crucial for understanding how climate change affects the soybean sector. The framework allows assessment of how production declines or price fluctuations affect farmers' income, market stability, and national food security. This is achieved through economic indicators that integrate income losses, price volatility, and the potential consequences on food availability. For instance, a reduction in soybean yield in a country heavily reliant on soy as a feed ingredient can lead to increased meat and dairy prices, affecting both food security and local consumption. By linking environmental and production data to economic indicators, the framework helps policymakers allocate financial resources, plan crop insurance programs, and implement measures to mitigate the economic effects of climate-induced production losses.

3.5.4. Strategic Responses

Strategic responses include interventions and policies aimed at adapting to climate change and mitigating its adverse effects. The framework proposes an adaptive response matrix that connects production components, environmental stressors, and economic impacts to identify the most effective interventions. These strategies include technological innovations such as drought- and pest-resistant soybean varieties, supportive agricultural policies like crop insurance and subsidy programs, and farmer training initiatives to improve resource management efficiency. For example, precision farming training programs can help farmers optimize planting schedules, select appropriate varieties, and manage fertilizer and water use effectively. Governments can also implement financial support programs for farmers in drought- or flood-prone areas to ensure stable production and maintain food security. These strategic responses enable the design of practical adaptation plans that enhance production resilience, reduce economic losses, and safeguard food security against future climate challenges.

This framework represents an innovative and comprehensive model that integrates scientific knowledge on production, environmental factors, economic impacts, and strategic responses to enhance the resilience and sustainability of soybean production under ongoing climate change. Its significance lies in providing a practical, multi-level tool that helps understand the complex interconnections among these factors and supports data-driven decision-making. At the production level, the framework assists farmers in identifying the most effective agronomic practices, selecting suitable soybean varieties, and optimizing resource use, including water and fertilizers. It also enables the evaluation of seed quality, irrigation techniques, and fertilization strategies, thereby maintaining high productivity even under variable climatic conditions.

At the environmental level, the framework allows for precise monitoring of environmental risks and their impacts on crop performance, such as temperature increases or reduced rainfall affecting yields. It provides mechanisms to predict potential reductions in yield and crop quality and supports preventive measures, such as adjusting planting schedules, improving soil fertility, or using organic mulches to retain soil moisture, thereby promoting long-term environmental sustainability. At the economic level, the framework helps assess the impacts of climate change on farm income, price fluctuations, market stability, and local and global food security. By linking production and environmental data with economic indicators, it enables policymakers to plan financial support, crop insurance, and compensation programs, reducing economic losses and ensuring the stability of the agricultural sector and dependent communities. At the policy and strategic level, the framework provides decision-makers with a tool to develop effective adaptation strategies, including adopting new technologies, implementing supportive policies, and offering farmer training in resource management. It also enables governments and international organizations to design flexible response programs for future challenges, ensuring food security, economic sustainability, and strengthening resilience of soybean production systems.

4. Conclusion

Climate change, extreme weather events, and global market volatility pose significant challenges to soybean production, affecting yield, crop quality, and the economic sustainability of the sector. Environmental factors, including fluctuations in temperature, rainfall patterns, soil quality, and biotic stresses such as pests and diseases, directly influence plant growth, reproductive performance, and seed composition. At the same time, global supply-demand dynamics and geopolitical conditions play a critical role in shaping international soybean prices, complicating market stability and influencing farmers' production decisions and strategies. Addressing these challenges requires a multidimensional approach that encompasses advanced plant breeding through stress-resistant and genetically improved varieties, precision agriculture, optimized input management, and strategic climate adaptation measures. Farmer education and training further enhance resilience and productivity by equipping producers with the skills needed to respond effectively to price volatility, extreme climatic conditions, and biotic pressures.

Additionally, sustainable agricultural practices, investment in local storage infrastructure, and international cooperation are essential to ensure market stability and food security, particularly in countries heavily reliant on soybean imports. Enhancing the resilience, efficiency, and sustainability of production systems is crucial not only to meet global food demand but also to maintain economic and environmental stability. Coordinated efforts in plant breeding, agricultural management, market regulation, and climate adaptation are essential to ensure that soybean production can withstand current and future challenges, thereby contributing to global food security and sustainable agriculture.

This study proposes an innovative approach that should be implemented through an Integrated Framework for Soybean Resilience and Strategic Adaptation to Climate Change. This framework combines scientific knowledge with practical application to assess risks, identify strategic solutions, and strengthen resilience and sustainability in soybean production systems. It transforms theoretical knowledge into an actionable tool for policymakers, farmers, and researchers, facilitating the adoption of proactive adaptation strategies. Ultimately, the framework empowers production systems to withstand future environmental pressures, maintain productivity levels, reduce economic losses, and ensure long-term food security and economic stability.

Ultimately, this study effectively summarizes its findings, yet its significance extends into the future by highlighting the practical and scientific implications of the research. The study recommends the formulation of supportive policies to promote the adoption of early adaptation strategies and sustainable technologies in soybean production, ensuring the resilience of production systems against future climate changes. Furthermore, it outlines clear directions for implementing the Integrated Framework for Soybean Resilience and Strategic Climate Adaptation, by combining scientific knowledge with practical applications, guiding efforts to enhance farmers' capacity to withstand environmental pressures, maintain productivity, reduce economic losses, and ensure long-term food security and economic stability.

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Data Availability Statement

The data used for this study are available upon request from the author.

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Conflicts of Interest

The author declares no conflict of interest.

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