Field Crop 2025, Vol.8, No.3, 113-125
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Review and Progress Open Access

Impact of Drip Irrigation and Fertigation on Water and Nutrient Use Efficiency in Maize Fields

Jinhua Cheng, Shanjun Zhu, Wei Wang

Institute of Life Sciences, Jiyang College of Zhejiang A&F University, Zhuji, 311800, Zhejiang, China

Corresponding email: wei.wang@jicat.org

Field Crop, 2025, Vol.8, No.3 doi: 10.5376/fc.2025.08.0012

Received: 11 Mar., 2025

Accepted: 22 Apr., 2025

Published: 14 May, 2025

Preferred citation for this article:

Cheng J.H., Zhu S.J., and Wang W., 2025, Impact of drip irrigation and fertigation on water and nutrient use efficiency in maize fields, Field Crop, 8(3): 113-125 (doi: 10.5376/fc.2025.08.0012)

Abstract Drip irrigation and integrated water and fertilizer technology, as an advanced water-saving and efficient agricultural measure, have shown significant effects in increasing production, saving water, improving quality and enhancing efficiency in corn production. Based on a review of the research progress at home and abroad in the past five years, this study systematically analyzed the influence mechanisms of drip irrigation and water and fertilizer integration on water use efficiency (WUE) and nutrient use efficiency (NUE) in maize fields. The results show that drip irrigation can optimize the distribution of soil moisture, reduce the loss of ineffective moisture, and improve the water consumption efficiency of corn. Integrated water and fertilizer management promotes the absorption and utilization of nutrients such as nitrogen, phosphorus and potassium by corn through simultaneous water and fertilizer supply, enhancing photosynthesis and dry matter accumulation. Compared with traditional irrigation and fertilization methods, drip irrigation with integrated water and fertilizer can significantly increase corn yield (generally by 5% to 20%) and quality (such as grain protein content), improve water use efficiency by 20% to 50%, and increase nutrient use efficiency by more than 30%. In addition, this technology can effectively save 30% to 40% of irrigation water, reduce nutrient loss and greenhouse gas emissions, and has obvious ecological and environmental benefits. At the end of this article, combined with the practical case of water and fertilizer integration of corn drip irrigation in the North China Plain, the application effect and limitations were evaluated, and suggestions for promotion and application were put forward. Research suggests that further optimizing the irrigation and fertilization system, reducing costs and strengthening intelligent management are important directions for improving the water and fertilizer utilization efficiency of corn and achieving sustainable agricultural development.

Keywords Corn; Drip irrigation; Integrated water and fertilizer management; Water use efficiency; Nutrient utilization efficiency

1 Introduction

Water shortage and inefficient utilization of fertilizers are among the key problems restricting the sustainable development of corn production in China (Wu et al., 2017; Shi et al., 2023). In China, agricultural water consumption accounts for over 70% of the country's total water consumption, among which irrigation water makes up more than 90% of agricultural water use. However, the water use efficiency is relatively low. The efficiency of the traditional flood irrigation method is only about 30% to 50%, resulting in a large amount of water evaporation and deep seepage loss. Meanwhile, long-term excessive fertilization has led to a nitrogen fertilizer utilization rate of less than 40% for corn, resulting in leaching or volatilization of the remaining nutrients. This not only wastes resources but also causes environmental problems such as nitrate pollution in groundwater and greenhouse gas emissions (Chen et al., 2023; Yin et al., 2024). It is reported that the application of chemical fertilizers in China has basically zero growth since 2015, but the fertilizer utilization rate of major food crops still needs to be further improved.

Drip irrigation and integrated water and fertilizer technology organically combine irrigation and fertilization, and is regarded as an effective way to solve the above problems (Wu et al., 2017; Song et al., 2024). Drip irrigation is an efficient water-saving irrigation technology. It can uniformly and slowly deliver water to the area near the root zone of crops in the form of "small water droplets and high frequency" through pipeline networks and drippers. The irrigation water utilization efficiency is as high as 80%-95%, which is much higher than 25%-50% of surface flood irrigation (Ma et al., 2022). Integrated water and fertilizer management utilizes the drip irrigation system to deliver water-soluble fertilizers to the soil along with the irrigation water, achieving "simultaneous application of water and fertilizer and supply as needed", which can significantly improve fertilizer utilization efficiency, reduce fertilizer usage by more than 30% to 50% while maintaining the yield level (Fan et al., 2020; Guo et al., 2022). These technologies have been widely applied in arid and semi-arid regions and in facility agriculture, achieving remarkable results. For instance, in cotton production in Xinjiang, drip irrigation and fertilization have significantly increased the per-unit yield and the efficiency of water and fertilizer utilization. In India and other places, it has also demonstrated its water-saving and yield-increasing effects on economic crops such as cumin. In recent years, with the reduction of equipment costs and the renewal of concepts, drip irrigation and water and fertilizer integration have begun to be promoted and applied in the main corn-producing areas of China (such as the North China Plain). This technology is of great significance for alleviating over-exploitation of groundwater in the north, reducing fertilizer pollution, and increasing corn yield and benefits (Li et al., 2023).

This study aims to integrate the latest research progress, deeply analyze the influence mechanisms of drip irrigation and water and fertilizer integration on water use efficiency and nutrient use efficiency in corn fields, and evaluate their comprehensive effects on yield, quality and the environment. Compared with existing studies, this paper focuses on the systematic coupling analysis of the efficient utilization of water and nutrients, and highlights the comparative reference of the latest research achievements at home and abroad in recent years. Through this research, it is expected to provide theoretical basis and data support for the production practice of improving the water and fertilizer utilization efficiency of corn, and put forward suggestions for the large-scale promotion and application of related technologies.

2 Basic Principles of Drip Irrigation and Integrated Water and Fertilizer Management

2.1 Development and application of drip irrigation technology

Drip irrigation technology originated in Israel in the 1960s. Due to its outstanding water-saving performance, it was quickly promoted to arid and semi-arid regions around the world. In a drip irrigation system, irrigation water is slowly and evenly dripped into the soil near the crop roots through pipes and emitters, thereby maintaining the soil in the root zone at an appropriate moisture level. Compared with traditional surface irrigation, drip irrigation significantly reduces the ineffective evaporation and deep seepage loss of water on the soil surface. Its field irrigation efficiency can generally reach 85%-95%, which is significantly higher than 30%-40% of flood irrigation (Wu et al., 2017; Liu et al., 2023). According to statistics, by 2020, the area of efficient water-saving irrigation in China had exceeded 67 million mu, among which drip irrigation accounted for a considerable proportion (Wu et al., 2021). The large-scale application of drip irrigation technology has effectively alleviated the shortage of agricultural water in many areas. For instance, after the introduction of drip irrigation in farmlands in North China, due to precise irrigation and obvious water-saving effects, the seasonal irrigation quota for corn per mu was reduced from 200 to 250 cubic meters in the past to about 150 cubic meters. Meanwhile, the yield could also increase, demonstrating good comprehensive benefits (Li et al., 2024).

2.2 Core mechanism of integrated water and fertilizer management

Integrated water and fertilizer management is a new agricultural technology that combines and synchronizes the processes of irrigation and fertilization. The core mechanism lies in using irrigation pipes to deliver water-soluble fertilizers to the root zone soil in a timely and appropriate manner according to the needs of crops, thereby achieving "watering and fertilizing simultaneously", and meeting the synchronous demands of crops for water and nutrients at different growth stages. Compared with the traditional method of separating irrigation and fertilization, water and fertilizer integration has obvious advantages: Firstly, nutrients directly enter the concentrated distribution area of crop roots along with the irrigation water, which can significantly reduce the fixation and leaching of nutrients in the soil and improve the effective utilization rate of fertilizers (Sampathkumar and Pandian, 2010). Studies have shown that the application of drip irrigation fertilization technology can increase the utilization rate of nitrogen fertilizer by 10 to 30 percentage points, and the utilization rates of nutrients such as phosphorus and potassium are also significantly improved (Govada et al., 2024). Secondly, the simultaneous supply of water and fertilizer is conducive to coordinating the water physiology and nutrient physiology processes of crops. When the soil moisture is sufficient, the root system of crops has an enhanced ability to absorb nutrients, and the applied fertilizers can be absorbed and utilized more efficiently. Conversely, an adequate supply of nutrients promotes the absorption and utilization of water by crops, thereby achieving a coordinated improvement in water use efficiency and nutrient use efficiency. This "water and fertilizer synergy effect" is particularly evident under the condition of water and fertilizer integration (Fanish, 2013). Thirdly, the integration of water and fertilizer can achieve precise supply according to the needs of crops. By adjusting the timing and frequency of irrigation and fertilization, it is possible to achieve frequent irrigation with small amounts of water and multiple topdressing with small amounts of fertilizer, avoiding the waste of water and nutrients caused by traditional flood irrigation and large-scale fertilization at one time.

2.3 Coupling effect of drip irrigation and integrated water and fertilizer management in corn production

The combination of drip irrigation technology and water and fertilizer integration has played a significant role in coupling and enhancing efficiency in corn production. Firstly, drip irrigation provides an accurate and efficient means of water and fertilizer integration, enabling water and nutrients to be distributed synchronously and evenly in the soil of the corn root zone. This synchronous supply in terms of space and time avoids the significant fluctuations in local soil dryness and nutrient concentration in the traditional way, creates a stable and suitable rhizesphere environment, and promotes the growth of corn roots and nutrient absorption (Figure 1) (Hou et al., 2022). Secondly, the characteristic of small moist areas in drip irrigation keeps the local roots of corn at a relatively high nutrient concentration, which is conducive to improving the efficiency of nutrient uptake. Meanwhile, frequent small-scale irrigation ensures that the soil moisture content does not change drastically due to fertilization, thus avoiding the stress on crops caused by the sudden transition from flood to drought. Research shows that the application of drip irrigation and integrated water and fertilizer technology on summer corn in the north can achieve efficient and coordinated supply of water and nutrients, significantly increasing production compared with the traditional flood irrigation + one-time fertilization treatment.

3 Influencing Mechanism of Water Use Efficiency in Corn Fields

3.1 Characteristics and regulation of soil moisture distribution

The spatial distribution of soil moisture under drip irrigation conditions is significantly different from that under the traditional flood irrigation method. The dripper supplies water in a point source manner, forming a "moist body" in the soil. The soil moisture content near the moist area is high, while the soil far from the dripper maintains a relatively low moisture content, creating a distinct moist gradient. This water distribution characteristic ensures that the soil moisture near the root zone of crops is always maintained at an appropriate level, while the soil between rows is relatively dry, thereby reducing ineffective evaporation water consumption. In a typical flood irrigation situation, the excessive water flow causes the soil moisture to become saturated after irrigation and quickly seep to the deep layers, which not only wastes water but may also lead to nutrient leaching loss. However, due to the small amount of water applied each time in drip irrigation, the soil moisture is mainly distributed in the root active layer (such as the 0-40 cm soil layer), and the deep seepage is significantly reduced (Amiri et al., 2019; Gao et al., 2020). This indicates that drip irrigation achieves high-efficiency water supply with "small amounts and multiple times" by altering the pattern of soil moisture distribution. To fully leverage this advantage, it is necessary to rationally regulate the operating parameters of the drip irrigation system, including the flow rate of the drippers, the spacing between drippers, the irrigation cycle and the amount of water injected each time. Through the optimized design of drip irrigation parameters, the size and shape of the moist body can be controlled to match the distribution of corn roots, thereby maximizing water use efficiency.

3.2 Influence of drip irrigation on the water consumption pattern of corn

Drip irrigation has significantly changed the water consumption dynamics and process of corn. Under traditional flood irrigation conditions, the water consumption of corn mainly depends on the consumption of soil moisture after irrigation. It is characterized by a rapid increase in soil moisture after irrigation, followed by a gradual decrease in moisture content due to large-scale transpiration of crops and soil evaporation, until a peak occurs again in the next irrigation. The water consumption process shows periodic "sawtooth" fluctuations. Under drip irrigation conditions, due to the high irrigation frequency and small amount of water replenishment each time, soil moisture can be maintained at a relatively stable level. The water consumption of corn is closer to the mode of continuous water absorption as needed, and the fluctuation range of soil moisture is reduced. This change is beneficial for corn to maintain a stable water physiological state and improve water use efficiency (WUE) (Wu et al., 2021; Liu et al., 2023).

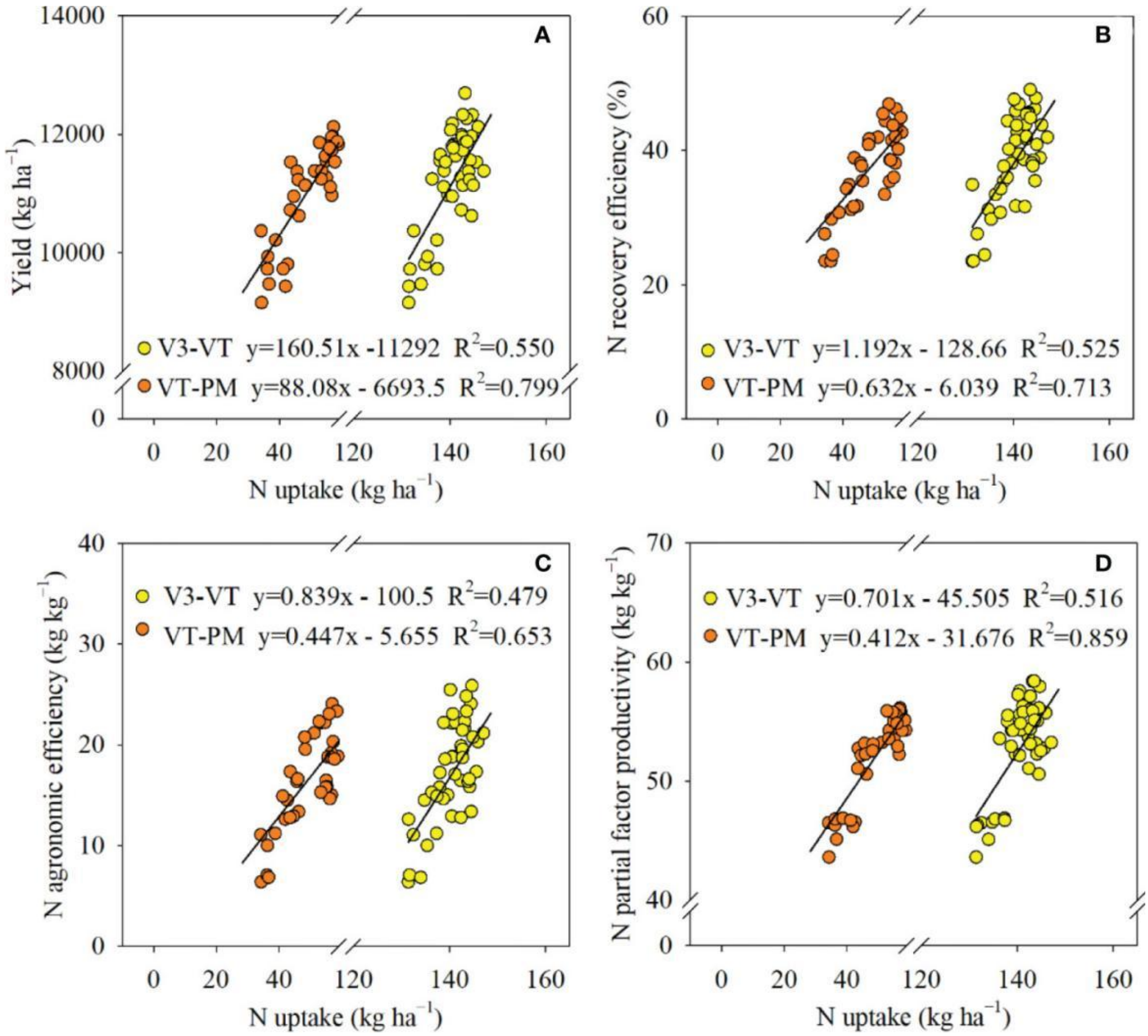

Figure 1 Linear regressions between N uptake and yield (A), N recovery efficiency (B), N agronomic efficiency (C), and N partial factor productivity (D) before (V3-VT) and after (VT-PM) tasseling stages of maize in 2018, 2019, and 2020. Growth stages: V3, third-leaf; VT, tasseling; PM, physiological maturity (Adopted from Hou et al., 2022)

In addition, drip irrigation has changed the proportion of water consumption at each growth stage of corn. Since drip irrigation usually provides timely water supply and avoids water shortage during the seedling stage, the water consumption of corn in the early stage is guaranteed. In the middle and later stages, by regulating the irrigation quota, an optimized water consumption pattern of "sufficient in the early stage, controlled in the water and ear period, and replenished in the grouting period" can be achieved. This water distribution is more in line with the growth requirements of corn. It can reduce excessive irrigation from jointing to tasking while ensuring that the corn does not suffer from drought during the filling period. It not only avoids ineffective evaporation but also helps to form a strong root system and ear position distribution. Practical experience has shown that reasonable drip irrigation regulation can reduce water consumption without lowering the yield. For example, in the 7-year experiment in the northwest region, the cumulative water consumption of drip irrigation treatment was reduced by approximately 180 mm compared with flood irrigation treatment, but the plant height, dry matter accumulation and grain yield of corn were significantly increased (Yang et al., 2018; Liu et al., 2022). This indicates that drip irrigation can achieve "the same or even higher yield with less water consumption" by optimizing the water-consuming process, that is, the efficiency of the so-called "water-for-production" has been greatly improved. Of course, the specific water consumption pattern of corn under drip irrigation conditions is also influenced by climatic conditions and management methods.

3.3 Method for determination and evaluation of water use efficiency

The water use efficiency (WUE) of corn is usually expressed by the yield obtained per unit of water consumption, that is, WUE = grain yield/total water consumption of crop transpiration-evaporation. In field experiments, the determination of WUE generally requires monitoring the soil moisture changes, precipitation and irrigation volume throughout the growth period, and calculating the crop evapotranspiration (ET). Common methods include soil moisture balance method and water balance calculation model, etc. Among them, the soil moisture balance method calculates the total water consumption ET of crops by measuring the changes in soil water storage during sowing and harvesting, and by estimating precipitation, irrigation and runoff seepage, and then combines the yield to calculate WUE. Under drip irrigation conditions, since deep seepage and surface runoff are usually small, it can be approximately considered that ET = rainfall + irrigation-increase in soil water storage (Liu et al., 2023). It should be noted that WUE evaluation can not only calculate the total water consumption (referred to as the WUE throughout the entire growth period), but also calculate the irrigation water utilization efficiency (IWUE) for the irrigation water portion, that is, IWUE = yield/irrigation water volume, to measure the utilization efficiency of the irrigation water itself. When rainfall is uncontrollable, IWUE can better demonstrate the effectiveness of irrigation measures. In drip irrigation experiments, the IWUE of different irrigation treatments is often compared to evaluate the water-saving effect. For instance, a certain study compared the IWUE of fully irrigated and under-irrigated corn. The result showed that the IWUE of under-irrigated corn was significantly higher than that of fully irrigated corn (El-Hendawy et al., 2014).

4 Influencing Mechanism of Nutrient Utilization Efficiency in Corn Fields

4.1 Nutrient migration and distribution under integrated water and fertilizer conditions

Under traditional fertilization methods, fertilizers are usually applied to the soil at one time, and the migration and distribution of nutrients in the soil are affected by processes such as rainfall, irrigation, and soil adsorption and fixation. A large number of studies have shown that after conventional field nitrogen application, only 30% to 40% of the nitrogen is absorbed and utilized by crops, and the remaining considerable part is leachate to the deep layer in the form of nitrate nitrogen or lost in gaseous form (Bi et al., 2021). The integration of water and fertilizer management effectively alters the migration patterns and spatio-temporal distribution of nutrients in the soil profile through multiple applications of small doses. On the one hand, the nutrients evenly applied with the drip irrigation water are mainly concentrated in the moist area around the dripper, and the nutrient concentration decreases as the distance from the dripper increases. Since the root system of corn is also mainly distributed in the soil near the plant boundary, the integration of water and fertilizer can keep the soil nutrient concentration in the root zone at a relatively high level and increase the nutrient supply around the root system (Li et al., 2008). On the other hand, the high-frequency nature of drip irrigation results in a relatively small amount of nutrients being applied each time, making it difficult to achieve deep breakthroughs in the cross-section of nutrients. Most of the nutrients remain within the active layer of the root system. Especially when nitrogen exists in the form of nitrate, it is prone to be leached to the deep layers with water and even enter groundwater. Under drip irrigation conditions, due to the small amount of water applied in a single irrigation, nitrate nitrogen mainly accumulates within the soil layer of 30 to 60 cm and is promptly absorbed by the root system.

4.2 Influence of drip irrigation mode on the absorption efficiency of nitrogen, phosphorus and potassium

Different drip irrigation and fertilization modes (such as fertilization frequency, fertilization amount, and drip irrigation methods, etc.) will have a significant impact on the efficiency of corn in absorbing nutrients such as nitrogen, phosphorus, and potassium. In terms of nitrogen, an appropriate level of nitrogen supply is particularly crucial for the high yield and efficiency of drip irrigation corn. Studies have shown that under drip irrigation conditions, the amount of nitrogen fertilizer required by corn can be lower than that of traditional fertilization, while crops can still obtain sufficient nitrogen to achieve high yields (Fanish and Muthukrishnan, 2013). This indicates that under the drip irrigation system, there is also an optimal range for the absorption of potassium by crops. When excessive nutrient supply exceeds the absorption capacity of crops, the nutrient utilization efficiency will be reduced (Li et al., 2014). There is a significant interaction in the absorption of the three major nutrients, nitrogen, phosphorus and potassium, under the condition of drip irrigation and water and fertilizer. For instance, an appropriate supply of nitrogen can promote the absorption of phosphorus and potassium by the root system, while conversely, sufficient phosphorus and potassium nutrition enhances the plant's utilization efficiency of nitrogen. Therefore, it is necessary to comprehensively optimize the ratio and supply strategy of nitrogen, phosphorus and potassium to maximize the overall utilization of nutrients. In conclusion, different drip irrigation and fertilization modes have a significant impact on the nutrient absorption efficiency of corn. Reasonably determining the amount and proportion of fertilizer application, choosing appropriate drip irrigation methods (such as surface drip irrigation or shallow-buried drip irrigation), and scientifically arranging the frequency of fertilization are all important measures to improve the absorption and utilization efficiency of nitrogen, phosphorus and potassium.

4.3 Physiological basis for improving nutrient utilization efficiency

Drip irrigation and integrated water and fertilizer management not only enhance the utilization rate of nutrients on a macro level in the field, but also the underlying physiological mechanisms of crops deserve attention. Firstly, a stable and sufficient supply of water and fertilizer is conducive to improving the morphology and enhancing the function of corn root systems. Under drip irrigation conditions, corn roots tend to be more distributed in the surface layer and the moist area of the dripper, with an increase in root length density and the number of root hairs, thereby enhancing the absorption capacity of the root system for water and nutrients (Guo et al., 2024). Meanwhile, the continuous and appropriate soil moisture avoids the inhibition of the root system by drought stress, keeping the root vitality at a relatively high level. Under conditions of adequate water and fertilizer, the chlorophyll content in corn leaves is relatively high and the photosynthetic rate is faster. Especially in the later stage of grain filling, it can maintain a strong photosynthetic production capacity, providing sufficient assimilation products for nutrient assimilation. Overall, the physiological basis for improving nutrient utilization efficiency through drip irrigation and integrated water and fertilizer management lies in: optimizing the root-crown relationship to promote root absorption and leaf assimilation functions; By delaying aging and enhancing photosynthetic efficiency, the amount of nutrients assimilated by crops has been increased. By coordinating the source-reservoir relationship, the transport efficiency of nutrients to grains was enhanced (Zhang et al., 2023). These physiological improvements jointly support the efficient utilization of nutrients by corn. In actual production, this suggests that we should precisely control the supply of water and fertilizer through the drip irrigation system based on the growth and development characteristics of corn, so as to meet the physiological needs of crops at each stage and fully exert the potential for increased production and efficient utilization of nutrients of crops themselves.

5 Combined Effect of Drip Irrigation and Integrated Water and Fertilizer Management on Corn Yield and Quality

5.1 Regulatory mechanism of the output formation process

The formation of corn yield depends on three factors: the number of ears, the number of grains per ear and the grain weight. Water and fertilizer conditions have a significant impact on all these three factors. Drip irrigation and integrated water and fertilizer system effectively regulates the yield formation process by improving the growth environment and promoting the growth and development of corn at all growth stages (Guo et al., 2022). Firstly, in terms of the number of established ears, an adequate and balanced supply of water and fertilizer has increased the emergence rate and individual robustness of corn, reduced the mortality rate and weak plant rate during the seedling stage, and is conducive to achieving a higher effective number of ears. Appropriate water and fertilizer conditions also reduce nutrient competition during the differentiation period of male and female panicles, lower the rate of flower degeneration, and ensure panicle size and panicle grain count from the reproductive source (Mahboob et al., 2020). Secondly, in terms of the number of grains per ear, the integrated water and fertilizer system of drip irrigation mainly ensures the water and fertilizer requirements during the tasseling and silk production period of corn. This period is a crucial window for determining the number of grains per panicle. If the supply of water or nutrients is insufficient, it is prone to pollen sterility or poor silk dry pollination, resulting in bald tips and grain loss. Drip irrigation fertilization can keep the soil moist and maintain a high nitrogen level before and after tasseling, prolonging the vitality of pollen and filaments, thereby increasing the success rate of pollination and fertilization as well as the seed setting rate (Deng et al., 2012). In practice, timely water and fertilizer replenishment during the silk production period through drip irrigation can significantly reduce the length of bald tips and increase the number of grains per spike.

5.2 The improvement effect on the quality characteristics of corn

In addition to yield, the integrated drip irrigation and water and fertilizer system also has a certain impact and improvement effect on the quality of corn kernels. The quality of corn kernels usually includes nutritional qualities such as crude protein, crude fat and starch content, as well as process qualities such as bulk density and particle size uniformity. The level and mode of water and fertilizer supply directly affect the grain filling rate and nutrient accumulation, thereby influencing these quality indicators. Under conditions of adequate water and fertilizer, corn can obtain more nitrogen for the synthesis of grain protein, and thus the crude protein content often increases. Studies have shown that moderate irrigation can reduce the starch content in grains while slightly increasing the protein content. This is because the proportion of protein in the assimilation products of plants increases when there is sufficient water, while the proportion of carbohydrates is higher under drought conditions (Mahboob et al., 2020). Drip irrigation with integrated water and fertilizer is conducive to protein synthesis and accumulation by maintaining soil moisture and sufficient available nitrogen (Saracoglu and Oktem, 2021; Du et al., 2024).

5.3 Evaluation of economic and ecological benefits

In addition to yield, the integrated drip irrigation and water and fertilizer system also has a certain impact and improvement effect on the quality of corn kernels. The quality of corn kernels usually includes nutritional qualities such as crude protein, crude fat and starch content, as well as process qualities such as bulk density and particle size uniformity. The level and mode of water and fertilizer supply directly affect the grain filling rate and nutrient accumulation, thereby influencing these quality indicators. Under conditions of adequate water and fertilizer, corn can obtain more nitrogen for the synthesis of grain protein, and thus the crude protein content often increases. Studies have shown that moderate irrigation can reduce the starch content in grains while slightly increasing the protein content. This is because when there is sufficient water, the proportion of protein in the assimilation products of plants rises, while under drought conditions, the proportion of carbohydrates is higher. Drip irrigation with integrated water and fertilizer is conducive to protein synthesis and accumulation by maintaining soil moisture and sufficient available nitrogen (Brar et al., 2021; Guo et al., 2022; Wu et al., 2025).

6 Environmental Effects and Significance for Sustainable Development

6.1 Water resource conservation and improvement of irrigation efficiency

The development of drip irrigation and integrated water and fertilizer management is of great significance for alleviating the pressure on agricultural water use and improving the efficiency of water resource utilization. Corn is a crop with a large water demand. Under the traditional flood irrigation mode, the irrigation quota is high and the utilization rate is low, resulting in the waste of water resources and the over-exploitation of groundwater. Drip irrigation achieves the same or even higher yield with less irrigation water by reducing ineffective evaporation and leakage, significantly enhancing the irrigation water productivity. According to statistics, drip irrigation for corn can save 20% to 40% of irrigation water compared with traditional border irrigation, and increase water productivity by more than 30% (Wu et al., 2017; Ma et al., 2022). In a certain demonstration in the North China Plain, the total irrigation amount during the growth period of corn under the drip irrigation water and fertilizer model was approximately 120 mm, which was only about half of that under the traditional furrow irrigation, but achieved a slightly higher yield per mu (Tian et al., 2017). This phenomenon of "saving water without reducing production" fully demonstrates the water-saving potential of drip irrigation technology. Large-scale promotion of drip irrigation will have a positive impact on the balance of regional water resources. Take North China as an example. In this area, excessive groundwater has been exploited for agricultural irrigation for many years, resulting in a continuous decline in the groundwater level. If the field corn is generally irrigated by drip irrigation, the amount of water taken per mu per year can be reduced by dozens of cubic meters. In the long run, it is expected to slow down the expansion of the groundwater funnel.

6.2 Control of nutrient loss and non-point source pollution

One of the main sources of agricultural non-point source pollution is that excessive fertilizer nutrients in farmland enter water bodies through runoff and leaching. Under the traditional fertilization and irrigation model, excessive fertilizers are often applied at one time. When there is heavy rain or flood irrigation, nutrients such as nitrogen and phosphorus in the soil that are not absorbed by crops are prone to be lost with water, causing pollution to the surface and groundwater. Drip irrigation and integrated water and fertilizer technology has demonstrated unique advantages in reducing nutrient loss and controlling non-point source pollution. On the one hand, drip irrigation and fertilization reduce the occurrence of surface runoff. As drip irrigation is a type of local micro-irrigation, water seeps slowly into the soil and does not form large-scale surface runoff, thus avoiding the problem of nutrient loss along with runoff. Especially in sloping or gully areas, flood irrigation often leads to slope runoff carrying away nutrients, while drip irrigation has a small water supply and almost no runoff, significantly reducing the risk of eutrophication of surface water bodies (Song et al., 2022). On the other hand, drip irrigation reduces the deep leaching of nutrients. Under drip irrigation conditions, the leaching and volatilization of nitrogen in maize fields are much lower than those in traditional irrigation methods, and the apparent utilization rate of nitrogen is correspondingly increased (Liu et al., 2014). This means that through drip irrigation and fertilization, the total amount of nitrogen entering the environment is reduced, effectively controlling nitrogen loss in farmland. For phosphorus, due to its poor mobility in the soil, drip irrigation avoids soil erosion and granular loss of phosphorus caused by flood flow, and also helps to reduce the risk of eutrophication of surface water bodies (Qian et al., 2011). Apart from nitrogen and phosphorus, the significant loss of potassium is generally not severe. However, drip irrigation and fertilization can still reduce the downward migration of potassium in the soil profile, keeping it at the surface layer for crop utilization.

6.3 The ecological and environmental effects of drip irrigation and water and fertilizer integration

Drip irrigation and water and fertilizer integration not only achieve increased production and efficiency but also bring about a series of positive ecological and environmental effects, which is of great significance to the sustainable development of agriculture. First, it helps maintain the regional water ecological balance. Traditional agriculture over-extracts groundwater for irrigation, leading to ecological problems such as river drying up and wetland shrinking. Promoting drip irrigation for water conservation can reduce excessive consumption of water resources in agriculture and alleviate the disturbance to the natural hydrological cycle. Take North China as an example. Agricultural water use occupies a large amount of groundwater. After the promotion of drip irrigation, the downward trend of groundwater levels is expected to slow down, which is conducive to protecting the base flow of rivers and the ecological environment of wetlands. The second is to reduce the carbon footprint and greenhouse gas emissions of agricultural production. Drip irrigation of water and fertilizer reduces the excessive use of nitrogen fertilizer, thereby lowering greenhouse gases such as nitrous oxide (N_2O) produced by soil nitrification and denitrification (Zheng et al., 2023). Third, it is conducive to maintaining soil health and biodiversity. Excessive traditional fertilization can cause soil acidification and salinization, and disrupt the balance of the soil microbial community. Drip irrigation water and fertilizer, due to precise fertilization and reduction of surface salt accumulation, can to a certain extent avoid soil acid-base imbalance and salt accumulation, and maintain the stability of soil physical and chemical properties (Figure 2) (Çetin and Akalp, 2019). Fourth, it has promoted the green transformation of agricultural inputs and management methods. Drip irrigation water and fertilizer technology encourages the use of new and highly efficient fertilizers such as water-soluble fertilizers and slow-release fertilizers, reducing the excessive input of traditional large-scale chemical fertilizers. This actually promoted the optimization of the agricultural input structure and reduced environmental risks. In recent years, some innovative technologies such as oxygenated drip irrigation and the application of degradable mulching film under film drip irrigation have also been combined with drip irrigation water and fertilizer, adding the finishing touch to the improvement of ecological benefits (Song et al., 2024).

Figure 2 Use of drip irrigation for ornamental plants (Adopted from Çetin and Akalp, 2019)

7 Practice of Integrated Water and Fertilizer Drip Irrigation Model for Corn in the North China Plain

7.1 Basic situation of the test area and treatment design

To verify the benefits of drip irrigation and water and fertilizer integration in corn production, this study conducted field experiments in typical corn-growing areas of the North China Plain. The experimental site has a warm temperate semi-humid climate with an annual precipitation of about 500 to 600 mm. The soil is loam with medium fertility, but there is a risk of nitrogen leaching loss. The local traditional pattern is two harvests of winter wheat and summer corn. Corn is often irrigated by furrow irrigation 4 to 5 times, combined with the application of fertilizers, with an average yield of about 600 kilograms per mu. Groundwater is the main water source. Long-term over-exploitation has led to a continuous decline in water level, and water-saving technologies are urgently needed (Ning et al., 2024). The experiment was conducted for two consecutive years from 2019 to 2020, with three treatments: T1 was traditional border irrigation and fertilization (base fertilizer + two top dressings, total nitrogen approximately 20 kg per mu, irrigation volume about 150 mm); T2 is a medium-input drip irrigation and water and fertilizer integration method. It adopts "large ridge double-row" planting, reducing the total amount of nitrogen fertilizer by 20%. It is applied in three installments along with the drip irrigation, with a total irrigation volume of 100-120mm, which is 20%-30% less than the traditional method. T3 is a high-input treatment. Fertilizer is supplied in sufficient quantities (about 18 kg of nitrogen per mu). Small water drip irrigation (20 mm) is carried out every 10 days from jointing to filling stage, for a total of 5 to 6 times, with a total irrigation volume of approximately 150 mm. Except for water and fertilizer management, all other measures remain the same.

7.2 Performance results of water and fertilizer utilization efficiency and yield

The results of two years of field trials show that drip irrigation with integrated water and fertilizer has significant advantages over traditional methods in corn production. In terms of yield, T1 averaged 618.5 kg per mu, while T2 and T3 were 649.0 kg and 653.5 kg respectively, with growth rates of 5.0% and 5.7%. Although the increase in production is not significant, it was achieved under the condition of reduced irrigation and fertilization, which is of great significance. The increase in yield mainly stems from the rise in the number of grains per panicle and the weight of a thousand grains. In terms of water use efficiency (WUE), T1 consumes approximately 410 mm of water, while T2 and T3 consume 370 mm and 380 mm respectively, a reduction of about 10%. The slight increase in output significantly raised WUE, with T1 at 1.50 kg/m³, T2 at 1.76, and T3 at 1.72, increasing by 17.3% and 14.7% respectively. Among them, T2 was the highest, indicating that moderate water and fertilizer conservation can effectively reduce ineffective water consumption. In terms of nutrient utilization efficiency, the nitrogen fertilizer utilization rate of T1 is approximately 35%, while that of T2 and T3 reaches 48% and 47% respectively. The phosphorus utilization rate has risen from 20% to 25%-27%. The potassium utilization rate has increased from 15% to over 30%. Although T3 has a higher fertilizer input, its efficiency is not superior to that of T2, indicating that moderate fertilization is actually more beneficial. In terms of irrigation water utilization efficiency

(IWUE), T1 was 4.12 kg/m³, while T2 and T3 reached 6.49 and 6.11 respectively, an increase of nearly 50%. In conclusion, the integration of water and fertilizer through drip irrigation has achieved "less water and less fertilizer without reduced yield", and significantly improved the efficiency of resource utilization and economic benefits.

7.3 Feasibility and limitations of promotion and application

As one of the major grain-producing areas in China, the North China Plain has the potential and demand for large-scale promotion of drip irrigation and water and fertilizer integration. From the results of this case experiment, it can be seen that the drip irrigation water and fertilizer model is technically feasible and effective in the cultivation of summer corn in North China. Firstly, in terms of irrigation water sources, groundwater in the North China Plain coexists with surface water from rivers such as the Yellow River and the Haihe River. By building field pipe networks, it is possible to ensure water supply for large-scale field drip irrigation. In this experiment, the water source from the well was used for drip irrigation. Both the pressure and water quality met the requirements (no dripper blockage occurred after the suspended solids in the water were filtered by sand and gravel) (Tian et al., 2017). Secondly, the technology of drip irrigation under film has certain compatibility with the mechanized production of corn. In this experiment, after laying the drip irrigation tape and plastic film, mechanical sowing and harvesting went basically smoothly, and only minor modifications to the seeder were required. The large-ridge double-row planting mode adopted in the experiment increased the density to a certain extent and exerted the yield-increasing potential of the variety under precise water and fertilizer supply by drip irrigation (Guo et al., 2022). Secondly, water and fertilizer management under this model is relatively simple, and farmers can master it after training. For instance, the technicians of the cooperative can complete the injection of water and fertilizer with the help of simple fertilizer tanks, achieving simultaneous irrigation and fertilization in the fields, which greatly saves the labor and time for fertilization.

The advantages of integrated water and fertilizer irrigation through drip irrigation are obvious, but there are many problems in its promotion. The biggest obstacle is money. The investment in pipe networks and equipment is high, which small-scale farmers find hard to bear without subsidies. Moreover, their income is also affected by fluctuations in grain prices and utilities (Song et al., 2024). Secondly, there is the usage threshold. The maintenance of drippers and the control of fertilization concentration both require experience. Once the operation is improper, it may cause blockage or damage to the seedlings. Therefore, technical services are indispensable. Planting systems also bring troubles. For example, in the wheat-corn rotation in North China, agricultural machinery and drip irrigation tapes often conflict. Either the pipes break down or the mechanical efficiency decreases. There must be matching machinery and models (Abubakar et al., 2022;). Water resource allocation is equally complex. Drip irrigation requires stable water pressure. If each household operates independently, water usage conflicts are inevitable. Unified management by cooperatives or water associations is more realistic. There is also the issue of ecological benefits. Water conservation and weight loss are beneficial to the environment, but the short-term gains for farmers are limited and not easily reflected on the accounts. Therefore, policy subsidies and publicity guidance are very important. For farmers to truly accept it, apart from reliable technology, there must also be demonstration bases to show visible results, financial support to lower the threshold, and professional teams to provide services. Overall, this technology is feasible for corn production in the North China Plain, but it can only be widely promoted on a large scale if the policy, organization and technical support are all in place.

8 Conclusion

Some of the results do not seem prominent on the surface, with the increase in production mostly ranging from 5% to 15%, but this was achieved under the conditions of water conservation and fertilizer reduction. The core function of drip irrigation is to reduce evaporation and leakage, concentrating water in the root zone. As a result, the output per cubic meter of water increases by 30% to 50%, and the overall water-saving rate reaches 20% to 40%. The value of integrated water and fertilizer management lies in the utilization rate of nutrients. The fractional supply of fertilizers along with water increases the utilization rate of nitrogen fertilizers by 10 to 30 percentage points, and even doubles the utilization rate of potassium fertilizers. In terms of quality, although the increase in grain weight and protein content is limited, the changes are stable. The economic benefits are equally remarkable. The income per mu often increases by over 100 yuan, and nitrogen leaching and greenhouse gas emissions decrease by 30% to 50%. In the experiments in the North China Plain, the yield per mu increased by 5% through drip irrigation and fertilization, the WUE rose by 17% to 18%, and the nitrogen fertilizer utilization rate increased from 35% to 48%. Moreover, this was achieved under the conditions of 20% water conservation and 20% nitrogen reduction, further demonstrating its potential.

There is more than one way to improve efficiency. In some places, emphasis is placed on optimizing the system. For instance, precise water and fertilizer supply based on the growth period of corn, with water and fertilizer replenishment during the jointing, tasseling and filling stages. The economic plan is to control the entire irrigation process at 100-120 mm and apply nitrogen fertilizer at 180-240 kg/hm² in three installments. However, beyond the system, the operational proficiency of farmers is equally crucial. From system installation to clogging prevention and maintenance, fertilizer dissolution and fertilizer concentration control, training is indispensable. The selection of inputs also affects the effect. Fully water-soluble fertilizers, appropriate drip irrigation tapes and filtration devices can ensure the smooth operation of the system. Recyclable drip irrigation tapes can also reduce costs. In terms of management models, scattered farmers are prone to problems, while unified construction and maintenance by cooperatives can reduce costs and ensure standardization. Finally, policies and demonstrations are indispensable. Financial subsidies, loan support and the construction of demonstration sites can make farmers more willing to adopt new technologies.

Although drip irrigation and integrated water and fertilizer management have its advantages, there are still many problems. How to reduce evaporation in arid areas and how to coordinate rain farming and drip irrigation in rainy areas all require further research. The response of crops to water and fertilizer methods remains unclear. Root morphology, transport protein expression and photosynthetic efficiency may all be affected. There are also potential risks in the soil aspect. Although drip irrigation under film saves water, it may cause salt accumulation in non-moist areas, thereby affecting soil quality and the stability of microbial communities. The future development directions also include intelligence and precise control. Real-time regulation by sensors and big data seems ideal, but its actual effect remains to be tested. In addition, the combination of drip irrigation with measures such as straw mulching, organic fertilizer substitution, and conservation tillage may create a synergistic effect. Future research needs to strike a balance between field applications and molecular mechanisms, enhancing efficiency while also taking ecological sustainability into account.

Acknowledgments
We would like to express our heartfelt thanks to anonymous reviewers who have gave guidance for this study.

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.

References
Abubakar S., Hamani A., Wang G., Liu H., Mehmood F., Abdullahi A., Gao Y., and Duan A., 2022, Growth and nitrogen productivity of drip-irrigated winter wheat under different nitrogen fertigation strategies in the North China Plain, Journal of Integrative Agriculture, 22(3): 908-922.
https://doi.org/10.1016/j.jia.2022.08.107

Amiri Z., Gheysari M., Mosaddeghi M., Tabatabaei M., and Moradiannezhad M., 2019, Determination of the suitable location of soil moisture sampling in drip-tape irrigation management in a maize field, Journal of Water and Soil Science, 23(2): 45-54.
https://doi.org/10.29252/jstnar.23.2.45

Bi Y., Wu W., Hou L., Liao R., Bi X., Wang L., and Chen Y., 2021, Quantifying the spatial distribution of soil nitrogen under long-term drip fertigation, Water, 14(9): 1337.
https://doi.org/10.21203/rs.3.rs-864058/v1

Brar A., Buttar G., and Vashist K., 2001, Enhancing crop and water productivity of spring maize (*Zea mays*) through drip fertigation, Indian Journal of Agronomy, 64(1): 87-92.
https://doi.org/10.59797/ija.v64i1.5238

Çetin Ö., and Akalp E., 2019, Efficient use of water and fertilizers in irrigated agriculture: drip irrigation and fertigation, Acta Horticulturae et Regiotecturae, 2(2019): 97-102.
https://doi.org/10.2478/ahr-2019-0019

Chen S., Liu W., Morel J., Parsons D., and Du T., 2023, Improving yield, quality, and environmental co-benefits through optimized irrigation and nitrogen management of hybrid maize in Northwest China, Agricultural Water Management, 290: 108577.
https://doi.org/10.1016/j.agwat.2023.108577

Deng L., Tu P., Ye Q., Gong L., and Zhang C., 2012, Effects of drip irrigating liquid fertilizer on growth,yield and quality of sweet maize, Journal of Maize Sciences, 20(1): 119-122, 127.

Du R., Li Z., Xiang Y., Sun T., Liu X., Shi H., Li W., Huang X., Tang Z., Lu J., Chen J., and Zhang F., 2024, Drip fertigation increases maize grain yield by affecting phenology, grain filling process, biomass accumulation and translocation: a 4-year field trial, Plants, 13(14): 1903.
https://doi.org/10.3390/plants13141903

El-Hendawy S., Kotab M., Al-Suhaibani N., and Schmidhalter U., 2014, Optimal coupling combinations between the irrigation rate and glycinebetaine levels for improving yield and water use efficiency of drip-irrigated maize grown under arid conditions, Agricultural Water Management, 140: 69-78.
https://doi.org/10.1016/J.AGWAT.2014.03.021

Fan J., Lu X., Gu S., and Guo X., 2020, Improving nutrient and water use efficiencies using water-drip irrigation and fertilization technology in Northeast China, Agricultural Water Management, 241: 106352.
https://doi.org/10.1016/j.agwat.2020.106352

Fanish S., and Muthukrishnan P., 2013, Nutrient distribution under drip fertigation systems, World Journal of Agricultural Sciences, 9(3): 277-283.

Fanish S.A., 2013, Influence of drip fertigation and intercropping on yield, agronomic efficiency and partial factor productivity of maize, Madras Agricultural Journal, 100(1-2): 102.
https://doi.org/10.29321/maj.10.001248

Gao J., Yan Y., Hou X., Liu X., Zhang Y., Huang S., and Wang P., 2020, Vertical distribution and seasonal variation of soil moisture after drip-irrigation affects greenhouse gas emissions and maize production during the growth season, Science of the Total Environment, 763: 142965.
https://doi.org/10.1016/j.scitotenv.2020.142965

Govada D., Mrudhula K.A., Medida S.K., Ramesh G., Babu K.G., and Naik B.S., 2024, Evaluation of saline water effects on use efficiency and soil nutrient availability of maize (*Zea mays* L.) under drip fertigation, Plant Science Today, 11(2): 486-495.
https://doi.org/10.14719/pst.2871

Guo D., Chen C., Zhou B., Ma D., Batchelor W., Han X., Ding Z., Du M., Zhao M., Li M., and Ma W., 2022, Drip fertigation with relatively low water and N input achieved higher grain yield of maize by improving pre-and post-silking dry matter accumulation, Sustainability, 14(13): 7850.
https://doi.org/10.3390/su14137850

Guo Y., Wang Z., and Li J., 2024, Effects of phosphorus fertilizer type and dripline depth on root and soil nutrient distribution, nutrient uptake, and maize yield under subsurface drip fertigation, Field Crops Research, 318: 109585.
https://doi.org/10.1016/j.fcr.2024.109585

Hou Y., Xu X., Kong L., Zhang L., Zhang Y., and Liu Z., 2022, Improving nitrogen contribution in maize post-tasseling using optimum management under mulch drip irrigation in the semiarid region of Northeast China, Frontiers in Plant Science, 13: 1095314.
https://doi.org/10.3389/fpls.2022.1095314

Li C., Han W., and Peng M., 2024, Effects of drip and flood irrigation on carbon dioxide exchange and crop growth in the maize ecosystem in the Hetao Irrigation District, China, Journal of Arid Land, 16(2): 282-297.
https://doi.org/10.1007/s40333-024-0093-0

Li J., Du Z., Li Y., and Li B., 2008, Water and nitrogen distribution and summer maize growth in subsurface drip irrigation system as affected by spatial variations of soil properties, Scientia Agricultura Sinica, (6): 1717-1726.

Li Q., Zhang Y., Hu W., Hu G., Meng F., Feng G., and Liu X., 2014, Effects of drip fertilization on growth, nutrient uptake and yield of maize, Chinese Journal of Soil Science, 45(5): 1195-1201.

Li Z., Zou H., Lai Z., Zhang F., and Fan J., 2023, Optimal drip fertigation regimes improved soil micro-environment, root growth and grain yield of spring maize in arid northwest China, Agronomy, 13(1): 227.
https://doi.org/10.3390/agronomy13010227

Liu M., Liang F., Li Q., Wang G., and Jia H., 2023, Enhancement growth, water use efficiency and economic benefit for maize by drip irrigation in Northwest China, Scientific Reports, 13(1): 8392.
https://doi.org/10.1038/s41598-023-35611-9

Liu M., Wang G., Liang F., Li Q., Tian Y., and Jia H., 2022, Optimal irrigation levels can improve maize growth, yield, and water use efficiency under drip irrigation in northwest China, Water, 14(23): 3822.
https://doi.org/10.3390/w14233822

Liu R., Kang Y., Pei L., Wan S., Jiang S., Liu S., Ren Z., and Yang Y., 2014, Chemical fertilizer pollution control using drip fertigation for conservation of water quality in Danjiangkou Reservoir, Nutrient Cycling in Agroecosystems, 98(3): 295-307.
https://doi.org/10.1007/s10705-014-9612-2

Liu Y., Yang H., Li J., Li Y., and Yan H., 2018, Estimation of irrigation requirements for drip-irrigated maize in a sub-humid climate, Journal of Integrative Agriculture, 17(3): 677-692.
https://doi.org/10.1016/S2095-3119(17)61833-1

Ma C., Liu S., Wang X., Wang L., Muhammad T., Xiao Y., Wang Y., Sun Z., and Li Y., 2022, Coupling regulation of root-zone soil water and fertilizer for summer maize with drip irrigation, Water, 14(22): 3680.
https://doi.org/10.3390/w14223680

Mahboob A., Shoaib M., Manzoor M., Arshad M., Mahboob I., Habib H., and Akram M., 2020, Improving yield and quality of maize by different drip-fertigation rates of N, P and K fertilizers, Soil & Environment, 39(1): 50-58.
https://doi.org/10.25252/se/20/132080

Ning D., Chen H., Qin A., Gao Y., Zhang J., Duan A., Wang X., and Liu Z., 2024, Optimizing irrigation and N fertigation regimes achieved high yield and water productivity and low N leaching in a maize field in the North China Plain, Agricultural Water Management, 301: 108945.
https://doi.org/10.1016/j.agwat.2024.108945

Qian X., Shen G., Gu H., Pugliese M., and Gullino M., 2011, Effects of drip fertigation management on nutrient losses and pear production at Chongming Dongtan in Yangtze River Estuary, China, Advanced Materials Research, 396: 1716-1724.
https://doi.org/10.4028/www.scientific.net/AMR.396-398.1716

Sampathkumar T., and Pandian B., 2010, Efficiency of applied nutrients and SPAD values in hybrid maize under drip fertigation, Madras Agricultural Journal, 97(7-9): 237-241.

Saracoglu M., and Oktem A., 2021, The effect of nitrogen application in different doses by fertigation method on grain yield, yield components and quality of corn (*Zea mays* L.), Applied Ecology & Environmental Research, 19(6): 5017-5031.
https://doi.org/10.15666/aeer/1906_50175031

Shi J., Zhou H., Xu M., Zhang Q., Li J., and Wang J., 2023, Fertilization highly increased the water use efficiency of spring maize in dryland of northern China: a meta-analysis, Agronomy, 13(5): 1331.
https://doi.org/10.3390/agronomy13051331

Song K., Qin Q., Yang Y., Sun L., Sun Y., Zheng X., Lü W., and Xue Y., 2022, Drip fertigation and plant hedgerows significantly reduce nitrogen and phosphorus losses and maintain high fruit yields in intensive orchards, Journal of Integrative Agriculture, 22(2): 598-610.
https://doi.org/10.1016/j.jia.2022.08.008

Tian D., Zhang Y., Mu Y., Zhou Y., Zhang C., and Liu J., 2017, The effect of drip irrigation and drip fertigation on N_2O and NO emissions, water saving and grain yields in a maize field in the North China Plain, Science of the Total Environment, 575: 1034-1040.
https://doi.org/10.1016/j.scitotenv.2016.09.166

Wu W., Xu X., and Sokolowski E., 2017, Enhancing maize productivity via drip irrigation and drip fertigation on a sandy soil in northeast China, e-ifc, 50: 1-39.

Wu Y., Bian S., Liu Z., Wang L., Wang Y., and Xu W., 2021, Drip irrigation incorporating water conservation measures: effects on soil water-nitrogen utilization, root traits and grain production of spring maize in semi-arid areas, Journal of Integrative Agriculture, 20(12): 3127-3142.
https://doi.org/10.1016/s2095-3119(20)63314-7

Yin R., Gu X., Cheng Z., Li W., Wang Y., Zhao T., Cai W., Du Y., and Cai H., 2024, Optimizing nitrogen application patterns and amounts to improve maize yield and water-nitrogen use efficiencies in the Loess Plateau of China: a meta-analysis, Field Crops Research, 318: 109599.
https://doi.org/10.1016/j.fcr.2024.109599

Zhang A., Wang X., Zhang D., Dong Z., Ji H., and L, H., 2023, Localized nutrient supply promotes maize growth and nutrient acquisition by shaping root morphology and physiology and mycorrhizal symbiosis, Soil and Tillage Research, 225: 105550.
https://doi.org/10.1016/j.still.2022.105550

Zheng J., Zhou M., Zhu B., Fan J., Lin H., Ren B., and Zhang F., 2023, Drip fertigation sustains crop productivity while mitigating reactive nitrogen losses in Chinese agricultural systems: evidence from a meta-analysis, Science of the Total Environment, 886: 163804.
https://doi.org/10.1016/j.scitotenv.2023.163804