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# Agronomic Optimization of Fertilization and Irrigation Regimes for High-Yield Soybean Cultivation

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**Abstract** Soybean (*Glycine max*) is a globally important crop serving as a major source of food, feed, and industrial products, yet achieving consistently high yields under diverse agro-ecological conditions remains a significant challenge. In this study, we explored the agronomic optimization of fertilization and irrigation regimes to enhance soybean yield through a comprehensive analysis of nutrient requirements, targeted fertilization strategies, and precision irrigation practices. We examined the macronutrient and micronutrient demands of soybean across different growth stages and highlighted innovations such as integrated nutrient management, site-specific applications, and controlled-release fertilizers. Irrigation scheduling based on evapotranspiration models and soil moisture sensors was evaluated, along with the impacts of drought and waterlogging on yield and plant physiology. Furthermore, we analyzed the synergistic effects of fertigation, nutrient-water interactions, and the use of advanced precision agriculture tools-including remote sensing, UAVs, and AI-based decision support systems. A case study in the U.S. Midwest soybean belt demonstrated the successful application of variable rate fertilization and automated irrigation, leading to significant yield improvements and reduced environmental impact. This research underscores the importance of synchronizing nutrient and water management in soybean production and suggests future directions for integrating climate-resilient strategies and farmer-accessible technologies to support sustainable intensification.
**Keywords** Soybean yield optimization; Fertilization strategies; Irrigation scheduling; Precision agriculture; Nutrient-water interactIons

## 1 Introduction

The value of soybeans (*Glycine max*) has actually been deeply rooted in people's minds for a long time. Not only is it eaten by humans and livestock, but it can also be transformed into industrial oil, biodiesel, and even a good helper for improving soil structure (Zhong and Zhong, 2024). Especially in countries like Brazil, the United States and China, the position of soybeans is so stable that it needs no further elaboration-it supports a large part of agriculture. Even better, as a leguminous crop, it inherently possesses the ability to fix nitrogen, which significantly contributes to the sustainable development of agriculture (Galeriani et al., 2022; Li et al., 2022; Liborio et al., 2023).

However, reality is not always idealized. In many places, growing soybeans is no easy task. Insufficient water, unscientific irrigation, and lack of nutrients in the soil. These are all real problems. Especially nitrogen, phosphorus, potassium and trace elements like boron, the deficiency of any one of them will have a considerable impact on the output. In arid and semi-arid regions, the key issue to be addressed is how to make good use of water. However, in areas where the soil is not fertile to begin with, what to apply and how to apply it are particularly crucial. Moreover, as the climate becomes increasingly unpredictable and the soil itself varies greatly, it is not easy to achieve both high production and environmental protection (Zhang et al., 2023; Tadesse et al., 2024; Zhang et al., 2024).

Therefore, this study does not intend to delve into theoretical models at great height, but rather focuses on the specific practices of fertilization and irrigation in high-yield soybean cultivation. We have focused on some practical strategies, such as drip irrigation, water-scarce irrigation, groundwater irrigation, combined with the balanced application of major and micronutrients, as well as the combined use of organic conditioners. The aim is all to achieve higher yields, more efficient resource utilization, and less environmental impact. It is worth mentioning that the article also emphasizes the importance of "adapting measures to local conditions". Different regions and different varieties should adopt different methods. At the same time, we also explored possible future directions, including the development of precision agriculture and the breeding potential of stress-resistant varieties.

## 2 Nutrient Requirements of Soybean

### 2.1 Macronutrient demands: nitrogen fixation, phosphorus uptake, and potassium balance

Soybeans, as a crop, have a relatively high demand for nitrogen, phosphorus and potassium, all of which are crucial for their healthy growth, good fruiting and high yield. However, unlike other crops, soybeans' dependence on nitrogen is somewhat "special"-mainly not through application, but through their own "cliques" to cooperate with rhizobia to fix nitrogen from the air. This symbiotic interaction can sometimes bring 50 to 300 kilograms of nitrogen per hectare to the soil, which is why it is particularly important in the protein synthesis and vegetative growth stages (Dass et al., 2022). But then again, nitrogen alone is not enough. If phosphorus supply is insufficient, there will be many problems-root development will be affected and seed formation may also go wrong. Some research indicates that up to 81% of the phosphorus at harvest is actually concentrated in the grains (Bagale, 2021), which suggests that it plays a significant role in the formation of grains. What about potassium? Although often overlooked, it is actually crucial for enzyme activity, water regulation, and pod fullness, especially when the plant enters the later stage of growth and just begins to form pods, its absorption is the most active (De Almeida et al., 2017). Even the absence of any one of these three elements will affect the development of the plant. Especially nitrogen and potassium, once the supply is insufficient, not only will the plants grow slowly, but the final yield will also shrink significantly.

### 2.2 Role of micronutrients: boron, zinc, and molybdenum in reproductive development

Although trace elements like boron, zinc and molybdenum may not sound so "hardcore", their role in soybeans is by no means significant. Take boron for example. The formation of cell walls cannot do without it, and its absence during the reproductive period directly affects the podding rate and final yield (Tarar et al., 2022). Zinc is often sprayed on the leaf surface during the flowering and podding period. Experiments have shown that doing so can indeed significantly increase the number of pods and seeds. Molybdenum, on the other hand, is somewhat like a "behind-the-scenes hero". It participates in the fixation of nitrogen and the synthesis of proteins. Although the amount used is not large, without it, nitrogen cannot be utilized at all. During critical growth periods, such as from flowering to the fruiting stage, foliar spraying of these micronutrients not only helps increase yield but also enhances the plant's stress resistance and nutrient utilization efficiency (Figure 1) (Dimkpa et al., 2017). So, although these elements may seem insignificant at first glance, if they were to be lacking, the problem would be much greater.

### 2.3 Stage-specific nutrient uptake and its implications for timing of application

Soybeans are not the kind that can be eaten from beginning to end. Their nutrient absorption is rhythmic and can be viewed in stages. For instance, potassium and iron are mostly absorbed in the later stage of vegetative growth. However, substances like nitrogen, phosphorus, calcium, magnesium, sulfur, zinc, manganese, boron and copper have a more uniform absorption time and are quite crucial both during the vegetative growth period and the filling period (Bender et al., 2015). However, it should be noted that the absorption of many trace elements before flowering is actually not high, even less than 17% of the total amount for the entire season (Gaspar et al., 2018). This indicates that the reproductive growth stage is the "key supply period". Therefore, foliar spraying at stages like R3 (pod formation stage) and R5 (grain swelling stage) has been proven to be a relatively effective strategy. When it comes to fertilizing, "timing the right time" is more important than "applying a large amount". Only by rationally arranging the application timing and ensuring that plants can absorb sufficient nutrients when needed can both yield and resource utilization efficiency be achieved.

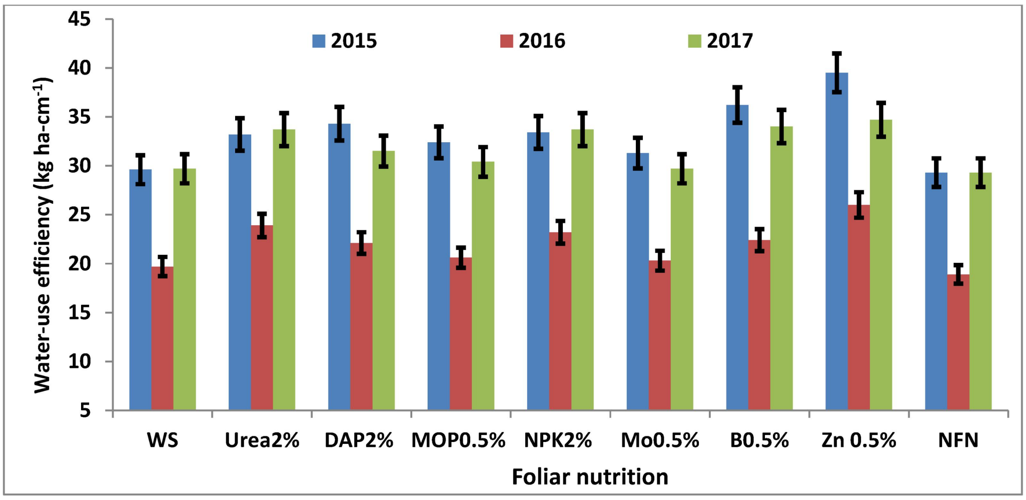


Figure 1 Water-use efficiency in soybean under different foliar-applied nutrients (2015-2017). WS: water spray, Urea2%: 2% urea solution, DAP2%: 2% di-ammonium phosphate solution, MOP0.5%: 0.5% muriate of potash solution, NPK2%: 2% solution of 19:19:19 NPK, Mo0.5%: 0.5% molybdenum solution, B0.5%: 0.5% boron solution, Zn 0.5%: 0.5% chelated-Zn solution, and NFN: no-foliar nutrition (Adopted from Dass et al., 2022)

## 3 Fertilization Strategies for Optimal Yield in Soybean Cultivation

### 3.1 Integrated nutrient management: combining organic and inorganic sources

Not all fertilizers are effective for whoever uses them. An increasing number of experiments have shown that the combined use of organic and inorganic fertilizers brings more practical benefits than using either one alone (Amiri et al., 2021; Iqbal et al., 2022). For instance, some people have tried to halve the recommended dose of NP fertilizer and add an equal amount of vermicompost, or combine broiler bedding with diammonium phosphate. As a result, both seed yield and biological yield have significantly increased, and the harvest index is also higher. Moreover, in some cases, these alone are not enough. Especially in areas with poor soil nutrition, adding some biological inoculants, such as slow-growing rhizobia, can further promote plant growth and help it fix more fixed nitrogen. This approach, called "Integrated Nutrient Management (INM)", not only boosts yields but also helps reduce reliance on chemical fertilizers, making it an attempt towards sustainability (Turabi et al., 2024).

### 3.2 Site-specific nutrient management: tailoring applications using soil testing and sensors

Not every plot of land is the same. What to apply and how much to apply depend on the "foundation" of the soil. Site Nutrition Management (SSNM) is precisely based on this, using soil testing, nutrition maps, and even sensors to "tailor" fertilization plans. Compared with the approach of "one formula for the entire field", this method can ensure that every plot of land and every row of crops get just the right amount of food. The experimental data are quite convincing. Combinations like N43P43K50 are based on soil test results. The number of pods, seed yield and economic benefits after fertilization with it are basically superior to those of traditional schemes (Kaur et al., 2020). However, conversely, if these "local differences" are ignored or certain key nutrients are omitted, the yield and income may be directly "discounted". This has been verified in some plots (Almeida et al., 2023).

### 3.3 Controlled-release and foliar fertilizers: innovations for increased efficiency

The emergence of controlled-release fertilizers and foliar fertilizers has somewhat changed some old concepts. For instance, controlled-release urea, wrapped with a layer of polymer on the outside, can allow nutrients to "come slowly" and keep up with the rhythm of crop demands. During the critical period of soybeans, such as the R3 period, using controlled-release urea is much more stable than applying it all at once. The yield can be increased by 5% to 9% without affecting the nitrogen fixation of rhizobia (Pierozan et al., 2023). Sometimes, the "form" of fertilizer also affects its effect. For example, the compound phosphate fertilizer such as struvite-polysulfide not only releases slowly, but also promotes better root development, and the overall biomass also increases accordingly (Valle et al., 2022). For instance, spraying a little zinc during the podding stage is indeed helpful in improving seed quality and yield, especially in soils with insufficient nitrogen (Cuesta et al., 2023). In addition to enhancing efficiency, these strategies also have a potential advantage-reducing emissions. Whether it is controlled-release fertilizer or foliar spraying, both can reduce nutrient loss and greenhouse gas emissions as a whole, which is a good direction for climate-friendly agriculture (Hasukawa et al., 2021).

## 4 Irrigation Management in Soybean Cultivation

### 4.1 Critical growth stages for irrigation: flowering and pod filling phases

It's not about keeping a close eye on the water throughout the entire growing season, but rather seizing several key opportunities (Li et al., 2024). After soybeans enter the reproductive period, especially from the flowering stage (R1-R2) to the fruiting stage (R3-R6), they become particularly sensitive to water. Once water is scarce at this time, not only will the pods be produced less, but the seeds will also be lighter, and the yield will naturally decline. If drought occurs during flowering or podding, the yield loss can even reach 73% to 82%, and the weight per 100 grains during the fruiting stage will also decrease significantly. But it doesn't mean that the entire process must be filled with water. Studies have pointed out that even replenishing water only during these "critical window periods" can maximize yield and water use efficiency (Kanade et al., 2019; Heatherly, 2022; Tang et al., 2024). Sometimes, even if irrigation is delayed until the pods are just beginning to form or are about to fill up, as long as there is no water shortage during that "sensitive period", the effect is not much different from that of full-season irrigation.

### 4.2 Irrigation scheduling: use of evapotranspiration models and soil moisture sensors

Ultimately, how to use water and when to use it really can't be done without watching. Effective irrigation plans often rely on models and tools to "assist in decision-making". Climate-based evapotranspiration (ET) models, soil moisture sensors (such as substrate potential sensors), and some physiological signals of plants themselves, such as canopy temperature or crop water stress index, are all available means. Many studies have shown that methods that trigger irrigation based on soil moisture thresholds are more stable in increasing yields and improving the physiological state of crops than those that merely rely on weather conditions or plant characteristics (Franca et al., 2024; Xie et al., 2024). Especially when the drip irrigation system is used in conjunction with precise planning, the dual improvement of water use efficiency and yield becomes more significant (Morbidini et al., 2023). In addition, some models, such as InfoCrop-Soybean or AquaCrop, can also simulate the best irrigation timing very well after being tuned with local data. When dealing with years with variable climates, such tools can also be regarded as good assistants for "stabilizing water supply and production" (Jha et al., 2018; Morales-Santos et al., 2023).

### 4.3 Impact of water stress and waterlogging on yield and physiological functions

Too little water is not good, and too much water can also cause problems. Especially once soybeans enter the reproductive period, the lack of sufficient water directly affects their height, leaf area and total aboveground biomass, and ultimately leads to a loss in seed yield (Wei et al., 2018). Among them, the flowering and podding stages are the most vulnerable to "injury". Drought not only inhibits the external growth of plants, but also causes a simultaneous decline in internal photosynthesis, stomatal conductance and chlorophyll levels. It is also prone to oxidative stress and cell membrane damage (Dong et al., 2019). Although some functions can be restored after replenishing water, the extent to which they can be restored depends on the severity and duration of the drought at that time (Cui et al., 2020). On the other hand, although the impact of waterlogging is not as frequently mentioned as that of drought, it can still damage yields and physiological processes. If such extreme situations happen to occur at a critical stage, they can still completely disrupt the previous efforts. In conclusion, whether it is due to water shortage or overwatering, the result may lead to "reduced yield", especially during the period from flowering to podding. Maintaining a stable input of water is of vital importance.

## 5 Interactions Between Irrigation and Fertilization in Soybean Cultivation

### 5.1 Synergistic effects on nutrient uptake and root zone dynamics

Soybeans often perform better when water and fertilizer are well combined. It's not that all technical means must be employed. Instead, in many cases, such as in arid regions or calcareous soil conditions, as long as water management and fertilization are carried out in the right rhythm, the root system can play a greater role, and the activity of soil microorganisms will also increase (Rajanna et al., 2022; Amine et al., 2024; Khalili et al., 2024.

Combinations such as water-scarce irrigation combined with foliar iron spraying, or simultaneous irrigation with the recommended amount of fertilizer, often result in higher chlorophyll content, smoother stomatal conductance, and an overall improvement in metabolic levels. Not only that, protein synthesis is also more active, and ultimately good results can be seen in both yield and nutrient absorption. If asked why it is so obvious, many people attribute it to the changes in root vitality and the rhizosphere environment.

### 5.2 Fertigation techniques for synchronized nutrient-water delivery

In drip irrigation or underground irrigation systems, water and nutrients are precisely delivered to the roots at the same time. This "synchronous operation" is very effective for soybeans. Compared with the old-fashioned methods of spreading fertilizer or flooding, this approach is more economical and efficient. For instance, even a moderate amount of nitrogen fertilizer (such as 20 to 40 kilograms per hectare), combined with underground irrigation, can increase soybean yields by over 80% compared to the control group without irrigation or application. Studies have found that in intercropping systems and water-scarce areas, as long as the field water holding capacity is controlled at 80% and combined with a reasonable amount of nitrogen fertilizer, both yield and water and fertilizer utilization rate can reach a good level (Dou et al., 2022; Dwivedi et al., 2020; Hyuk et al., 2023; Luo et al., 2023). Of course, this approach must also be based on "precise matching"; otherwise, over-injection will be counterproductive.

### 5.3 Risks of nutrient leaching and runoff under over-irrigation

Excessive irrigation is an old problem. When the water goes down, the fertilizer follows, especially the nitrate. Once it flows out of the root zone, not only will plants fail to absorb it, but it may also pollute water bodies and waste resources in vain. A considerable number of field experiments and percolation instrument monitoring data have indicated that the amount of nitrogen loss significantly increases under high irrigation rates or heavy rain weather, and this loss varies from year to year, greatly influenced by management methods (Lee et al., 2017; Li et al., 2018; Azad et al., 2020). Coarse-grained soil is particularly prone to problems. Although drip irrigation or an optimized irrigation plan can reduce some losses, if fertilization is too vigorous or irrigation control is inadequate, phosphorus and potassium may still be carried away. So, it's not that you can't irrigate, but the key is not to overdo it or apply too much. To ensure production, you must first preserve the nutrients in the soil.

## 6 Advances in Precision Agriculture Tools for Soybean

### 6.1 Remote sensing and UAVs for monitoring crop water and nutrient status

Whether farmland is short of water or not and whether plants have sufficient nutrients can no longer be judged solely by human eyes. Nowadays, satellites, hyperspectral and multispectral sensors, and even small unmanned aerial vehicles can all come in handy. These remote sensing technologies can provide a lot of key data, such as vegetation index, chlorophyll content, soil moisture status, crop maturity, etc. Through these data, managers can identify problems earlier and intervene earlier. Among them, the flexibility of drones is particularly worth mentioning. It is not as weather-restricted as satellites and has a lower cost, making it more suitable for precise field management. Whether it is to identify local areas lacking water or fertilizer or to demarcate different management zones, targeted fertilization or irrigation becomes easier to achieve (Sishodia et al., 2020; Omia et al., 2023; Sangeetha et al., 2024). Of course, data alone is not enough. When multi-source remote sensing information is combined with advanced data analysis methods, the accuracy of output prediction is significantly improved, and management decisions become more confident (Lu et al., 2024; Shi et al., 2024).

### 6.2 Decision support systems and AI-based irrigation-fertilization scheduling

Not everyone can understand those sensor data, nor does everyone have the time to keep an eye on the weather and soil changes every day. At this point, decision support systems (DSS) and artificial intelligence (AI) become particularly practical. They can automatically integrate data sent back by remote sensing, field records and various sensors to help users "make judgments". Compared with traditional models, AI, especially deep learning frameworks, is better at handling disordered and multi-variable time series data. For example, how the output changes and when it is more appropriate to apply fertilizer or water can all be predicted by the model (Singh, 2024; Mehedi et al., 2024). Many DSS are still Web platforms. Farmers only need to log in to generate variable application maps and receive real-time suggestions based on specific soil, crop types and climatic conditions. These systems are not complex, but the functions behind them can greatly enhance operational efficiency and accuracy (Naresh et al., 2024).

### 6.3 Role of GIS and variable rate technology (VRT) in optimizing input application

The vast field is not a "flat canvas", but rather "fertile soil on one side and a bit poor on the other", and variability is quite common. GIS and VRT were precisely created for this purpose. The GIS system integrates remote sensing, soil sampling and yield data, can demarcate management zones and also output "prescription maps" for VRT equipment to use. The operation mode of VRT is actually very straightforward-it will automatically adjust which plot of land requires more application and which plot can apply less. The use of water, fertilizers and even pesticides has become more targeted. This not only reduces waste but also lowers the environmental impact and helps growers save a considerable amount of input costs (Getahun et al., 2024). This approach is increasingly being used in areas with complex soil conditions or large plot areas, especially for medium and large-sized farms that are willing to invest in equipment and pursue meticulous management (Schimmelpfennig and Lowenberg-Deboer, 2020).

## 7 Case Study

### 7.1 Region: Midwest U.S. soybean belt

The farmland conditions in the Midwestern United States are complex, and the distribution of soil nutrients is often not very uniform. Some plots have abundant phosphorus and potassium, while others have significantly low levels. In the face of such differences, many local growers have begun to adopt variable fertilization (VRF) to "prescribe the right medicine". This method is based on grid sampling and zonal management, which can customize different amounts of phosphorus (P) and potassium (K) for different areas, thus making the best use of fertilizers where they are most needed. Of course, those who used it early also had concerns, as the increase in production was not always so obvious. However, in recent years, with the advancement of soil data analysis and crop growth monitoring methods, combined with local management approaches, the effect of VRF has become more stable and controllable (Pawase et al., 2023).

### 7.2 Technology used: integration of NDVI, soil maps, and automated irrigation control

Only when the combination of technologies is skillfully applied can management efficiency be truly enhanced. In the central and western regions, some farms have integrated the NDVI vegetation index, soil maps and automatic irrigation systems, achieving "dynamic adjustment and precise response" in field management (Figure 2). The NDVI index is obtained through canopy sensors or drones, which can reflect the growth and nutrient status of soybeans in real time, helping to identify "what needs to be supplemented and what is not lacking". Meanwhile, the soil maps drawn by grid sampling and remote sensing have become the "base map" references for fertilization and irrigation (Miller et al., 2023). Automatic irrigation systems are not used in isolation either. They are usually linked with soil moisture sensors and regulated at fixed points according to the management area. The approach of not overwatering and not randomly spreading fertilizer is precisely the key to supporting the efficient growth of crops (Serrano et al., 2020).

### 7.3 Outcomes: 12%~18% yield increase, reduced nitrogen runoff, and economic benefits

Are these technologies worth piling up together? Judging from the data, the answer is affirmative. In these fields in the Midwestern United States that adopt integrated NDVI, soil maps and automatic irrigation systems, the average yield has increased by 12% to 18%. The reasons are not complicated either: nutrient absorption has improved, input matches crop demands more precisely, and water is utilized more efficiently (Farias et al., 2023). In addition, the problems of nitrogen loss and leaching have also been alleviated. The combination of precise fertilization and precise irrigation has reduced the pressure on the environment and made the ecological account look much better. Let's talk about economic benefits. Although more equipment and technology have been invested, in terms of ultimate returns, as the output and input efficiency improve, profits will naturally increase. It is no wonder that an increasing number of large-scale growers are beginning to proactively embrace these methods.

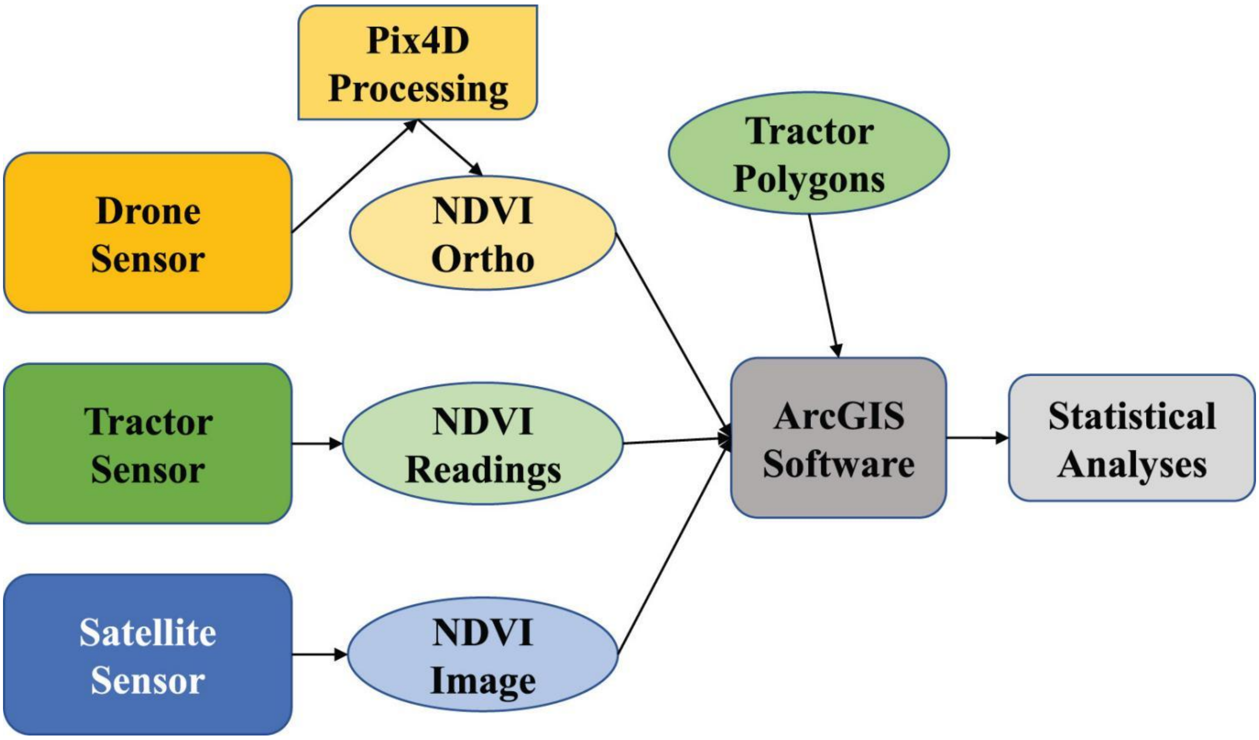


Figure 2 Workflow of NDVI collection and processing (Adopted from Miller et al., 2023)

## 8 Concluding Remarks

As for whether the output of soybeans can be increased, the answer has actually been there for a long time. Whether the variety is suitable, whether the climate and soil are compatible, and whether fertilization and irrigation can keep up, these basically determine whether a piece of land can truly "reach its potential". Research indicates that if key points such as planting density, sowing time, and water and fertilizer management are all properly arranged, the actual yield of soybeans can increase by 19%, and the yield gap can also be narrowed by approximately 14%. But the situation is not always so ideal. If the climate is too extreme or management fails to keep up, these potentials may also be discounted. For instance, during some crucial growth stages, if the temperature is appropriate (such as a diurnal temperature difference of around 35°C/27°C), and combined with irrigation and topdressing, the photosynthesis, nutrient absorption and yield composition of crops can all reach a good level. However, once the temperature is too high and the drought lasts too long, the effect will be hard to guarantee.

In recent years, considerable progress has indeed been made in areas such as genetic breeding, precision agriculture, and integrated management. The resilience and output capacity of the soybean system have also been continuously enhanced. But to be honest, some fundamental problems have not been completely solved. In small-scale farming systems or areas that rely on rain farming, the promotion of irrigation and fertilization techniques has not been smooth. Poor social and economic conditions, uneven distribution of rainfall, and the lack of localized planting suggestions have all become practical obstacles. Moreover, we still know very little about the long-term sustainability of input usage. For instance, there have been few systematic studies on the leaching of fertilizers and changes in soil health to date. Another difficulty is that many genetic mechanisms related to high yield and stress resistance have not been fully analyzed yet, which undoubtedly slows down the pace of climate-adaptive breeding.

Next, the research may need to be more "inward". Genomics, gene editing and wild germplasm resources should be well utilized, with the goal of breeding varieties that can truly withstand heat and drought. From a technical perspective, AI-driven decision-making systems, remote sensing, and variable application technologies should also be combined to further optimize input efficiency and minimize environmental burdens as much as possible. However, no matter how advanced the technology is, it's all in vain if no one uses it. Therefore, if the "last mile" issues such as solidifying promotion services, delivering seeds and agricultural supplies to farmers, and tailoring suggestions to local conditions are not resolved, the previous efforts will be difficult to materialize. Overall, for the future soybean production to maintain a steady growth, it still needs to rely on the three lines of genetics, agronomy and technology to develop simultaneously, and no one can be left behind.

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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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