Molecular Soil Biology 2025, Vol.16, No.3, 126-136
http://bioscipublisher.com/index.php/msb

Research Article Open Access

Effects of Different Fertilization Strategies on Yield and Quality of Edible Sorghum

Mengting Luo [1,2]
1 Cuixi Academy of Biotechnology, Zhuji, 311800, Zhejiang, China;
2 Hainan Institute of Tropical Agricultural Resources, Sanya, 572000, Hainan, China
Corresponding email: mengting.luo@cuixi.org
Molecular Soil Biology, 2025, Vol.16, No.3 doi: 10.5376/msb.2025.16.0013
Received: 04 Apr., 2025
Accepted: 07 May, 2025
Published: 21 May, 2025

Preferred citation for this article:
Luo M.T., 2025, Effects of different fertilization strategies on yield and quality of edible sorghum, Molecular Soil Biology, 16(3): 126-136 (doi: 10.5376/msb.2025.16.0013)

Abstract This study looked at whether different fertilization methods affect the yield and quality of edible sorghum. We found that organic fertilizers (like straw, chicken manure, pig manure) and chemical fertilizers were more effective than chemical fertilizers alone. This significantly increased sorghum yields and made the soil more nutrient-rich. Some combinations yielded 10% to 110% more than before. Soil quality also improved. Increasing the amount of nitrogen fertilizer was very helpful for sorghum growth. Sorghum grew faster and had higher fresh and dry weights. It also had higher nutrients such as protein and fat. Using nitrogen fertilizers (like lime ammonium nitrate and urea) with water irrigation also made the ears heavier and had more grains. If organic fertilizers were used in combination with chemical fertilizers, such as straw plus NPK compound fertilizer, not only did the yield increase, but the sorghum also had better nutrients such as protein and fat. This method also helped improve quality. When using less fertilizer, some ecological planting methods are also effective. For example, the method of bio-fertilizer and intercropping can also make sorghum grow well, and improve both yield and feed quality.
Keywords Sorghum (*Sorghum bicolor* L.); Fertilization strategy; Yield; Quality; Organic-inorganic combination

1 Introduction

Sorghum (*Sorghum bicolor* L.) is a crop with many uses and is important all over the world. It can be used as food, but is also often used to make feed, syrup and alcohol. It has strong adaptability and can grow in drought or poor soil. Therefore, sorghum is very helpful for food security and farmers' income (Kubiku et al., 2022; Akinseye et al., 2023; Sadafzadeh et al., 2023). Now that the population is increasing, people are more and more particular about the quality of food, which makes people have higher requirements for the yield and quality of sorghum. In order to meet this demand, many studies have begun to focus on how to grow sorghum in a more efficient and sustainable way (Wang et al., 2024; 2025).

Now agricultural development emphasizes sustainability, that is, it is necessary to grow more food and protect the environment. Therefore, how to use fertilizer well has become a problem of particular concern to everyone. Reasonable fertilization can not only make sorghum grow more and better, but also improve the soil, make fertilizer use more efficient, and reduce damage to the environment (Ganyo et al., 2019; Bartzialis et al., 2023; Sadafzadeh et al., 2023; Wang et al., 2024; 2025).

It is not clear which of the different fertilization methods, such as organic fertilizer, inorganic fertilizer, biological fertilizer, or combined with irrigation, is the most suitable and how to combine them to be the most effective. These issues need further sorting and analysis. This review mainly wants to summarize the effects of various fertilization methods on sorghum yield and quality. We focused on organic fertilizers, inorganic fertilizers, and biofertilizers, as well as their use in combination with irrigation (Ganyo et al., 2019; Kubiku et al., 2022; Akinseye et al., 2023; Bartzialis et al., 2023; Sadafzadeh et al., 2023; Wang et al., 2024; 2025).

We compared the effects of these methods in different environments and planting methods, trying to find good ways to improve sorghum yield and quality at the same time. Finally, we also proposed some issues that should be focused on in the future, such as how to maintain soil nutrient balance, how to use fertilizers more efficiently, and

which fertilization methods are more environmentally friendly. These ideas can provide references for green planting of sorghum and sustainable agricultural development.

2 Agronomic Importance of Edible Sorghum

2.1 Nutritional content (protein, starch, polyphenols, micronutrients)

Sorghum is a nutritious grain. It contains a lot of protein, starch, polyphenols and trace elements. Studies have found that the protein content of sorghum is about 9.59% to 13.60%. It also contains a variety of amino acids needed by the body, such as lysine and methionine. Sorghum also contains a lot of iron and zinc. The iron content is about 35.26 to 156.32 mg/kg, and the zinc content is between 14.45 and 44.46 mg/kg (Andiku et al., 2022; Makebe and Shimelis, 2023). In addition, sorghum polyphenols have antioxidant effects, which are good for health. Because of these nutritional characteristics, sorghum is very helpful in preventing malnutrition and supplementing trace elements, and is a healthy food worth promoting.

2.2 Versatility in food industries: gluten-free products, syrups, brewing

Sorghum is naturally gluten-free, so it is particularly suitable for people with gluten allergies or intolerance. Now many gluten-free foods, such as bread and cakes, are made with sorghum (Hao et al., 2021; Hossain et al., 2022). In addition to being a food, sorghum can also be used to make beverages such as syrup, sorghum wine and beer, and can also be used as animal feed. This shows that it has many uses in food and industry. In addition, sorghum straw and other parts have high yields, making them very suitable for use as biofuels and industrial raw materials, which is an environmentally friendly and sustainable choice (Hao et al., 2021; Liu et al., 2025).

2.3 Global production trends and regional focus (e.g., Africa, Asia, U.S.)

Sorghum is the fifth largest cereal crop in the world. It is mainly grown in Africa, Asia and the United States, and is very important for the food problem of about 750 million people in the world (Hao et al., 2021; Khalifa and Eltahir, 2023; Getahun et al., 2025) (Figure 1). In sub-Saharan Africa and South Asia, sorghum is a staple food for many people every day. It can grow well in arid, barren and hot environments (Hossain et al., 2022; Khalifa and Eltahir, 2023). Although climate change has brought many difficulties in recent years, sorghum production has been increasing through the selection of new varieties and improved fertilization and management methods, especially in Africa, where it has performed very well (Khalifa and Eltahir, 2023). Some places in the United States and Asia are also promoting the multiple uses and industrialization of sorghum, hoping to use it more widely and better.

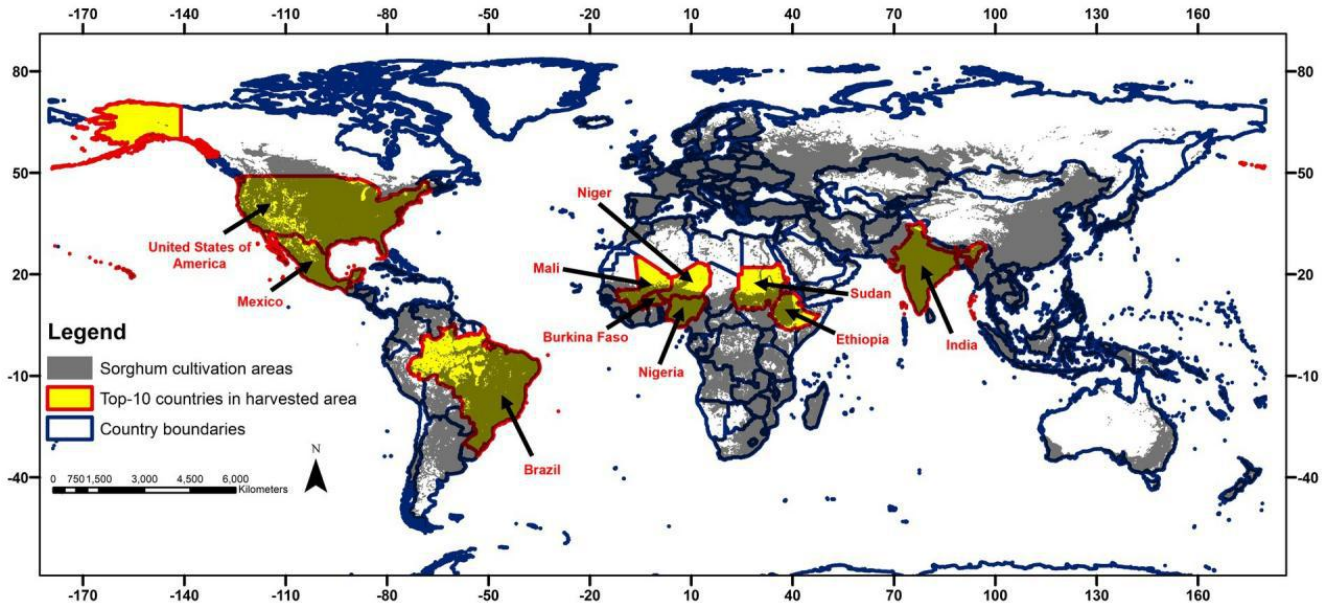

Figure 1 Map of the global distribution of sorghum cultivation areas (Adopted from Khalifa and Eltahir, 2023)

3 Sorghum Physiology and Nutrient Requirements

3.1 Overview of growth stages (germination to grain filling)

Sorghum is a relatively drought-tolerant and barren-tolerant grain crop. Its entire growth process roughly includes several stages: germination, emergence, jointing, heading, flowering and grain filling. Adverse weather such as drought will affect seed germination and embryonic development. As a result, photosynthesis becomes weaker and nutrient transport is unbalanced, which may eventually affect grain filling, resulting in reduced yield and poor quality (Abreha et al., 2022). Sorghum has different nutritional requirements at different growth stages. Sometimes the absorption capacity is strong, and sometimes it is weak. Therefore, scientific fertilization is critical throughout the growth period, which can help sorghum grow smoothly throughout the entire cycle.

3.2 Macronutrient and micronutrient needs during development

Sorghum is rich in nutrients. It contains a lot of protein and dietary fiber, as well as B vitamins (such as thiamine, riboflavin, and niacin), vitamin E, and some minerals, such as phosphorus, magnesium, iron, and zinc (Stefoska-Needham et al., 2015; de Morais et al., 2017; Xiong et al., 2019; Tanwar et al., 2023). In the process of sorghum growth, nitrogen, phosphorus, and potassium are particularly important nutrients, especially during the period from jointing to filling, when their demand is the highest (Li et al., 2023). Although trace elements such as iron, zinc, manganese, and copper are used less, they are also very useful for improving the quality of sorghum. However, in some areas, the content of potassium, calcium, manganese, and copper in sorghum grains is low, which needs to be solved by supplementing fertilizers or breeding new varieties (Jean-Baptiste et al., 2021; Palé et al., 2022). Soil type, climate conditions and planting methods also affect the absorption and accumulation of these nutrients (Li et al., 2023; Osman et al., 2022).

3.3 Nutrient uptake efficiency characteristics unique to sorghum

One characteristic of sorghum is that it is very good at "saving" nutrients. Even in saline-alkali or arid areas, it can still maintain good yield and quality (Abreha et al., 2022; Li et al., 2023). When growing sorghum in saline-alkali land, the amount of nitrogen fertilizer should be determined according to the soil. For example, inland saline-alkali land is recommended to use 100 kg/hectare of nitrogen fertilizer, while coastal saline-alkali land requires 150 kg/hectare. If there is more organic matter in the soil, the effect of nitrogen fertilizer will be better (Li et al., 2023). Combining organic fertilizers with chemical fertilizers, such as using 75% of the recommended amount of fertilizer, plus some zeolite, pressed mud or biofertilizers, can also make sorghum grow better, and improve yield and quality. In addition, the protein, minerals and some active ingredients in sorghum grains that are beneficial to the human body also respond quickly to changes in fertilizers, indicating that scientific management of nutrients is really important (de Morais et al., 2017; Xiong et al., 2019; Tanwar et al., 2023).

4 Classification of Fertilization Strategies

4.1 Synthetic fertilizers: NPK blends, urea, ammonium nitrate

Nowadays, many people use synthetic fertilizers when growing sorghum, such as NPK compound fertilizer, urea and ammonium nitrate. These fertilizers can make sorghum grow faster and stronger, especially in fields with irrigation conditions, the effect is more obvious (Ismaeil et al., 2024; Sebetha and Modisapudi, 2025). Nitrogen fertilizers such as urea, ammonium nitrate and ammonium sulfate can increase sorghum ear weight, biomass and grain yield. NPK compound fertilizer can not only increase production, but also improve nutrients such as protein and fat (Ivanina et al., 2019; Ismaeil et al., 2024). Chemical fertilizers should not be used indiscriminately. If used too much, nutrients in the soil will be lost and even pollute the environment. So be sure to control the amount when using (Wang et al., 2024).

4.2 Organic amendments: Farmyard manure, compost, biochar

In addition to chemical fertilizers, there are many organic fertilizers that can be used, such as farmyard manure, compost and biochar. These fertilizers can increase the organic matter in the soil, improve the soil structure, and increase the activity of microorganisms, which is conducive to the growth of sorghum (Tonitto and Ricker-Gilbert, 2016; Oueda et al., 2025; Wang et al., 2025). Materials such as livestock manure, straw return to the field, and compost can effectively improve soil fertility and sorghum yield. Some organic fertilizers, such as Bokashi, can

also increase the types of nutrients in the soil and enrich the microorganisms in the soil (Wang et al., 2025; Oueda et al., 2025). Although the yield-increasing effect of organic fertilizers may not be as obvious as that of chemical fertilizers, it can improve soil health, is suitable for long-term use, and is also beneficial to sustainable planting (Tonitto and Ricker-Gilbert, 2016; Oueda et al., 2025).

4.3 Integrated Nutrient Management (INM): Combination of organic and inorganic

Integrated nutrient management, that is, the combination of organic and inorganic fertilizers, is a more comprehensive approach. It can not only increase yields, but also do not damage the soil, and maintain the diversity of soil ecology. Many studies have found that this combination is very effective. For example, the combination of poultry manure plus diammonium phosphate, straw plus NPK fertilizer, can not only increase sorghum yield, but also improve protein and other quality parameters (Tonitto and Ricker-Gilbert, 2016; Ivanina et al., 2019; Akinseye et al., 2023; Oueda et al., 2025; Wang et al., 2025). For example, returning straw to the field and appropriately reducing nitrogen fertilizer, or using poultry manure and fertilizer together, can not only make sorghum grow well, but also improve soil quality, and it is more cost-effective (Ivanina et al., 2019; Akinseye et al., 2023; Wang et al., 2025).

4.4 Biofertilizers: Nitrogen-fixing and phosphorus-solubilizing microbes

Biofertilizers use beneficial microorganisms to help sorghum absorb nutrients, such as nitrogen-fixing and phosphate-solubilizing bacteria. They can help sorghum grow better, absorb more nutrients, and increase yields. Some studies have used biofertilizers together with chemical fertilizers and organic fertilizers, and found that sorghum grows stronger and has higher yields and quality. These microorganisms can improve the environment around the roots, making it easier for nutrients to be converted and absorbed. Biofertilizers are particularly suitable for use in organic farming and integrated management systems, and they perform well.

5 Effects of Nitrogen Fertilization

5.1 Nitrogen's role in vegetative growth and grain protein content

Nitrogen fertilizer is very important for sorghum, both for making it grow well and for improving its quality. As long as there is enough nitrogen fertilizer, the sorghum will be taller, with larger leaves and thicker stems. There will also be more chlorophyll in the leaves, stronger photosynthesis, and more vigorous growth of the whole plant (Elnasikh and Ibrahium, 2015; Bartzialis et al., 2023; Ismaeil et al., 2024; Wang et al., 2024). Nitrogen fertilizer can also increase the protein content in grains and forage, and improve nutritional content such as protein and starch, which is good for both eating and making feed (Modisapudi and Sebetha, 2022; Bartzialis et al., 2023; Ismaeil et al., 2024). Different nitrogen fertilizers have different effects. For example, lime ammonium nitrogen and urea can significantly increase the protein content in grains, but the differences between them are also worth noting.

5.2 Influence on biomass, tillering, and yield response curves

If nitrogen fertilizer is used properly, the biomass and yield of sorghum will increase. Appropriate nitrogen fertilizer can make the aboveground part grow more, whether it is the weight of the ear, or the fresh weight and dry weight. Tillering will also increase, and ultimately more ears and grains can be harvested. However, nitrogen fertilizer should not be too much or too little. Too little is not enough, and too much is counterproductive. The change in yield is usually a trend of "first rise and then fall". Studies have found that the range of 144 to 160 kg/hectare is an ideal dosage, which not only has high yields, but also does not accumulate too much nitrate in the soil (Majrashi et al., 2022; Bartzialis et al., 2023; Wang et al., 2024; Obour et al., 2025). Under different farming methods, the effect of fertilization will also be different. For example, if no-till plots are combined with 45 to 90 kg/hectare of nitrogen fertilizer, the harvest can also be good and relatively stable (Majrashi et al., 2022; Obour et al., 2025).

5.3 Risks of overapplication (lodging, nitrate accumulation)

Although nitrogen fertilizer is important, there are many problems if it is used too much. First, too much nitrogen fertilizer will make sorghum grow too high and too fast, and the stems will become soft and easy to fall over. This will affect mechanical harvesting and may also affect yield (Shehab and Guo, 2021; Majrashi et al., 2022; Wang et

al., 2024). Second, too much nitrogen fertilizer will cause too much nitrate and hydrocyanic acid (HCN) to accumulate in the soil and plants. If there is a drought, it will be even more serious, and the safety of food and feed will become a problem (Shehab and Guo, 2021; Wang et al., 2024). Studies have shown that when the amount of nitrogen fertilizer exceeds 90 to 120 kg/hectare, the HCN level in the plant will rise rapidly, and the antioxidant capacity will decrease. Therefore, in arid areas, nitrogen fertilizer should not be applied too much, and yield, quality and safety must be taken into account (Shehab and Guo, 2021; Wang et al., 2024). Using too much nitrogen fertilizer will reduce fertilizer efficiency and increase the risk of environmental pollution, leading to nitrogen loss.

6 Phosphorus and Potassium Nutrition

6.1 Phosphorus: Root development, flowering, seed setting

Phosphorus is a very important nutrient in sorghum growth, especially when it grows roots, flowers and sets seeds. If there is enough phosphorus fertilizer, sorghum can grow more vigorously, accumulate more nutrients and have higher yields (Schlegel and Havlin, 2021; Guo et al., 2025). Some long-term field experiments have found that phosphorus fertilizer can not only increase grain yield, but also help the absorption of nitrogen fertilizer, saving fertilizer and money (Schlegel and Havlin, 2021). In addition, phosphorus is mostly concentrated in the grains, so it has a great impact on the final yield and quality (Ivanina et al., 2021). In saline-alkali land, if 60 kg/hectare of phosphorus fertilizer is used together with nitrogen fertilizer, the harvest index and nutrient absorption effect of sorghum can be significantly improved (Guo et al., 2025).

6.2 Potassium: Disease resistance, drought tolerance, grain filling

Potassium is also critical for sorghum, especially in disease resistance, drought resistance and grain filling. Potassium is mainly stored in the stems of sorghum, which can enhance the resistance of the plant and help maintain water balance (Ivanina et al., 2021). Studies have found that when more nitrogen fertilizer is applied, the potassium content in the leaves and stems of sorghum will also increase, so that dry matter accumulation will increase and yield will increase (Kostadinova et al., 2018; Todorov et al., 2020). If potassium fertilizer is applied properly, it can make sorghum photosynthesis more efficient and have better nutritional quality. The effect of potassium fertilizer is particularly obvious in difficult environments such as drought or saline-alkali land (Abbaszadeh-Dahaji et al., 2020; Gulzhaina et al., 2025). With more potassium, the grains are fuller, and the yield and quality are naturally better (Ivanina et al., 2021; Guo et al., 2025).

6.3 Synergistic and antagonistic interactions with nitrogen

Nitrogen, phosphorus, and potassium affect each other. Many studies have found that applying nitrogen and phosphorus together is better than applying them separately. This combination can increase grain yield and make fertilizer utilization more efficient (Zhu et al., 2020; Schlegel and Havlin, 2021; Guo et al., 2025) (Figure 2). When there is more nitrogen fertilizer, plants absorb phosphorus and potassium more strongly. In other words, phosphorus and potassium can be better absorbed and utilized only when there is enough nitrogen fertilizer (Kostadinova et al., 2018; Todorov et al., 2020). But if all three nutrients are lacking, nitrogen is often the first to be affected. Insufficient nitrogen will slow down the overall growth of sorghum and also reduce the absorption of phosphorus and potassium (Zhu et al., 2020). Scientifically combining nitrogen, phosphorus and potassium fertilizers is the key to improving sorghum yield and quality. This not only makes good use of nutrients, but is also more environmentally friendly and sustainable.

7 Organic and Bio-based Fertilizers

7.1 Impact on soil health and microbial activity

Organic and biofertilizers are very good for soil. They make soil healthier and increase the variety and activity of microorganisms in the soil. For example, using materials such as cow dung and pine needles together with organic acids and beneficial bacteria (such as *Priestia megaterium* and *Trichoderma harzianum*) can reduce salt in the soil, increase nutrients, and promote better root growth and photosynthesis, which is very helpful for the growth of sweet sorghum (Xue et al., 2024). In Burkina Faso, studies have found that after using organic fertilizers such as Bokashi, the organic matter content of the soil increased, and there were more large animals in the soil, with a

richer variety, indicating that the soil ecology is more active (Oueda et al., 2025). Biofertilizers such as rhizobia and arbuscular mycorrhizal fungi can also help sorghum absorb more nitrogen, phosphorus, and potassium, while improving its water utilization efficiency and drought resistance (Kamali and Mehraban, 2020; Kareem and Hamed, 2024).

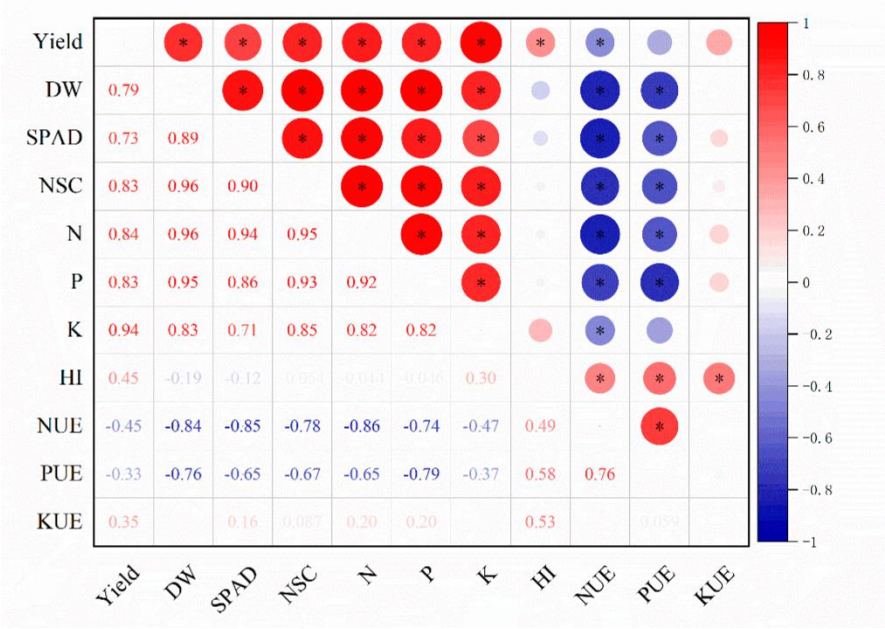

Figure 2 Relationships between all measured characteristics of sorghum grown in saline soils. DW: dry weight; N: aerial N accumulation; P: aerial P accumulation; K: aerial K accumulation. *: significant difference at $p \leqslant 0.05$ (Adopted from Guo et al., 2025)

7.2 Long-term yield stability and environmental benefits

The long-term use of organic fertilizers and biofertilizers is conducive to the stability of sorghum yields and can also increase year by year. Many studies have shown that whether used alone or with chemical fertilizers, these fertilizers can make sorghum grow better, whether it is biomass, grain yield or quality indicators, there are significant improvements. Moreover, the yield is relatively stable in harsh environments such as drought or saline-alkali land (Kamali and Mehraban, 2020; Kareem and Hamed, 2024; Xue et al., 2024). They can also reduce dependence on chemical fertilizers, reduce pollution, improve soil structure, make the land more fertile, and the ecological environment healthier (Hassanen and Abotaleb, 2020; Rizvi et al., 2021). Some biofertilizers, such as phosphate bacteria, not only help absorb nutrients, but also inhibit pathogens, so that less pesticides are used (Rizvi et al., 2021).

7.3 Comparison with synthetic options in cost and effectiveness

Compared with chemical fertilizers, organic fertilizers and biofertilizers are also competitive in improving sorghum yield and quality. Some experiments have found that when organic fertilizers or biofertilizers are used alone, although the yield may not be as good as full fertilizers, if the two are used together, the amount of chemical fertilizers can be reduced by 25% to 50%, while still achieving similar or even better yields and quality (Akhtar et al., 2020; Hassanen and Abotaleb, 2020). These fertilizers have little pressure on the environment. The longer they are used, the better the soil structure and fertility will be, bringing considerable ecological and economic benefits (Hassanen and Abotaleb, 2020; Rizvi et al., 2021). In some places, people also use resources around them, such as poultry manure and crop straw, to make their own fertilizers, which can also save some costs (Oueda et al., 2025).

8 Yield and Quality Metrics in Response to Fertilization

8.1 Yield components: plant height, panicle length, 1000-grain weight

Different fertilization methods can significantly improve sorghum yield performance. For example, using organic

fertilizers and chemical fertilizers together, reducing the amount of chemical fertilizers, and adding trace elements can make sorghum grow taller, with longer ears and heavier 1 000-grain weight. It used only 75% of the recommended amount of chemical fertilizers, plus zeolite, pressed mud, and biological agents. As a result, plant height increased by 23.73%, ear length increased by 31.34%, and 1 000-grain weight increased by 30.67%. Nitrogen fertilizers and irrigation can also make sorghum grow taller and have larger leaves. Studies have found that higher plant heights are associated with higher yields (Wang et al., 2024). Organic fertilizers such as poultry manure and cow dung can increase yields by 8% to 110% when used with chemical fertilizers. However, different sorghum varieties respond differently to fertilizers (Akinseye et al., 2023). The effects of NPK compound fertilizers and zinc fertilizers vary in different terrains. The effects are most obvious in lowlands, but not so strong in highlands (Desta et al., 2022).

8.2 Quality traits: starch content, tannin levels, protein content

Fertilization not only increases yields, but also affects the quality of sorghum grains. For example, under normal irrigation conditions, there is little difference in protein, starch, and minerals (such as phosphorus and calcium) between nanofertilizers and ordinary chemical fertilizers. But if there is drought, the effect of nanofertilizers is obvious, with protein content increasing to 21.5%, tannins also increasing (0.373%), and fat and phosphorus absorption improving (Kazemi et al., 2022). The combination of organic fertilizers and chemical fertilizers can also increase soluble solids (that is, Brix value) and juice extraction rate. Higher levels of these two indicators indicate that starch and sugar content have also increased.

8.3 Trade-offs and correlations (e.g., yield vs. protein)

Yield and quality cannot always be achieved at the same time. Some studies have found that more nitrogen fertilizers can indeed increase yields, but protein content may not necessarily increase as well. Sometimes, changes in nutrients such as protein and tannins are affected by fertilizer type and weather (Kazemi et al., 2022). While pursuing high yields, costs and the environment must also be considered. Although some fertilization schemes produce more, they also cost more money, which may not be cost-effective (Tonitto and Ricker-Gilbert, 2016; Akinseye et al., 2023).

9 Case Study: Field-Based Evaluation of Fertilization Regimes

9.1 Location and Setup: Describe a selected representative study (e.g., from India, Nigeria, or U.S. Midwest)

The experiment was conducted in the Ganges River Basin in India using a randomized block design. Ten different fertilization methods were set up, and each treatment was replicated three times. These methods included conventional NPK fertilizers, compost, fertilizers and organic fertilizers (such as 75% of the recommended amount of fertilizers with zeolite, filter press mud and biological agents), and single biological fertilizer treatments.

9.2 Treatments compared: Control, NPK, compost, INM, biofertilizer

The treatments used in the experiment included:
No fertilizer (control group)
NPK fertilizers (100% recommended amount and 75% recommended amount)
Compost (such as filter press mud)
Integrated nutrient management (INM: 75% fertilizer + zeolite + filter press mud + biological agents)
Biological fertilizers (such as Bio-Nima)

9.3 Results summary: Key differences in yield, quality, cost-efficiency

Yield performance: Integrated nutrient management (INM) has the best effect. Plant height increased by 23.73%, dry matter increased by 42.25%, ear length increased by 31.34%, grain yield increased by 53.25%, and thousand-grain weight also increased by 30.67%.

Quality improvement: INM can also increase the Brix value by 37.67% and the juice extraction rate by 39.04%, indicating that the quality of sorghum has also improved.

Cost and benefit: The INM model can not only increase production and improve quality, but also save the use of chemical fertilizers, which is more economical and uses resources more efficiently (Akinseye et al., 2023).

Performance of biofertilizer: Although biofertilizer requires less investment, it can also increase nutrients such as protein and sugar. Moreover, it has high land utilization rate and good economic benefits, which is especially suitable for small farmers (Sadafzadeh et al., 2023).

9.4 Implications: Practical recommendations drawn from real-world data

Recommended approach: In places where chemical fertilizers are unaffordable or where sustainable farming is desired, it is recommended to use the INM method, which combines organic and chemical fertilizers. This method not only increases sorghum production and improves quality, but also reduces dependence on chemical fertilizers and improves soil health (Akinseye et al., 2023; Wang et al., 2025).

Low-input recommendations: For those with limited investment or engaged in ecological agriculture, you can consider using biofertilizers and intercropping. This can further improve the nutrition and income of sorghum, and is particularly suitable for small farmers and ecological agricultural areas (Sadafzadeh et al., 2023).

Take measures according to local conditions: Conditions vary from place to place. The fertilization plan should be flexibly selected based on the local soil, climate and cost conditions, such as using NPK, compost, INM or biofertilizer. Only in this way can a balance be found between increasing production, improving quality and sustainable development (Tonitto and Ricker-Gilbert, 2016; Akinseye et al., 2023; Wang et al., 2025).

10 Future Directions and Conclusions

At present, many studies have proved that methods such as the combination of organic fertilizer and chemical fertilizer, the addition of trace elements, straw return to the field, nitrogen fertilizer combined with drip irrigation, and rainwater collection can significantly improve the yield and quality of edible sorghum. To achieve truly precise nutrient management, there are still many problems to be solved. In particular, under different soil, climate and variety conditions, how to make sorghum absorb well without polluting the environment, there is no unified approach at present. Climate change is becoming more and more obvious, and the rainfall time and distribution are becoming more and more unstable, which poses new challenges to fertilization methods. Therefore, "climate-smart fertilization" such as "delayed fertilization" and small drip irrigation combined with fertilizer control also requires more research to ensure stable and continuous production of sorghum.

To promote these efficient and environmentally friendly fertilization methods, technology alone is not enough, and policies and farmers' participation are also needed. In order for farmers to use them and use them well, technical training and agricultural extension services must be strengthened. We must teach everyone how to use organic fertilizers, how to supplement trace elements, how to return to the field, and how to collect rainwater. Letting farmers understand the benefits of these methods and learn how to operate them is a key step in improving yield and quality. It is recommended that the government and relevant departments increase training efforts, bring new methods of precision fertilization and climate adaptation into the fields, and encourage farmers to use more diverse and environmentally friendly solutions.

In the future, sorghum fertilization methods should not only focus on yield and quality, but also consider ecological impacts. By rationally matching organic and chemical fertilizers, controlling water and fertilizers, using climate-adaptive management methods, and training farmers, both yield and environment can be improved, achieving a "win-win" situation. In the future, sorghum fertilization should be more precise, smarter, and more ecological. This will ensure food security and allow agriculture to go further and more steadily.

Acknowledgments

The author would like to express the gratitude to the two anonymous peer researchers for their constructive suggestions on the manuscript.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a

potential conflict of interest.

References

Abbaszadeh-Dahaji P., Masalehi F., and Akhgar A., 2020, Improved growth and nutrition of sorghum (*Sorghum bicolor*) plants in a low-fertility calcareous soil treated with plant growth-promoting rhizobacteria and Fe-EDTA, Journal of Soil Science and Plant Nutrition, 20(1): 31-42.
https://doi.org/10.1007/s42729-019-00098-9

Abreha K.B., Enyew M., Carlsson A.S., Vetukuri R.R., Feyissa T., Motlhaodi T., Ng'uni D., and Geleta M., 2022, Sorghum in dryland: morphological, physiological, and molecular responses of sorghum under drought stress, Planta, 255(1): 20.
https://doi.org/10.1007/s00425-021-03799-7

Akhtar S., Bashir S., Khan S., Iqbal J., Gulshan A. B., Irshad S., Batool S., Ahmad N., and Rizwan M.S., 2020, Integrated usage of synthetic and bio-fertilizers: an environment friendly approach to improve the productivity of sorghum, Cereal Research Communications, 48(2): 247-253.
https://doi.org/10.1007/s42976-020-00029-w

Akinseye F. M., Birhanu B. Z., Ajeigbe H. A., Diancoumba M., Sanogo K., and Tabo R., 2023, Impacts of fertilization management strategies on improved sorghums varieties in smallholder farming systems in Mali: Productivity and profitability differences. Heliyon, 9(3): e14497.
https://doi.org/10.1016/j.heliyon.2023.e14497

Andiku C., Shimelis H., Shayanowako A. I., Gangashetty P. I., and Manyasa E., 2022, Genetic diversity analysis of East African sorghum (*Sorghum bicolor* [L.] Moench) germplasm collections for agronomic and nutritional quality traits, Heliyon, 8(6): e09690.
https://doi.org/10.1016/j.heliyon.2022.e09690

Bartzialis D., Giannoulis K. D., Gintsioudis I., and Danalatos N. G., 2023, Assessing the efficiency of different nitrogen fertilization levels on sorghum yield and quality characteristics, Agriculture, 13(6): 1253.
https://doi.org/10.3390/agriculture13061253

de Morais Cardoso L., Pinheiro S. S., Martino H. S. D., and Pinheiro-Sant'Ana H. M., 2017, Sorghum (*Sorghum bicolor* L.): Nutrients, bioactive compounds, and potential impact on human health, Critical Reviews in Food Science and Nutrition, 57(2): 372-390.
https://doi.org/10.1080/10408398.2014.887057

Desta G., Amede T., Gashaw T., Legesse G., Agegnehu G., Mekonnen K., and Whitbread A., 2022, Sorghum yield response to NPKS and NPZn nutrients along sorghum-growing landscapes, Experimental Agriculture, 58: e10.
https://doi.org/10.1017/S0014479722000072

Elnasikh M.H., and Ibrahium M.S., 2015, Effect of nitrogen fertilization on growth, yield and ethanol production of sweet sorghum (*Sorghum bicolor* (L. Moench), Omdurman Islamic University Journal, 11(2): 383-359.
https://doi.org/10.52981/oiuj.v11i2.1716

Ganyo K. K., Muller B., Ndiaye M., Gaglo E. K., Guissé A., and Adam M., 2019, Defining fertilization strategies for sorghum (*Sorghum bicolor* (L.) Moench) production under Sudano-Sahelian conditions: Options for late basal fertilizer application, Agronomy, 9(11): 697.
https://doi.org/10.3390/agronomy9110697

Getahun A., Alemu A., Nida H., and Woldesemayat, A., 2025, Multi-locus genome-wide association mapping for major agronomic and yield-related traits in sorghum (*Sorghum bicolor* (L.) moench) landraces. BMC Genomics, 26(1): 304.
https://doi.org/10.1186/s12864-025-11458-4

Gulzhaina A., Mambetov K., Dzhakupova I., Bozhbanov A., and Dilnoza K., 2025, Comparative analysis of the influence of biologically active substances on photosynthetic productivity of Sorghum Saccharatum, International Journal of Innovative Research and Scientific Studies, 8(3): 1836-1844.
https://doi.org/10.53894/ijirss.v8i3.6892

Guo X., Wu Q., Wang L., Zhou G., Zhu G., Suliman M. S. E., and Nimir N. E. A., 2025, Optimum nitrogen and phosphorus combination improved yield and nutrient use efficiency of sorghum in saline soil, Plants, 14(1): 102.
https://doi.org/10.3390/plants14010102

Hao H., Li Z. Leng C., Lu C., Luo H., Liu Y., Shang L., and Jing H.C., 2021, Sorghum breeding in the genomic era: opportunities and challenges, Theoretical and Applied Genetics, 134(7): 1899-1924.
https://doi.org/10.1007/s00122-021-03789-z

Hassanen S. A., and Abotaleb H., 2020, Potential for improving sorghum productivity and quality by organic-bio and mineral fertilizers under soil lands conditions, Journal of Current Trends in Agriculture and Environmental Sustainability, 1: 103.

Hossain M.S., Islam M.N., Rahman M.M., Mostofa M.G., and Khan M.A.R., 2022, Sorghum: A prospective crop for climatic vulnerability, food and nutritional security, Journal of Agriculture and Food Research, 8: 100300.
https://doi.org/10.1016/j.jafr.2022.100300

Ismaeil F.M., Ahmed S.E.E., Jabereldar A.A., and Ahmed E.E.B.M., 2024, Effect of different nitrogen levels on yield and quality of forage sorghum (*Sorghum bicolor* L. Moench cv. Abusabien), Asian Journal of Advances in Agricultural Research, 24(7): 28-38.
https://doi.org/10.9734/ajaar/2024/v24i7520

Ivanina V.V., Pashynska K.L., and Kostashchuk M.V., 2019, Effect of fertilizers on the grain yield and quality of grain sorghum, Advanced Agritechnologies, 7: 6.
https://doi.org/10.47414/na.7.2019.204801

Ivanina V., Pashynska K., and Smirnykh V., 2021, Removal and balance of nutritional elements in the agrocenosis of sorghum for grain depending on fertilizer system, Visnyk Agrarnoi Nauky, 99(12): 28-32.
https://doi.org/10.31073/agrovisnyk202112-03

Jean-Baptiste T.S., Mason Stephen C., Adama S., and Etienne B.S., 2021, Sorghum grain and stover nutrient concentrations as influenced by tillage and soil amendment in semi-arid Burkina Faso, Journal of Agriculture and Crops, 7(4): 116-125.
https://doi.org/10.32861/jac.74.116.125

Kamali S., and Mehraban A., 2020, Effects of Nitroxin and arbuscular mycorrhizal fungi on the agro-physiological traits and grain yield of sorghum (*Sorghum bicolor* L.) under drought stress conditions, PLoS ONE, 15(12): e0243824.
https://doi.org/10.1371/journal.pone.0243824

Kareem S.S., and Hamed B.A., 2024, The effect of adding bio and organic fertilizer under two levels of water stress on the readiness of NPK nutrients in the plant and the growth yield of the sorghum plant, IOP Conference Series: Earth and Environmental Science. IOP Publishing, 1371(8): 082010.
https://doi.org/10.1088/1755-1315/1371/8/082010

Kazemi E., Ganjali H. R., Mehraban A., and Ghasemi A., 2022, Yield and biochemical properties of grain sorghum (*Sorghum bicolor* L. Moench) affected by nano-fertilizer under field drought stress, Cereal Research Communications, 50(3): 397-405.
https://doi.org/10.1007/s42976-021-00198-2

Khalifa M., and Eltahir E.A., 2023, Assessment of global sorghum production, tolerance, and climate risk, Frontiers in Sustainable Food Systems, 7: 1184373.
https://doi.org/10.3389/fsufs.2023.1184373

Kostadinova S., Todorov Z., and Velinov I., 2018, Concentration of nitrogen, phosphorus and potassium in sorghum plants grown at different levels of nitrogen nutrition, Agro-knowledge Journal, 19(2): 127-136.
https://doi.org/10.7251/agren1802127k

Kubiku F.N.M., Mandumbu R., Nyamadzawo G., and Nyamangara J., 2022, Field edge rainwater harvesting and inorganic fertilizers for improved sorghum (*Sorghum bicolor* L.) yields in semi-arid farming regions of Marange, Zimbabwe, Heliyon, 8(2): e08859.
https://doi.org/10.1016/j.heliyon.2022.e08859

Li J., Lei S., Gong H., Liu Z., Zhang Y., and Ouyang Z., 2023, Field performance of sweet sorghum in salt-affected soils in China: A quantitative synthesis. Environmental Research, 222: 115362.
https://doi.org/10.1016/j.envres.2023.115362

Liu F., Wodajo B., Zhao K., Tang S., Xie Q., and Xie P., 2025, Unravelling sorghum functional genomics and molecular breeding: past achievements and future prospects, Journal of genetics and genomics, 52(6): 719-732.
https://doi.org/10.1016/j.jgg.2024.07.016

Majrashi M.A., Obour A.K., Moorberg C.J., Lollato R.P., Holman J.D., Du J., Mikha M., and Assefa Y., 2022, No-tillage and fertilizer-nitrogen improved sorghum yield in dryland wheat-sorghum-fallow rotation, Journal of Soil and Water Conservation, 77(6): 609-618.
https://doi.org/10.2489/jswc.2022.00241

Makebe A., and Shimelis H., 2023, Diversity analysis for grain nutrient content and agronomic traits among newly bred striga-resistant and *Fusarium oxysporum* f.sp. strigae (FOS)-compatible sorghum genotypes, Diversity, 15(3): 371.
https://doi.org/10.3390/d15030371

Modisapudi S.L., and Sebetha E.T., 2022, Sorghum grain quality as affected by different nitrogen fertilizer sources, cultivar and field condition, Journal of Agriculture and Crops, 8(4): 330-339.
https://doi.org/10.32861/jac.84.330.339

Obour A.K., Holman J.D., Prasad P.V.V., and Assefa Y., 2025, Grain sorghum yield stability as affected by nitrogen fertilizer, tillage, and yield environment. Crop Science, 65(2): e70050.
https://doi.org/10.1002/csc2.70050

Osman A., Abd El-Wahab A., Ahmed M.F.E., Buschmann M., Visscher C., Hartung C.B., and Lingens J.B., 2022, Nutrient composition and in vitro fermentation characteristics of sorghum depending on variety and year of cultivation in northern Italy, Foods, 11(20): 3255.
https://doi.org/10.3390/foods11203255

Oueda N., Avocefohoun D., and Doamba S.W., 2025, Effects of locally sourced organic fertilizers on sorghum yield in Burkina Faso, World Journal of Advanced Research and Reviews, 25(2): 684-693.
https://doi.org/10.30574/wjarr.2025.25.2.0459

Palé S., Mason S.C., Taonda S.J.B., Sermé I., and Sohoro A., 2022, Tillage, sole and intercrop systems and soil amendment influence on sorghum grain and stover nutrient levels, GSC Advanced Research and Reviews, 10(3): 151-158.
https://doi.org/10.30574/gscarr.2022.10.3.0065

Rizvi A., Ahmed B., Khan M.S., Umar S., and Lee J., 2021, Sorghum-phosphate solubilizers interactions: crop nutrition, biotic stress alleviation, and yield optimization. Frontiers in Plant Science, 12: 746780.
https://doi.org/10.3389/fpls.2021.746780

Sadafzadeh E., Javanmard A., Amani Machiani M., and Sofo A., 2023, Application of bio-fertilizers improves forage quantity and quality of sorghum (*Sorghum bicolor* L.) intercropped with soybean (*Glycine max* L.), Plants, 12(16): 2985.
https://doi.org/10.3390/plants12162985

Schlegel A.J., and Havlin J.L., 2021, Irrigated grain sorghum response to 55 years of nitrogen, phosphorus, and potassium fertilization. Agronomy Journal, 113(1): 464-477.
https://doi.org/10.1002/AGJ2.20453

Sebetha E.T., and Modisapudi S.L., 2025, The effect of different nitrogen fertilizer sources and field condition on sorghum yield performance, Interciencia, 59(2).
https://doi.org/10.59671/duji3

Shehab A.E.S.A.E., and Guo Y., 2021, Effects of nitrogen fertilization and drought on hydrocyanic acid accumulation and morpho-physiological parameters of sorghums, Journal of the Science of Food and Agriculture, 101(8): 3355-3365.
https://doi.org/10.1002/jsfa.10965

Stefoska-Needham A., Beck E.J., Johnson S.K., and Tapsell L.C., 2015, Sorghum: an underutilized cereal whole grain with the potential to assist in the prevention of chronic disease, Food Reviews International, 31(4): 401-437.
https://doi.org/10.1080/87559129.2015.1022832

Tanwar R., Panghal A., Chaudhary G., Kumari A., and Chhikara N., 2023, Nutritional, phytochemical and functional potential of sorghum: A review, Food Chemistry Advances, 3: 100501.
https://doi.org/10.1016/j.focha.2023.100501

Todorov Z., Velinov I., and Kostadinova S., 2020, Uptake and expense of nitrogen, phosphorus and potassium in grain sorghum depends on nitrogen fertilization. Agrofor, 5(1): 46-53.
https://doi.org/10.7251/agreng2001046t

Tonitto C., and Ricker-Gilbert J.E., 2016, Nutrient management in African sorghum cropping systems: applying meta-analysis to assess yield and profitability, Agronomy for Sustainable Development, 36(1): 10.
https://doi.org/10.1007/s13593-015-0336-8

Wang R., Wang C., Liu T., Chen Y., Liu B., Xiao J., Luo Y., and Chen L., 2025, Effects of different organic materials and reduced nitrogen fertilizer application on sorghum yield and soil nutrients, Scientific Reports, 15(1): 6914.
https://doi.org/10.1038/s41598-025-90584-1

Wang Z., Nie T., Lu D., Zhang P., Li J., Li F., Zhang Z., Chen P., Jiang L., Dai C., and Waller P.M., 2024, Effects of different irrigation management and nitrogen rate on sorghum (*Sorghum bicolor* L.) growth, yield and soil nitrogen accumulation with drip irrigation, Agronomy, 14(1): 215.
https://doi.org/10.3390/agronomy14010215

Xiong Y., Zhang P., Warner R.D., and Fang Z., 2019, Sorghum grain: From genotype, nutrition, and phenolic profile to its health benefits and food applications, Comprehensive Reviews in Food Science and Food Safety, 18(6): 2025-2046.
https://doi.org/10.1111/1541-4337.12506

Xue W., Yang S., Liu X., Qian M., Wang H., Yang H., Liu X., Shen Y., Li J., and Sun Z., 2024, Enhanced sweet sorghum growth and soil quality in coastal saline-alkali soils through organic acid-containing bio-based materials and microbial synergy, Agronomy, 15(1): 56.
https://doi.org/10.3390/agronomy15010056

Zhu Z., Li D., Wang P., Li J., and Lu X., 2020, Transcriptome and ionome analysis of nitrogen, phosphorus and potassium interactions in sorghum seedlings, Theoretical and Experimental Plant Physiology, 32(4): 271-285.
https://doi.org/10.1007/s40626-020-00183-w