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Review

Review on Drip Irrigation: Impact on Crop Yield, Quality, and Water Productivity in China

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Abstract: The scarcity of freshwater resources is a global concern that is exacerbated by an increasing global population and climate change induced by global warming. To address this issue, the largest water-consuming sector has taken a series of measures termed as drip irrigation schemes. The primary purposes of drip irrigation are to reduce water scarcity near the root zone, reduce evaporation, and decrease water use. The application scope of drip irrigation is getting wider and wider, with the number of papers related to drip irrigation increasing year by year from 1990 to 2022. This study reviews crops planted in China that had been irrigated by drip irrigation equipment. The effects of drip irrigation technology on crop growth, physiology, quality, yield, and water use efficiency are summarized. This paper also provides an overview of drip irrigation technology on crop root development and nitrogen uptake. Through a global meta-analysis, it is found that in the case of water shortage, drip irrigation can save water and ensure crop yield compared to flooding irrigation, border irrigation, furrow irrigation, sprinkler irrigation, and micro-sprinkler irrigation. When the drip irrigation amount is more (100–120%), drip irrigation significantly increases crop yields by 28.92%, 14.55%, 8.03%, 2.32%, and 5.17% relative to flooding irrigation, border irrigation, furrow irrigation, sprinkler irrigation, and micro-sprinkler irrigation, respectively. When water resources are sufficient, increasing the amount of drip irrigation also improves crop yield. Moreover, the researchers found that drip irrigation can reduce fertilizer leaching and soil salinity. However, more studies should be conducted in the future to enrich the research on drip irrigation. In conclusion, drip irrigation technology is effective in improving crop growth, water use efficiency, and reducing water scarcity while decreasing fertilizer leaching and soil salinity, making it an ideal solution to the issue of freshwater resource scarcity globally.

Keywords: drip irrigation; conventional irrigation; yield; quality; water productivity

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1. Introduction

The increasing population and harsh effects of climate change have intensified the pressure on agricultural production, creating a need to identify and promote sustainable practices. Thankfully, agricultural production can be steadily improved by utilizing irrigation, fertilizers, high-yielding seed varieties, and other techniques. However, it is important to note that the excessive use of these inputs can cause negative environmental and social impacts. For example, the overuse of nitrogen fertilizers can lead to undesirable environmental outcomes such as groundwater pollution, eutrophication of freshwater, and tropospheric pollution resulting from emissions of nitrogen oxides and ammonia gas [1]. Irrigated agriculture, which is the sector consuming the largest quantity of water, consumes 70% of water resources [2]. China is the world's largest irrigator, and its irrigated area reached 74 million hectares in 2019, of which 68 million hectares were cultivated land, accounting for 50.3 percent of the country's total cultivated land. Irrigation is a technical measure used to replenish water necessary for crop growth, and adequate water supply is critical for normal crop growth and high and stable yields. As a result, water conservation is a critical consideration. However, conventional irrigation methods not only result in overwatering but also raise the risk of groundwater pollution due to the leaching of chemicals and nutrients from the crop's root zone [3], contributing to the depletion of freshwater resources. China is the most populous country in the world. Currently, to meet food demand and minimize resource use, it is critical to adopt advanced agricultural technologies and management approaches to increase productivity per unit area in China.

As far as we know, the drip fertigation system is widely recognized as an advanced production technique. This system allows water and fertilizer to be efficiently and frequently delivered to the root zone of the crops through emitters or drippers [4–6]. Clearly, compared to other irrigation methods, drip irrigation is more efficient in terms of unit water productivity as it reduced water loss through seepage and evaporation [7,8]. Additionally, it allowed for better management of fertilizers and more efficient distribution of nutrients, resulting in reduced plant stress, earlier harvests, better crop quality, and increased yield homogeneity [9,10]. Pourgholam-Amiji et al. [11] noted that increasing crop productivity indirectly led to an increase in water resources, and increasing water productivity was an effective strategy to prevent the consumption of non-renewable water resources. The implementation of drip irrigation has undoubtedly resulted in revolutionary benefits [12].

Drip irrigation technology has undergone significant advancements, resulting in the development of sub-membrane drip irrigation, subsurface drip irrigation, aerated drip irrigation, and other irrigation technologies. Sub-membrane drip irrigation technology integrates the advantages of mulching and drip irrigation technology, which can effectively protect soil aggregate structure and improve soil physical and chemical properties. It can not only conserve soil moisture, reduce evaporation, and save water and fertilizer, but also increase yield and optimize quality, reduce the application amounts of pesticide–harmful pesticides, fertilizer leaching, and excessive consumption of nutrient elements [13]. Studies have shown that sub-membrane drip irrigation increased the yield of wheat by 14.6–19.6%, crop water productivity by 27.3–29.6%, and irrigation water productivity by 37.1–42.0% [14]. Subsurface drip irrigation is another novel drip irrigation technology that delivers water and liquid fertilizer into the crop root zone, through a drip irrigation pipe network system laid below the surface layer [15]. This method can effectively reduce deep seepage and soil evaporation, improve water use efficiency, save labor, and improve operation and management efficiency [16]. Aerated drip irrigation builds on subsurface drip irrigation, with air injected through external forces, which is pushed to crop root soil as required by subsurface irrigation devices, optimizing crop aeration and water use efficiency [17]. This technology is mainly used for greenhouse fruits and vegetables such as tomatoes, cucumbers, Chinese cabbage, pineapples, peppers, and watermelons. Yield and water use efficiency of crops have increased by 3.6~66.4% and 5.9~60.0%, respectively, after subsurface drip irrigation aeration [18–29]. Overall, drip irrigation technologies have played an essential role in enhancing crop yield and quality and promoting efficient water resource management. Therefore, in this study, we intend to provide a systematic literature review of drip irrigation to carry out an analysis of the works that have utilized the drip irrigation technique by analyzing its main physiological and agronomic effects on crops and its sensitivity to water stress, without forgetting the essential role of this irrigation technique in retaining the sustainable development of the environment.

2. Development of Drip Irrigation Technology in China and Research Progress

Drip irrigation is a precision agricultural technology that first calculates the amount of fertilizer and water required by the crop at different stages based on the principle of soil nutrient and water balance. It then uses a precision drip irrigation system to deliver the fertilizer in stages around the root zone of the crop. When combined with mulching, this technique improves fertilizer utilization and reduces water consumption. During irrigation, the system slowly and evenly delivers water to the soil near the plant roots at a certain pressure after filtering through the pipe network and outlet pipe. The drip irrigation system typically includes a water source project, a head hydroproject, water transmission and distribution pipelines, and emitters, among other components (Figure 1). Among all the components, the emitter plays a critical role in the drip irrigation system. Its primary function is to dissipate the pressure energy of the water flow through the complex internal flow channel structure, ensuring a steady and even water supply to the crops [30]. However, due to the narrow size of the energy dissipation channel (only 0.5~1.2 mm), it is susceptible to blockage by impurities present in the water source. This blockage can potentially affect the uniformity of irrigation and reduce the lifespan of the drip irrigation system, and sometimes necessitate its replacement [31,32]. Therefore, the filter screen is considered to be the cornerstone of drip irrigation technology. Typically, to ensure that the emitters are not blocked and extend the service life of drip irrigation systems, filters, and backwash facilities are usually installed at the irrigation head. In addition to the filter screen, the fertilizer and pesticide injection devices are also integral components of drip irrigation systems. These devices typically include pressure differential fertilizer tanks, Venturi fertilizer applicators, and proportional fertilizer pumps, which are commonly used worldwide [33]. Drip irrigation is currently the most widely utilized irrigation technology, owing to its numerous advantages [34]. The main features of this technology include (1) the simultaneous supply of water and fertilizer, exploiting synergies between the two; (2) the direct application of fertilizer to the roots, reducing the contact area between fertilizer and soil and, thus, reducing the fixation of fertilizer nutrients by the soil, facilitating nutrient uptake by the roots, and maintaining a higher phosphate concentration in the soil solution, compared to fertilizer spreading [35]; (3) long-lasting application of water and fertilizer, maintaining a relatively stable environment for root growth; and (4) flexible adjustment of the type, proportion, and quantity of nutrients supplied, according to climate, soil characteristics, and the nutritional requirements of crops at the different stages of growth and development. As sustainable agriculture gains widespread attention, the application of this technology is becoming increasingly common.

The advanced irrigation and fertilization technology created and developed by Israelis in the 1960s was the world's first drip irrigation system. This technology innovatively integrates the two important technologies of irrigation and fertilization in crop production, dissolving the fertilizer in water and applying it with the water through the irrigation system, with a reasonable proportion of nutrients according to the needs of the crop, and supplying the right amount at the right time, which is highly controllable. Firstly, by searching the keywords "drip irrigation" or "drip irrigated" or "trickle irrigation" or "drip fertigation", 5311 papers were downloaded from the Web of Science core collection between 1990 and 2022 [36]. Secondly, we used CiteSpace software to construct representative data of literature records in the field of drip irrigation research. Then, a visual stepwise synthesis co-citation network was constructed to visually analyze the structure of drip irrigation research [37]. Through an analysis of literature metrology software, it was found that drip irrigation was becoming a research hotspot, and the number of papers related to drip irrigation increased year by year from 1990 to 2022 (Figure 2). Countries with more papers published include China, USA, Spain, Brazil, India, etc. (Figure 3).

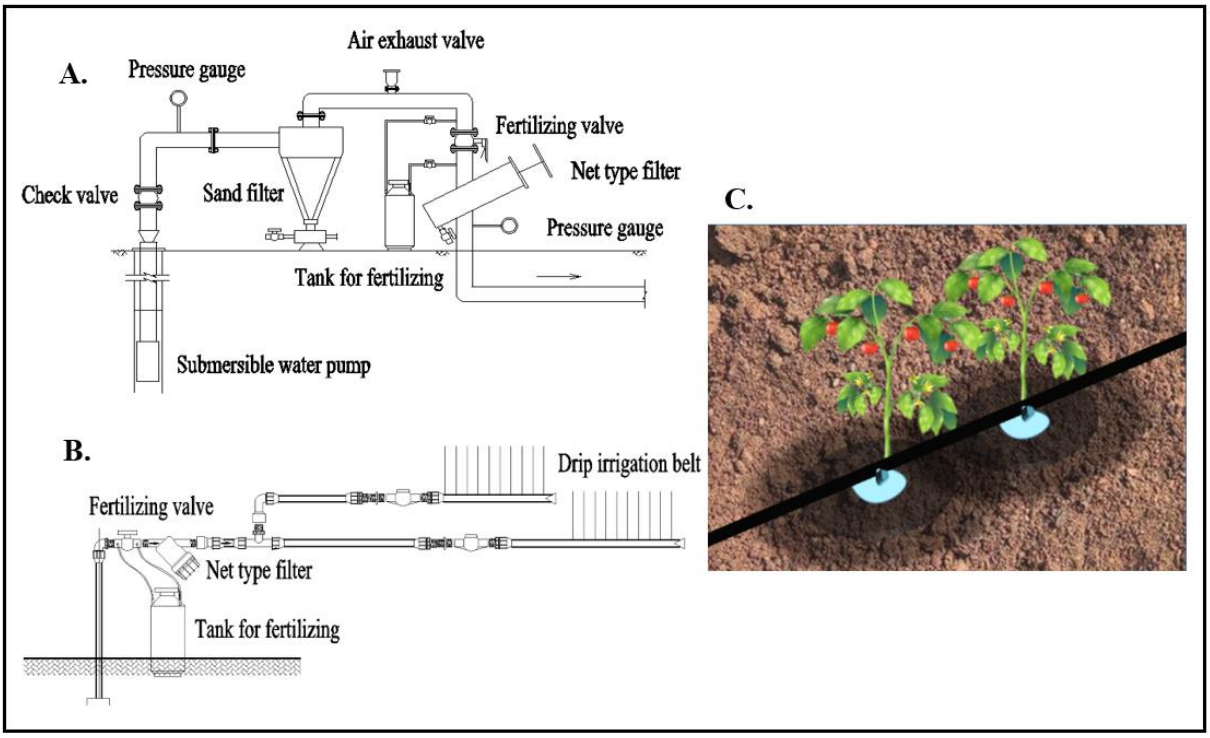

Figure 1. Layout of drip irrigation and fertilization system. (**A**) The head part of drip irrigation system. (**B**) Branch and capillary connection diagram of drip irrigation system. (**C**) Schematic diagram of ground drip irrigation.

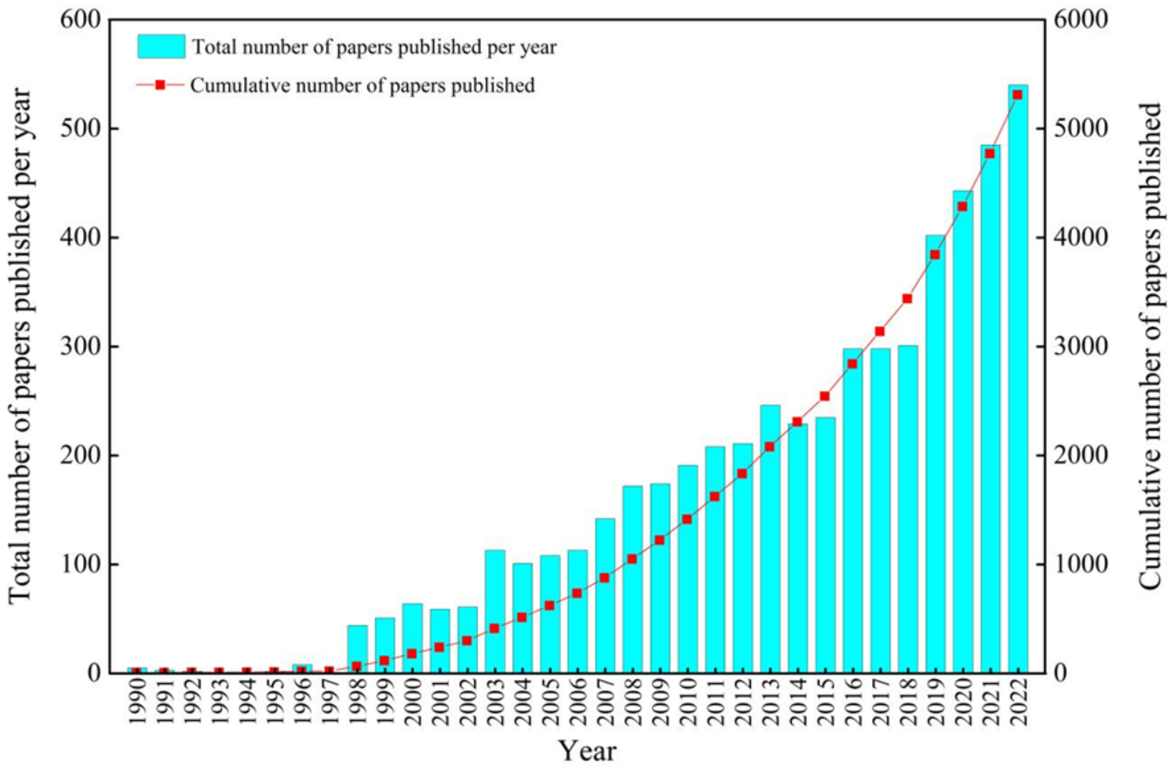

Figure 2. Distribution of the number of literature in the field of drip irrigation from Web of Science in 1990–2022.

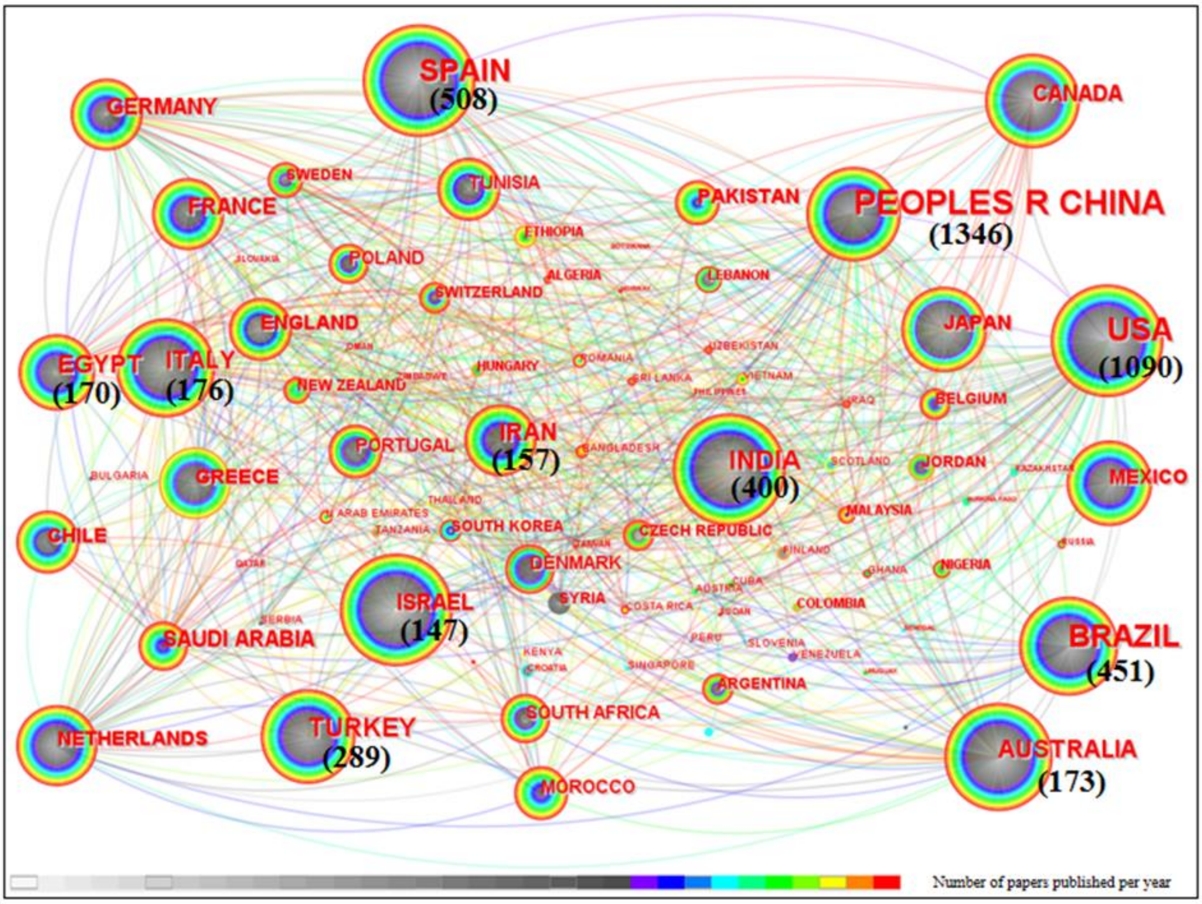

Figure 3. Distribution map of drip irrigation. Note: Font size represents the number of papers published; the larger the font, the more papers published; the numbers on the graph are the number of publications. Different colors represent the number of papers published in each country from 1990 to 2022. Connectivity between countries represents cooperation.

Since the introduction of drip irrigation technology in 1974, China has witnessed three stages of development. The first stage, before 1976, mainly involved learning and digesting the introduced technology. Based on the introduction of foreign equipment and technology, China began developing and producing domestic products and, eventually, formed equipment and technology with independent intellectual property rights. Using this as a foundation, China began researching the content of drip irrigation technology and started promoting the equipment on a pilot basis. The third and final stage began in the late 1990s and continues to the present day. It marks the formation of Yanshan drip irrigation technology, signifying that drip irrigation technology in China has entered the promotion stage. The theory and application of drip irrigation technology have gradually gained attention, prompting vigorous technical research and training programs while promoting and implementing the technique on a larger scale. Since 2003, irrigation and fertilization technology has been listed as one of the major water-saving technologies, and has been demonstrated and promoted in regions such as Xinjiang, Gansu, and Inner Mongolia. Drip irrigation technology has also been applied in other countries worldwide. China currently has the largest coverage of land area with drip irrigation systems in the world. In 2017, the area covered by water-saving irrigation systems totaled 34,319 kha [38]. Over time, drip irrigation technology has evolved from local experiments and demonstrations to large-scale popularization and application, expanding from North China to the northwest arid region, northeast cold temperate zone, and south subtropical region of China. However, drip irrigation technology is still in the development stage in China, and the application of and theoretical research on drip irrigation are gradually deepening. From 1990 to 2022, a total of 5831 papers on drip irrigation were downloaded from the China National Knowledge Infrastructure (CNKI) [39]. The majority of the literature analyzed was from the core journals of Peking University and EI. The research mainly focused on the impact of drip irrigation systems on water use efficiency, crop growth, photosynthetic characteristics, fruit yield and quality, soil moisture, temperature, salt content, emitter blockage, etc., in China (Figure 4).

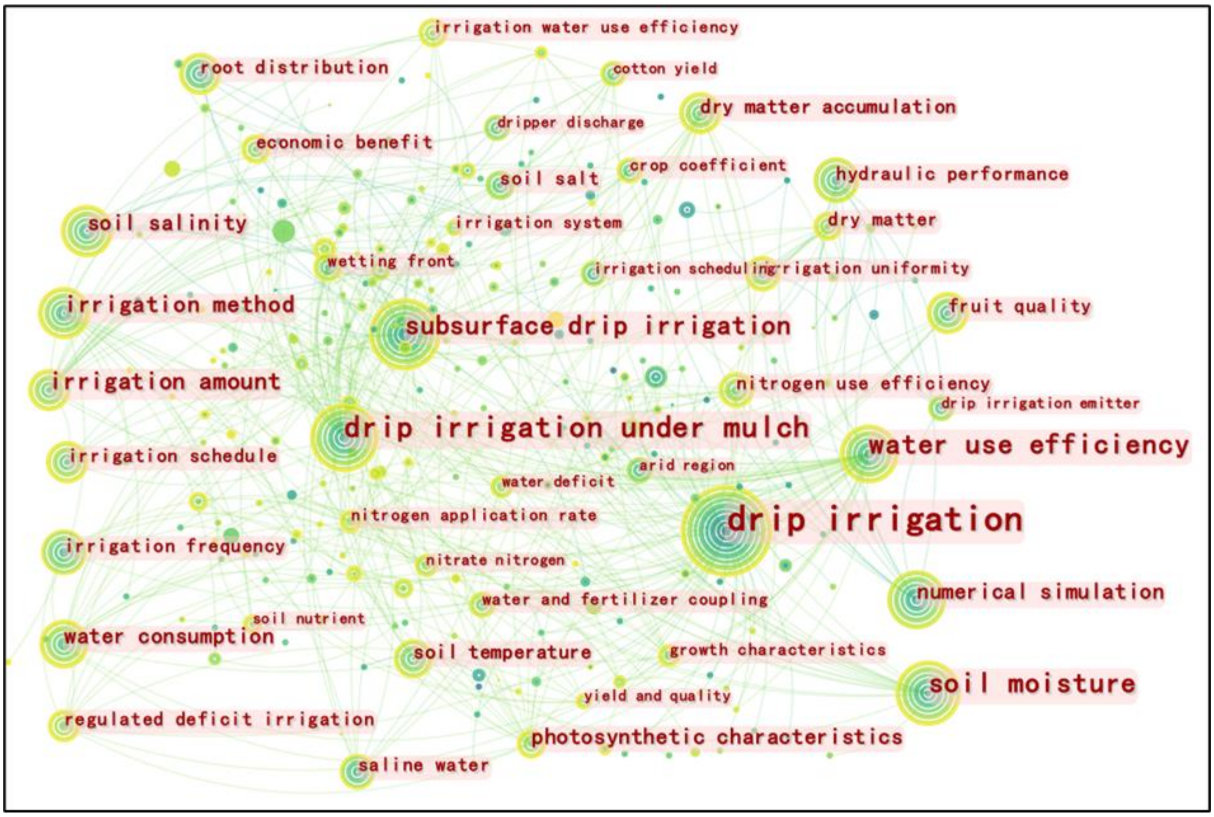

Figure 4. Research focus related to drip irrigation from 1990 to 2022 in China.

3. Effects of Drip Water and Fertilizer Availability on Crop Growth, Physiology, and Quality

3.1. Effects of Drip Water and Fertilizer Availability on Crop Growth and Physiology

Besides the climatic and soil characteristics, water and fertilizer are the main factors that influence crop growth and physiology. Rational coordination of water and fertilizer supply can improve the crop leaf area index (LAI) and photosynthetic capacity, promote the accumulation and transfer of biomass [40], and enhance crop population growth and development [41]. In recent years, many researchers have conducted numerous studies on the effects of surface drip irrigation, subsurface drip irrigation, sub-membrane drip irrigation, and aerated drip irrigation technologies on crop growth. For instance, Zhang et al. [42] found that shallow-buried drip irrigation combined with straw returning increased the spring maize leaf area index (LAI), relative content of chlorophyll (SPAD) values, photosynthetic rate at milk maturity, intercell CO_2 concentration, population photosynthetic potential, canopy photosynthetic capacity, dry matter accumulation, and transfer volume, compared to traditional border irrigation. Tian et al. [43] and Zhao et al. [44] demonstrated that compared to traditional border irrigation and fertilization methods, surface drip fertigation significantly increased the LAI; SPAD of flag leaf; net photosynthetic rate; stomatal conductance; transpiration rates; activities of antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT); and grain filling rate in winter wheat. Additionally, some other researchers compared surface drip irrigation with other irrigation methods and found that compared to furrow irrigation, sprinkler irrigation, border irrigation, and rainfed conditions, surface drip irrigation can improve the plant height, stem diameter, leaf area, dry matter accumulation, and nutrient absorption of maize [13,45], and had a positive effect on the improvement in the tillering number, plant height, and effective stem number of sugarcane [46,47]. Furthermore, sub-membrane drip irrigation technology has been found to further improve crop growth compared to drip irrigation without mulching. For instance, Peng et al. [48] noted that sub-membrane drip irrigation significantly increased the tillering rate, plant height, millable stalk number, and stalk formation rate of sugarcane. Du et al. [49] found that sub-membrane drip irrigation optimized the canopy structure of cotton and promoted the formation of photosynthetic products compared to traditional flood irrigation. Additionally, Yue et al. [50] revealed that greenhouse melon leaves with drip irrigation under a membrane had a 52.3% increase in net photosynthetic rate and a 39.0% increase in chlorophyll content, compared to traditional furrow irrigation. Liu et al. [51] conducted a comparison of various irrigation methods, including sub-membrane drip irrigation, flooding irrigation, open-field drip irrigation, furrow irrigation, and alternate furrow irrigation. The study showed that sub-membrane drip irrigation resulted in the highest net photosynthetic rate and total dry matter accumulation. In addition to traditional surface and subsurface drip irrigation, aerated drip irrigation has been invented. Through the use of subsurface drip irrigation aeration technology, plant height, and stem diameter can be increased. The researchers found that aerated irrigation can also enhance cucumber germination rates. Specifically, after three aerated irrigation sessions in the morning, midday, and evening, the peak germination rate increased by 27.5% compared to non-aerated treatment. Studies have demonstrated that cyclic aeration treatment can significantly enhance the dry matter, photosynthetic rate, stomatal conductance, and transpiration rate of Chinese cabbage, resulting in an increase of 42.0%, 868.6%, 157.1%, and 55.6%, respectively. Similarly, Venturi aerated irrigation has been found to increase the weight of watermelon leaves and stem by 7.5–50.3% and 34.8–64.7%, respectively. Furthermore, subsurface drip irrigation (SDI) micro nano bubble aeration has been shown to increase the plant height and stem diameter of spring maize by 4.3–11.5% and 8.4–29.7%, respectively [23,52–54]. These findings indicate that drip irrigation technology is an effective means to improve crop growth and physiological indicators.

3.2. Effects of Drip Irrigation on Crop Quality

Drip irrigation is a water-efficient and effective method of fertilization that can improve crop quality. The technology is widely used in crop cultivation across the world. Studies have shown that under drip irrigation conditions, an excess of water and fertilizers (including organic fertilizers) leads to a decrease in total sugar, vitamin C, and soluble solids in jujube, and an increase in the total acid content [55–57]. Recently, Wang et al. [58] set three drip irrigation treatments (the upper and lower limits of irrigation were 60–70%, 60–80%, and 60–90% of the field water holding rate) and took the flood irrigation as the control group, and found that the treatment with the upper and lower limits of irrigation of 60–80% in the drip irrigation was most beneficial to the improvement in the fruit quality of pear. Furthermore, other studies investigated the effects of irrigation and fertilization systems on the quality of various crops under drip fertigation with film. Zhao et al. [59], Yue et al. [50], Luo et al. [60], and Ma et al. [61] found that the proper combination of irrigation and fertilization systems under drip irrigation can improve the vitamin C, water-soluble sugar, and soluble solid contents, and sugar–acid ratio in crops such as pepper, muskmelon, tomato, and cucumber. Additionally, irrigation technology also plays a significant role in crop quality. Lian et al. [62] studied the effects of different irrigation methods on the quality of green radish and found that compared to border irrigation and sprinkler irrigation, the soluble solids in the upper and middle parts of the radish increased by 19.38% and 6.70% and by 19.13% and 7.20%, respectively, under drip irrigation. Furthermore, Wang et al. [63] conducted a study on the influence of three different drip irrigation methods (buried drip irrigation, alternate drip irrigation, and conventional drip irrigation) on grapes and found that buried alternate drip irrigation produced the highest soluble sugar content, reaching

20.3%, while there was no significant difference in anthocyanin content among the different treatments. However, Qiu et al. [64] discovered that compared to surface drip irrigation, inserted subsurface drip irrigation reduced the soluble sugar content of green peppers by 3.22–7.36%. However, Wang [65] found that aerated irrigation can improve the solubility of fig fruits' sexual solid content and increase the soluble sugar and vitamin C (Vc) contents when compared to treatments without aeration. Based on water and fertilizer regulation, aerated irrigation can further improve the quality of fruits and vegetables, such as increasing the acid–sugar ratio of watermelon by 11.2–54.4% and the vitamin C and soluble solid contents of tomatoes by 10.4–44.0% and 1.0–3.9%, respectively [18–29].

4. Effects of Drip Irrigation on Crop Yield and Water Productivity

4.1. Effects of Drip Irrigation on Crop Yield

Under the same fertilization and irrigation conditions, drip irrigation can effectively increase crop yield. The systems offer an irrigation efficiency rate of up to 90% [66]. Compared to conventional irrigation methods, drip irrigation has the ability to dramatically increase crop yields, water and fertilizer use efficiency, and crop quality, while also reducing pollution risks [67]. Studies have shown that compared to border irrigation, furrow irrigation, flooding irrigation, and rain-fed watermelon, cotton, wheat, maize, sunflower, potato, onion, and areca nut yields were significantly increased in China [68–75]. Additionally, previous research results demonstrated that potato yields under alternate subsurface drip irrigation in the root zone were better than those under furrow irrigation, micro-spray irrigation, and surface flood irrigation [76,77]. Zhang [42] reported that shallow-buried drip irrigation with straw returning significantly increased grain yields by 2.6% compared to traditional border irrigation. A global meta-analysis was performed in this review, analyzing 1164 comparisons (511 for yield, 195 for water productivity (WP, the ratio of crop yield to water consumption), and 456 for irrigation water productivity (IWP, the ratio of crop yield to irrigation water amount)) from 117 publications to systematically and quantitatively examine the responses of crops' yield, IWP, and WP to drip irrigation (Figure 5). The results show that when the amount of drip irrigation was less than the amount of flooding irrigation, border irrigation, furrow irrigation, sprinkler irrigation, and micro-sprinkler irrigation (<100%), drip irrigation resulted in significantly higher crop yields compared to flooding irrigation (95% CI: 6.12–7.55%) and furrow irrigation (95% CI: 6.74–7.93%). However, there was no significant difference in yield between drip irrigation and border irrigation or micro-sprinkler irrigation (Figure 5). Furthermore, in cases of water shortage, drip irrigation has been proven to save water and maintain crop yields, surpassing other irrigation methods. When the amount of drip irrigation was greater than the amount of the other five irrigation methods (100–120%), drip irrigation significantly increased crop yields by 28.92%, 14.55%, 8.03%, 2.32%, and 5.17% compared to flooding irrigation, border irrigation, furrow irrigation, sprinkler irrigation, and micro-sprinkler irrigation, respectively (Figure 5). When water resources are sufficient, increasing the amount of drip irrigation can also help to enhance crop yield.

4.2. Effects of Drip Irrigation on Water Productivity and Irrigation Water Productivity

A meta-analysis revealed that no matter if the amount of drip irrigation was lower (<100%) or higher (100–120%) than that of flooding irrigation, border irrigation, furrow irrigation, and sprinkler irrigation, drip irrigation improved WP and IWP compared to these other methods (Figure 5). Zhou et al. [78], Qiang et al. [68], Ran et al. [79], Liu et al. [72], and Huang et al. [80] also reported that drip irrigation could enhance crop water productivity when compared to furrow irrigation and flooding irrigation methods. Moreover, Sun et al. [81] simulated two cucumber growing seasons using the EU-Rotate_N model and discovered that drip irrigation was 60% more water-saving than border irrigation, and the irrigation water productivity was more than two times higher. Tian et al. [43] found that drip irrigation significantly enhanced winter wheat water productivity by an average of 57.58% compared to border irrigation. Lian et al. [62] investigated the impact of various irrigation techniques on green radish quality and observed that, in comparison to sprinkler and border irrigation, the volume of irrigation water was reduced by 39.49% and 61.89% under drip irrigation (with water savings of up to 580.5 m^3 hm^{-2} and 1444.5 m^3 hm^{-2}, respectively), and irrigation water productivity was boosted by 25.37% and 77.16%, respectively. Liu et al. [82] found that compared with flood irrigation, drip irrigation, spray irrigation, and micro-spray irrigation all significantly improved irrigation water productivity, with increases of 42.79%, 39.09%, and 47.71%, respectively. In a study by Fan [83], the water productivity of pepper under drip irrigation reached the maximum and was significantly better than those under pipe irrigation and micro-sprinkler irrigation ($p < 0.05$). The research also demonstrated that drip irrigation was the most effective water-saving technique for pepper in the studied region. Zhang [42] reported a 70.9% increase in irrigation water productivity using shallow-buried drip irrigation with straw returning compared to traditional border irrigation. Gao et al. [84] discovered that aerated drip irrigation, wherein air is injected into the soil by means of venturi air equipment or an air pump, can promote root absorption of soil water, resulting in improved water productivity for potato crops compared to non-aerated drip irrigation.

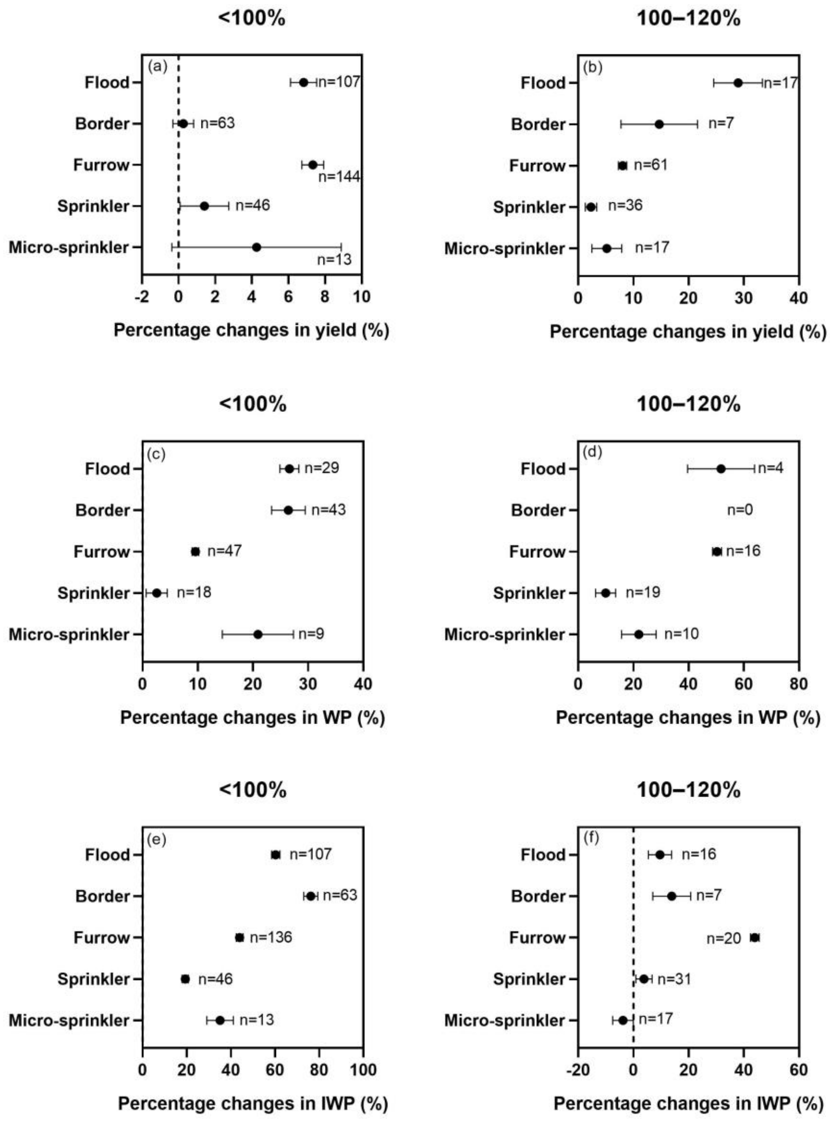

Figure 5. The effects of drip irrigation on crop yield, WP, and IWP as a percentage change in the control for different irrigation methods. A total <100% and 100–120% mean the drip irrigation amount

is less or higher than the amount of the five irrigation methods. If there is an overlap between the error bar and the Y axis, it is considered that there is no significant difference between the control group (five irrigation methods) and the experimental group (drip irrigation); otherwise, it is considered to be significant. Subfigures (**a**,**b**) are the effects of drip irrigation on crop yield as a percentage change in the control for different irrigation methods under <100% and 100–120%, respectively. Subfigures (**c**,**d**) are the effects of drip irrigation on WP as a percentage change in the control for different irrigation methods under <100% and 100–120%, respectively. Subfigures (**e**,**f**) are the effects of drip irrigation on IWP as a percentage change in the control for different irrigation methods under <100% and 100–120%, respectively.

5. Root Development and Nitrogen Uptake under Drip Irrigation

Drip irrigation provides small quantities of irrigation and fertilization in accordance with the needs of the crop, thereby maximizing nitrogen utilization efficiency and promoting root development. Studies have shown that using appropriate amounts of water and nitrogen can not only improve crop yield but also increase water and nitrogen uptake and utilization under drip irrigation [42].

5.1. Root Development in Drip Irrigation

Drip irrigation can regulate water and nitrogen uptake by impacting root development in the root zone. The growth of crops roots is promoted, which helps them absorb nutrients and water from a larger soil volume. Compared to traditional fertilization, drip fertilization can boost microbial biomass and root activity, and root distribution in the 0–80 cm soil layer (7.8–9.4%) [85]. Liu et al. [75] found that, as tea plants prefer acidic conditions, the pH value close to tea seedling roots reached 7.46 when sprayed, which significantly inhibited root fresh weight, total length, volume, and tip and cross numbers. This was not conducive to the growth of tea plants, indicating that drip fertigation may be a more appropriate technique. Singandhupe et al. [86] and Mahajan and Singh [87] discovered that the soil moisture content of the 15–30 cm layer under drip irrigation was substantially higher compared to furrow irrigation, which effectively reduced nitrate nitrogen leaching and promoted tomato root growth. Drip irrigation also alters water and fertilizer distribution characteristics in the root zone, affecting root distribution and absorption function compared to traditional irrigation fertilization methods [88]. Research conducted indicated that soil moisture retention, along with root length density, root surface area density and root volume density of wheat, was substantially greater through the use of membrane drip irrigation in comparison to traditional border irrigation within the 0–30 cm main infiltration layer [24]. The implementation of aeration subsurface drip irrigation technology resulted in a significant increase in the total root length, total root surface area, total root volume, and root activity of soybean, chickpea, and pumpkin. Tomato plants treated with this technology exhibited a 5.6–7.5% increase in root length and a 7.6–17.5% increase in root activity [89].

5.2. Nitrogen Uptake under Drip Irrigation

Nitrogen is the main limiting factor of plant growth. Additionally, irrigation and fertilization methods have a significant impact on crop nitrogen absorption and utilization. Tian et al. [43] found that drip irrigation increased winter wheat nitrogen partial productivity by an average of 57.58% compared to border irrigation. Liang et al. [90] took two seasons of plant tomatoes as the objects and collected leakage liquid with a leakage tank. They found that drip irrigation increased annual nitrogen uptake and nitrogen use efficiency by 21.4% and 47.5% compared to flood irrigation. In a pot experiment, Guo [91] found that nitrogen use efficiency decreased from 45% to 33% as the nitrogen application rate increased from 0 to 2.64 g per pot when reclaimed water was applied by drip irrigation. Sun et al. [81] found that nitrogen use efficiency was 41% and 44% higher for drip irrigation compared to border irrigation using the EU-Rotate_N model, respectively. Liu et al. [72] concluded that drip irrigation significantly improved the nitrogen uptake and fertilizer utilization rate of Welsh onion compared to ditch irrigation. Zhang [42] found that shallow-buried drip irrigation with straw returning significantly increased the total amount of nitrogen accumulation in plants before silking compared to traditional border irrigation. Additionally, nitrogen agronomic efficiency increased by 15.2%, but nitrogen physiological use efficiency and nitrogen harvest index decreased by 17.5% and 0.7%, respectively.

6. Drip Irrigation and Leaching

The increasing trend of drip irrigation also raises discussions about its benefits for water and nutrient leaching. Drip irrigation has the potential to regulate the amount of water and nutrients based on crop requirements, thus increasing resource use efficiency [92]. In addition to saving water and fertilizers, drip irrigation also reduces fertilizer leakage and outperforms traditional fertilization in conventional irrigation setups. This is particularly important in areas where the natural environment is sensitive, as environmental problems, such as climate change and nutrient pollution in water bodies, are often linked to the residual effects of chemical fertilizer use and fertilizer runoff [93].

Zhang et al. [57], Su et al. [94], and Ma et al. [88] found that high-flow drip irrigation promoted root growth horizontally, making it suitable for crops with strong horizontal root elongation. On the other hand, low-flow drip irrigation promoted vertical root growth, suitable for crops with strong vertical root elongation to avoid deep loss of exogenous selenium by controlling irrigation frequency and quota. Previous research had shown that compared to border irrigation, drip irrigation improved the root growth environment, accelerated the degradation of pesticides, and reduced pesticide residues in soil, thus reducing the risk of pesticide leaching [43,95]. Wei et al. [96] found that rain shelter cultivation and optimization of irrigation volume effectively reduced the risk of soil nitrogen leaching in grape drip irrigation. Meanwhile, Sun et al. [97] found that water-saving drip irrigation reduced phosphorus leaching in the daylily planting process. However, in arid areas with gravel sandy soil, Zhao et al. [59] found that when the drip irrigation amount of winter wheat exceeded 390 mm, significant leaching of nitrate nitrogen occurred below 60 cm. Luo et al. [98] replaced 40% of N fertilizer with organic fertilizer and used drip irrigation (30% water savings) to reduce nitrate N leaching from facility tomato and pepper plots by an average of 25.9% over two years. Additionally, Lei et al. [99] used the DNDC model to study the cucumber–tomato rotation system in vegetable plots and found that applying drip irrigation and increasing soil organic carbon content by 20% significantly reduced nitrate nitrogen leaching by 69.04% compared to flood irrigation. Liang et al. [90] found that compared to flood irrigation, drip irrigation decreased the annual leaching of mineral nitrogen and soluble organic nitrogen by 33.1% and 39.6%, respectively. Tang et al. [100] discovered that reducing water and fertilizer rates while increasing yield could improve the contents of nitrate nitrogen and available phosphorus in 0–20 cm soil, thus reducing fertilizer leaching in cucumbers grown in greenhouses. Zhang et al. [101] found that compared to traditional furrow irrigation and nitrogen fertilizer dosage, drip irrigation with reduced water and fertilizer rates significantly decreased nitrate nitrogen leaching in the 20–80 cm soil layer. Additionally, Zhang et al. [102] studied the effects of drip irrigation frequency and nitrogen on nitrate leaching and found that cumulative nitrogen leaching decreased with increased irrigation frequency at the same nitrogen application rate. Yin et al. [103] studied nitrogen loss in greenhouse vegetable soil under different water and fertilizer management and found that optimized drip irrigation significantly reduced nitrogen leaching by 72% to 87% compared to traditional border irrigation under the same fertilization conditions. Similarly, Sun et al. [81] found that nitrogen loss under drip irrigation was reduced by 63% to 76% compared to border irrigation. In addition, the nitrate nitrogen leaching risk was mainly affected by rainfall. The ranking of factors increasing the nitrate leaching was nitrogen fertilizer, deep percolation, nitrogen in irrigation, and initial soil nitrogen. Properly reducing nitrogen application rates under drip irrigation and reclaimed water irrigation can significantly reduce the risk of nitrate nitrogen leaching. The peak value of residual nitrate nitrogen in different precipitation years was closely related to precipitation, with the residual amount and leaching amount of soil nitrate nitrogen increasing with nitrogen application rates. Precipitation significantly affected nitrate nitrogen leaching, accounting for 50.62% and 34.82% of total leaching in wet and dry years, respectively [104].

7. Drip Irrigation and Soil Salinity

By conveying a small amount of appropriate fertilizer to the root layer of crops, drip irrigation can increase the absorption and utilization of fertilizer by crops under the condition of less irrigation water, thus reducing soil salinization. In arid and semi-arid regions, drip irrigation with high water-use efficiency has been widely used for mitigating water stress [105]. However, salt accumulation in the root zone is still prevalent under drip irrigation in fields with salinization inherited from soil parent materials [106]. Recent studies have suggested that a higher drip irrigation level can help salt migrate out of the root zone, while salt accumulation is more likely to occur in the root zone with a low drip irrigation level [107]. When soil was slightly salinized, 2625 m^3 hm^{-2} of irrigation quota with a nitrogen application rate of 150 kg hm^{-2} was found to be most suitable for cotton growth. When soil was heavily salinized, an irrigation quota of 3125 m^3 hm^{-2} with a nitrogen application rate of 300 kg hm^{-2} can effectively reduce the negative effects of soil salinization on cotton growth and maximize cotton yield [63]. Soil acidification and secondary salinization caused by irrigation and fertilization are key factors limiting sustainable irrigation practices. In litchi cultivation utilizing drip irrigation, a potassium–nitrogen fertilizer to phosphorus fertilizer ratio of 1:1 can help avoid soil acidification and secondary salinization, even in regions with abundant rainfall [74]. There was a significant positive correlation (R^2 = 0.97) between the soil desalinization rate and initial soil salt content under drip irrigation. Across the three planting areas investigated, the desalinization rate was found to be 4.75 g kg^{-1} annually for the 10 years under drip irrigation, while the desalinization rate for plots planted 14 years and 16 years was 0.59 and 0.47 g kg^{-1} annually, respectively. Using the Kriging interpolation method, the estimated soil desalination rates for three cotton fields with different initial salt content levels and different planting years were 85%, 53%, and 51%. For severely salinized soil, after 10 years of drip irrigation, the spatial heterogeneity of soil salinity decreased rapidly and tended to be homogenized, mainly due to the soil desalinization rate, initial salt content, and planting years [108].

Drip irrigation under a membrane altered the flow path of farmland irrigation water compared to traditional irrigation methods. When water infiltrates the soil, salt in the soil begins to spread, and the salt content around the soil infiltrated by water decreases gradually, forming a light salt zone conducive to plant root growth, which is ultimately beneficial for overall plant growth. Related studies have indicated that soil salt content changed significantly with an increase in irrigation amount. When soil water decreased or plant transpiration was intensified, soil salt content increased, salt accumulation occurred in the surface layer, sodium content was less in the middle soil, and soil salt content tended to remain stable in the deep soil [109]. Research has shown that soil salt content trends as follows: natural precipitation > drip irrigation > diffuse irrigation. Drip irrigation's water preservation and desalinization properties make it a suitable irrigation method for reducing soil salt content in severely salinized areas [109,110]. Wu et al. [111] investigated the effects of different drip irrigation amounts applied under a brackish water film on water and salt migration and cotton growth. Their results showed that desalinization zones could be formed under different irrigation quotas in the 0~20 cm range, and soil salinity in the 20~40 cm range changed significantly with increasing irrigation quota. Horizontally, narrow rows all showed desalinization zones with an increase in irrigation quota, while wide rows and intermembrane showed salt accumulation. Ma et al. [112] conducted a field experimental study on the influence of irrigation water quality and flow on soil salinity distribution under drip irrigation under a membrane. They found that a large drip flow increased the horizontal soil moisture radius and promoted the horizontal migration of soil salt, which mostly accumulated in the soil surface. On the other hand, a small drip flow can promote the vertical migration of water and salt in the soil, and salt in the soil can be pressed to deeper depths with water, where it is less harmful for plant growth. The effect of salt pressure is better than that of a large drip flow.

8. Factors Restricting the Application of Drip Irrigation Technology

8.1. Equipment Quality

One of the primary challenges in the development of drip irrigation is the quality of equipment. Despite years of technology introduction, digestion, and absorption, China has to develop the ability to produce complete sets of drip irrigation equipment independently. Moreover, while the performance of some drip irrigation equipment has approached that of foreign products, there is still a significant gap between some key equipment, including the first hub equipment, automatic control equipment, and advanced foreign products. For instance, the quality of drip irrigation and other related products manufactured in China has been unstable when it comes to pressure compensation, anti-blocking, irrigation uniformity, and material anti-aging.

8.2. Equipment Management and Use

The farmers' level of management of new technology and equipment for drip irrigation is often inadequate, resulting in the delayed maintenance of these devices. In turn, this leads to the cessation of the use of drip irrigation equipment. To maintain drip irrigation effectively, farmers need to have a high-quality filter, and they must regularly wash the filter net and drip irrigation belt. The inadequate management of drip irrigation equipment and neglecting regular maintenance can cause the blockage of drip irrigation belts, leading to a complete failure of the drip irrigation system.

8.3. Design

The theoretical level of the designer responsible for designing drip irrigation systems is often inadequate to execute the normative design of the project. This leads to the selection of low-quality drip irrigation equipment in the design process, resulting in poor system compatibility. Additionally, some designs only involve the placement of one drip irrigation belt on the widened surface of a field, leading to excessively long irrigation times and uneven water distribution.

8.4. Cost

Currently, the degree of land intensification in China is not significantly high, and the land is relatively dispersed. The average investment required for water-saving equipment for drip irrigation is about 3000–4000 CNY hm^{-2}. Therefore, for small-scale farmers, the cost of installing water-saving equipment for drip irrigation is relatively high. Moreover, farmers' income from water-saving is low since water resource tax has not been fully implemented in the agricultural sector. This results in low motivation among farmers to promote water-saving, which further compounds the problem of high installation costs for drip irrigation water-saving equipment. Therefore, drip irrigation equipment is mainly used for cash crops, such as cotton and vegetables, in China.

9. Conclusions

Firstly, the present study provides empirical evidence of the effects of drip irrigation technology in China on crops' growth, physiology, and quality. Our findings indicate that drip irrigation can significantly enhance the growth and physiological indices of crops and improve the overall quality of crops produced. Secondly, we offer a quantitative analysis to explain the advantages of drip irrigation in increasing crop yields and water use efficiency. Our analysis highlights the potential benefits of drip irrigation in terms of improving overall agricultural productivity and sustainability. Thirdly, numerous studies suggest that drip irrigation is helpful in promoting root development. The implementation of drip irrigation can simultaneously address both fertilizer and water applications, resulting in improved crop productivity and enhancing water and nutrient use efficiency. Such findings emphasize the importance of adopting drip irrigation and drip fertigation practices in modern agriculture. Fourthly, researchers have found that drip irrigation can decrease the leaching of nitrogen, further emphasizing the environmental benefits of implementing drip irrigation technology in agriculture. Fifthly, compared with other irrigation methods, drip irrigation can reduce soil salinity by reducing fertilizer application while maintaining crop yield and quality, making it a valuable tool for improving soil health and promoting sustainable agricultural practices. The last, despite the many benefits of drip irrigation technology, several factors limit its widespread adoption in agriculture. These factors can include high initial costs of installation and maintenance, variable water quality, limited technical knowledge and support for implementation, and institutional barriers such as water management policies and regulations. In conclusion, drip irrigation is primarily utilized in regions with low water availability, such as arid and semi-arid areas, and for crops grown in greenhouses, high-value crops, and intensive farming. Moreover, it can enhance crop production and quality, water use efficiency, and nitrogen use efficiency while conserving water resources. Due to its numerous benefits, drip irrigation has become a popular method of irrigation in modern agricultural practices.

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References

1. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.; Fetzer, I.; Bennett, E.; Biggs, R.; Carpenter, S. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *348*, 1217. [CrossRef] [PubMed]
2. FAO. Scheme Water Management. Rome, Italy. 2023. Available online: https://www.fao.org/land-water/water/water-management/zh/ (accessed on 14 February 2023).
3. Siyal, A.A.; Bristow, K.L.; Šimůnek, J. Minimizing nitrogen leaching from furrow irrigation through novel fertilizer placement and soil surface management strategies. *Agric. Water Manag.* **2012**, *115*, 242–251. [CrossRef]
4. Bajpai, A.; Kaushal, A. Soil moisture distribution under trickle irrigation: A review. *Water Supply* **2020**, *20*, 761–772. [CrossRef]
5. Ding, J.; Fang, F.; Lin, W.; Qiang, X.; Xu, C.; Mao, L.; Li, Q.; Zhang, X.; Li, Y. N_2O emissions and source partitioning using stable isotopes under furrow and drip irrigation in vegetable field of North China. *Sci. Total Environ.* **2019**, *665*, 709–717. [CrossRef] [PubMed]
6. Moursy, M.A.M.; ElFetyany, M.; Meleha, A.M.I.; El-Bialy, M.A. Productivity and profitability of modern irrigation methods through the application of on-farm drip irrigation on some crops in the Northern Nile Delta of Egypt. *Alex. Eng. J.* **2023**, *62*, 349–356. [CrossRef]
7. Flores, J.H.N.; Faria, L.C.; Neto, O.R.; Diotto, A.V.; Colombo, A. Methodology for determining the emitter local head loss in drip irrigation systems. *J. Irrig. Drain. Eng.* **2021**, *147*, 06020014. [CrossRef]
8. Fukai, S.; Mitchell, J. Factors determining water use efficiency in aerobic rice. *Crop. Environ.* **2022**, *1*, 24–40. [CrossRef]
9. Gebremeskel, G.; Gebremicael, T.G.; Hagos, H.; Gebremedhin, T.; Kifle, M. Farmers' perception towards the challenges and determinant factors in the adoption of drip irrigation in the semi-arid areas of Tigray, Ethiopia. Sustain. *Water Resour. Manag.* **2018**, *4*, 527–537. [CrossRef]
10. Zakhem, B.A.; Al Ain, F.; Hafez, R. Assessment of field water budget components for increasing water productivity under drip irrigation in arid and semi-arid areas, Syria. *Irrig. Drain.* **2019**, *68*, 452–463. [CrossRef]
11. Pourgholam-Amiji, M.; Liaghat, A.; Khoshravesh, M.; Azamathulla, H.M. Improving rice water productivity using alternative irrigation (case study: North of Iran). *Water Supply* **2020**, *21*, 1216–1227. [CrossRef]
12. Bansal, G.; Mahajan, A.; Verma, A.; Singh, D.B. A review on materialistic approach to drip irrigation system. *Mater. Today: Proc.* **2021**, *46*, 10712–10717. [CrossRef]
13. Jia, B.; Fu, J. Critical nitrogen dilution curve of drip-irrigated maize at vegetative growth stage based on leaf area index. *Trans. Chin. Soc. Agric. Eng.* **2020**, *36*, 66–73, (In Chinese with English abstract). [CrossRef]

14. Li, X.; Tian, D.; Guo, K.; Xu, B.; Zhao, S. Influence of mulch drip irrigation on wheat root distribution characteristics. *J. Irrig. Drain. Eng.* **2016**, *34*, 545–552, (In Chinese with English abstract). [CrossRef]
15. Cheng, X.; Xu, D.; Zhang, H. A summary of development and application situations for subsurface drip irrigation technique. *Water Sav. Irrig.* **1999**, *4*, 13–15, 42, (In Chinese with English abstract). [CrossRef]
16. Ayars, J.; Fulton, A.; Taylor, B. Subsurface drip irrigation in California-Here to Stay? *Agric. Water Manag.* **2015**, *157*, 39–47. [CrossRef]
17. Camp, C. Subsurface drip irrigation: A review. *Trans. ASAE* **1998**, *41*, 1353–1367. [CrossRef]
18. Zhu, Y.; Cai, H.; Song, L.; Chen, H. Impacts of oxygation on plant growth, yield and fruit quality of tomato. *Trans. Chin. Soc. Agric. Mach.* **2017**, *48*, 199–211, (In Chinese with English abstract). [CrossRef]
19. Cui, B.; Niu, W.; Du, Y.; Zhang, Q. Effects of nitrogen application and aerated irrigation on soil environment and yield in cucumber root area. *Water Sav Irrig.* **2020**, *4*, 27–32, (In Chinese with English abstract).
20. Cao, X.; Zheng, H.; Wang, J.; Li, H.; Feng, Y. Effects of subsurface drip irrigation with micro-nano bubble water on rhizosphere soil nutrients and yield of Alfalfa. *J. Irrig. Drain.* **2020**, *39*, 24–30, (In Chinese with English abstract). [CrossRef]
21. Li, J.; Pan, Y.; Jiao, X.; Hu, W.; Liu, Y. Effects of aerated irrigation rice growth and soil reducibility under wheat straw returning conditions. *Trans. Chin. Soc. Agric. Mach.* **2021**, *52*, 250–259, (In Chinese with English abstract). [CrossRef]
22. Zang, M.; Lei, H.; Bhattarai, S.; Balsys, R.; Xu, J. Effects of oxygation techniques on growth and physiology of vegetable under subsurface drip irrigation. *J. Drain. Irrig. Mach. Eng.* **2019**, *38*, 310–317, (In Chinese with English abstract). [CrossRef]
23. Liu, J.; Cai, H.; Zhang, M.; Chen, X.; Wang, J. Effect of airjection irrigation on growth and yield of mini-watermelon in greenhouse. *Water Sav. Irrig.* **2010**, *24*, 24–27, (In Chinese with English abstract).
24. Li, Y. Effect of Rhizosphere Aeration on Growth and Its Physiological Mechanism of Muskmelon and Tomato. Ph.D. Thesis, Northwest Agriculture & Forestry University, Yangling, China, 2016.
25. Wang, Y. Oxygen Mass Transfer Characteristics of Aeration Drip Irrigation and Its Effects on Pepper Growth and Soil Environment in Root Zone. Master's Thesis, Ludong University, Yantai, China, 2019.
26. Chen, X.; Jay, D.; Surya, B.; Manouchehr, T.; David, J. Impact of oxygation on soil respiration and crop physiological characteristics in pineapple. *J. Drain. Irrig. Mach. Eng.* **2010**, *28*, 543–547, (In Chinese with English abstract).
27. Abuarab, M.; Mostafa, E.; Ibrahim, M. Effect of air injection under subsurface drip irrigation on yield and water use efficiency of corn in a sandy clay loam soil. *J. Adv. Res.* **2013**, *4*, 493–499. [CrossRef] [PubMed]
28. Liu, X.; Liu, Z.; Lei, H.; Zang, M.; Liu, H. Comparisons of growth and yield of spring wheat treated with different oxygation techniques. *J. Drain. Irrig. Mach. Eng.* **2017**, *35*, 813–819, (In Chinese with English abstract). [CrossRef]
29. Chen, T.; Yao, B.; Xiao, W. Effect of aerobics irrigation on potato yield and water use efficiency. *China Rural Water Hydropower.* **2013**, *8*, 70–72, (In Chinese with English abstract). [CrossRef]
30. Li, Y.; Zhou, B.; Yang, P. Research advances in drip irrigation emitter clogging mechanism and controlling methods. *J. Hydraul. Eng-Asce.* **2018**, *47*, 103–114, (In Chinese with English abstract). [CrossRef]
31. Nakayama, F.S.; Bucks, D.A. Water quality in drip/trickle irrigation: A review. *Irrig. Sci.* **1991**, *12*, 187–192. [CrossRef]
32. Pei, Y.; Li, Y.; Liu, Y.; Zhou, B.; Shi, Z.; Jiang, Y. Eight emitters clogging characteristics and its suitability under on-site reclaimed water drip irrigation. *Irrig. Sci.* **2014**, *32*, 141–157. [CrossRef]
33. Li, J.; Du, Z.; Li, Y. Field evaluation of fertigation uniformity for subsurface drip irrigation systems. *Trans. Chin. Soc. Agric. Eng.* **2008**, *24*, 83–87, (In Chinese with English abstract). [CrossRef]
34. Ajdary, K.; Singh, D.; Khanna, M. Modelling of nitrogen leaching from experimental onion field under drip fertigation. *Agric. Water Manag.* **2007**, *89*, 15–28. [CrossRef]
35. Bar-Yosef, B. Advances in fertigation. *Adv. Agron.* **1999**, *65*, 1–77. [CrossRef]
36. Chen, C. Science mapping: A systematic review of the literature. *J. Data Inf. Sci.* **2017**, *2*, 1–40. [CrossRef]
37. Web of Science. Available online: https://www.webofscience.com/wos/alldb/basic-search (accessed on 1 March 2023).
38. National Bureau of Statistics. Available online: https://data.stats.gov.cn/search.htm?s (accessed on 1 March 2023).
39. CNKI. Available online: https://www.cnki.net/ (accessed on 1 March 2023).
40. Yang, Q.; Zhang, F.; Liu, X.; Ge, Z. Effects of different furrow irrigation patterns, water and nitrogen supply levels on hydraulic conductivity and yield of maize. *Trans. Chin. Soc. Agric. Eng.* **2011**, *27*, 15–21, (In Chinese with English abstract). [CrossRef]
41. Li, P.; Zhang, F. Effect of root zone water and nitrogen regulation on cotton population physiological indices under different furrow irrigation patterns. *Trans. Chin. Soc. Agric. Eng.* **2011**, *27*, 38–45, (In Chinese with English abstract). [CrossRef]
42. Zhang, M. Effects of Straw Returning and Irrigation Methods on Water and Nitrogen Use Efficiency and Soil Quality in Root Soil Layer of Spring Maize. Master's Thesis, Inner Mongolia University for Nationalities, Tongliao, China, 2021.
43. Tian, D.; Hou, C.; Ren, J.; Hao, L.; Li, Z. Effects of different irrigation methods and fertilizer amount on wheat yield and utilization of water, fertilizer and medicine. *Water Sav. Irrig.* **2022**, *10*, 100–104, (In Chinese with English abstract). [CrossRef]
44. Zhao, J.; Xu, X.; Qu, W.; Liu, S.; Xu, Y.; Meng, F.; Jia, J.; Zhao, C. Protective enzyme activity of flag leaf and yield of drip-irrigated winter wheat. *J. Irrig. Drain.* **2022**, *41*, 43–51, (In Chinese with English abstract). [CrossRef]
45. Li, M. Effects of different irrigation modes on physiological growth, yield and water use efficiency of maize. *Shaanxi Water Resour.* **2022**, *38*, 38–41. (In Chinese)
46. Deng, L.; Lu, S.; Shen, H.; Tu, P.; Zhang, C.; Chen, K. Effects of N application rate on growth of sugarcane under drip fertigation. *J. Irrig. Drain.* **2010**, *29*, 119–123, (In Chinese with English abstract). [CrossRef]

47. Tan, H.; Liu, Y.; Zhou, L.; Xie, R.; Yang, S.; Huang, J.; Huang, M. Reduction fertilization techonogies under drip for sugarcane irrigation. *Chin. J. Trop. Crops.* **2013**, *34*, 24–28, (In Chinese with English abstract).
48. Peng, L.; Cao, Z.; Cai, W.; Gan, Y.; Yang, B. Effects of reduced fertilization on main agronomic traits, yield and fertilizer utilization rate of sugarcane under mulched drip fertigation system. *Chin. J. Trop. Crops.* 2022. Available online: https://kns.cnki.net/kcms/detail/46.1019.S.20221115.1435.002.html (accessed on 17 January 2023). (In Chinese with English abstract).
49. Du, G. Effects of Irrigation Methods and Irrigation Amount on Canopy Structure and Canopy Photosynthetic Production in Cotton. Master's Thesis, Shihezi University, Shihezi, China, 2019.
50. Yue, W.; He, W.; Ding, C.; Bai, Y.; Zhou, Y.; Xi, H. Effects of different water and fertilization on nutrient uptake, yield and quality of greenhouse muskmelon under drip irrigation condition. *Acta Agric. Zhejiangensis.* **2021**, *33*, 2370–2380, (In Chinese with English abstract). [CrossRef]
51. Liu, Y.; Sun, F.; Liu, R.; Han, M.; Liu, J.; Li, F. Responses of Physiological indexes of drip-irrigated summer maize to different nitrogen application rates with mulched and unmulched. *J. Maize Sci.* 2022. Available online: https://kns.cnki.net/kcms/detail/22.1201.S.20221115.1704.002.html (accessed on 17 January 2023). (In Chinese with English abstract).
52. Liu, X. Efffects of Oxygenation of Subsurface Drip Irrigation with Micro Nano Gas on Corn Growth and Soil Health. Master's Thesis, China Agricultural University, Beijing, China, 2014.
53. Hu, D.; Liao, J.; Chen, Z.; Ding, X.; Luo, D. Effects of controlled irrigation and oxygenation on physiological and biochemical characteristics and water use efficiency of super rice. *J. Drain. Irrig. Mach. Eng.* **2020**, *38*, 500–505, 516, (In Chinese with English abstract). [CrossRef]
54. Zang, M.; Lei, H.; Liu, X.; Pan, H.; Xu, J. Oxygation promotes soil oxygen diffusion rate and nutrient utilization of winter wheat. *Acta Agric. Nucl. Sin.* **2020**, *34*, 1070–1078, (In Chinese with English abstract).
55. Ren, Y.; Wang, S.; Xie, L.; Dong, X. Effects of irrigation methods on water use efficiency and fruti quality of jujube in arid area. *Trans. Chin. Soc. Agric. Eng.* **2012**, *28*, 95–102, (In Chinese with English abstract). [CrossRef]
56. Ye, S.; Liu, T. Effects of different drip irrigation systems on yield and water use efficiency of pear-jujube in the Loess Plateau. *J. Irrig. Drain.* **2018**, *37*, 28–34, (In Chinese with English abstract). [CrossRef]
57. Zhang, Z.; Cai, H.; Guo, Y.; Geng, B. Experimental study on factors effecting soil wetted volume of clay loam under drip irrigation. *Trans. Chin. Soc. Agric. Eng.* **2002**, *18*, 17–20, (In Chinese with English abstract). [CrossRef]
58. Wang, Y.; Xu, H.; Guo, H.; He, M.; Shi, M.; Dou, Y.; Yang, K. Effects of different drip irrigation levels on quality, textrue and yield of Yuluxiang pear. *Heilongjiang Agric. Sci.* **2022**, *2*, 48–52, (In Chinese with English abstract). [CrossRef]
59. Zhao, J.; Yang, T.; Hu, W.; Ayiguli, W.; Amat, A.; Chen, K. Effects of water and nitrogen interaction on nitrate transport, nitrogen balance and water and nitrogen use efficiency in drip-irrigation wheat soil. *China Rural Water Hydropower* **2021**, *4*, 141–149, (In Chinese with English abstract). [CrossRef]
60. Luo, H.; Li, F. Water and nitrogen coupling effects and model under tomato drip irrigation. *Chin. Agric. Sci. Bull.* **2022**, *38*, 30–36, (In Chinese with English abstract). [CrossRef]
61. Ma, S.-T.; Wang, T.-C. Effects of drip irrigation on root activity pattern, root-sourced signal characteristics and yield stability of winter wheat. *Agric. Water Manag.* **2022**, *271*, 107783. [CrossRef]
62. Lian, X.; Wang, Y.; Liang, X.; Li, H.; Wang, Z. Effects of irrigation methods on yield, quality and economic benefit of green radish by sowing seed tape. *Tianjin Agric. Sci.* **2021**, *27*, 53–56, (In Chinese with English abstract). [CrossRef]
63. Wang, P.; Shi, W.; Zhang, Y. Improving soil water and nitrogen management to facilitate growth and water-nitrogen use efficiency of cotton in saline-alkali solis. *J. Irrig. Drain.* **2022**, *41*, 33–42, (In Chinese with English abstract). [CrossRef]
64. Qiu, H.; Zhang, W.; Liu, J.; Lv, M.; Wang, Y. Effects of drip irrigation patterns and biochar amendment on green pepper yield, quality and soil nitrogen transformational enzyme activities in greenhouse. *China Soils Fert.* **2022**, *9*, 67–74, (In Chinese with English abstract). [CrossRef]
65. Wang, J. Effects of Aerated Irrigation on Figs Growth and Soil Phosphorus Absorption and Transformation in Southern Xinjiang. Master's Thesis, Shihezi University, Shihezi, China, 2021.
66. Camp, C.R.; Lamm, F.R.; Evans, R.G.; Phene, C.J. Subsurface drip irrigation-Past, present, and future. National irrigation symposium. In Proceedings of the 4th Decennial Symposium, Phoenix, AZ, USA, 14–16 November 2000.
67. Fernández-Gálvez, J.; Simmonds, L.P. Monitoring and modelling the three-dimensional flow of water under drip irrigation. *Agric. Water Manag.* **2006**, *83*, 197–208. [CrossRef]
68. Qiang, X.; Sun, J.; Liu, H.; Ning, H.; Wang, F. Effects of drip irrigation with mulch on yield and water productivity in the watermelon-cotton intercropping system. *J. Irrig. Drain.* **2015**, *34*, 10–14, (In Chinese with English abstract). [CrossRef]
69. Xu, J.; Li, C.-F.; Meng, Q.-F.; Ge, J.-Z.; Wang, P.; Zhao, M. Effects of different drip-irrigation modes at the seedling stage on yield and water-use efficiency of spring maize in Northeast China. *Acta Agron. Sin.* **2015**, *41*, 1279–1286, (In Chinese with English abstract). [CrossRef]
70. Yang, H.; Li, X.; Wang, B.; Zhong, H.; Zhang, B.; Wang, Z. Effect of drip irrigation under plastic film mulching on soil water-heat utilization and high yield on oil sunflower. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 82–88, (In Chinese with English abstract). [CrossRef]
71. Zhao, Y.; Shi, S.; He, Z.; Lou, C. Effects of new slow-release fertilizer on potato yield and soil nutrient transport under different irrigation modes. *Jiangsu Agric. Sci.* **2016**, *44*, 130–132. (In Chinese) [CrossRef]

72. Liu, Y.; Cao, B.; Xu, K. Effects of irrigation modes and nitrogen, phosphorus and potassium ratios on yield and water and fertilizer productivity of welsh onion. *China Veget.* **2020**, *2*, 52–56. Available online: https://www.cnveg.org/CN/Y2020/V1/I2/52 (accessed on 17 January 2023). (In Chinese with English abstract).
73. Jiang, J.; Zhang, H.; Li, H.; Luo, T.; Xin, X.; Yang, F. Effects of different irrigation methods on growth, fruit quality and yield of arecanut. *Tianjin Agric. Sci.* **2021**, *41*, 1–4, (In Chinese with English abstract).
74. Bai, C.; Zhou, C.; Wang, X.; Luo, D.; Zhu, L.; Yao, L. Soil pH and salinity as affected by fertilizer ratio of potassium and nitrogen in drip fertigation and fertilization method in litchi. *Chin. J. Soil Sci.* **2021**, *52*, 1104–11136, (In Chinese with English abstract). [CrossRef]
75. Liu, Z.; Ye, Y.; Wang, L.; Zhang, Y.; Qi, Y.; Mu, J.; Zhang, L. Effects of drip irrigation and spray irrigation fertilization on spatial differentiation of soil nutrients and root growth of tea seedlings. *J. Soil Water Conserv.* **2022**, *36*, 330–339, (In Chinese with English abstract). [CrossRef]
76. Huang, H.; Li, W.; Xie, L.; Xiang, L.; Meng, X.; Xie, A.; Wei, L.; Chen, Q.; Nong, T. Effects of drip irrigation on agronomic characters and yield of sugarcane. *Modern Agric. Sci. Technol.* **2010**, *19*, 107–108. (In Chinese)
77. Zhang, Z.; Liang, B.; Li, J.; He, H.; Jin, S. Effects of different fertigation methods on yield and nutrient uptake of potato. *Chin. Agric. Sci. Bull.* **2013**, *29*, 268–272, (In Chinese with English abstract).
78. Zhou, S.; Zhang, F.; Wang, X.; Mi, G.; Mao, D. Comparative study on nitrogen absorption and utilization characteristics of different winter wheat varieties under high yield conditions. *Soil Fert.* **2000**, *4*, 20–24, (In Chinese with English abstract). [CrossRef]
79. Ran, Y.; Wu, W.; Liu, H.; Wang, S.; Tang, X. Response of mountain maize yield to ecological factors under the condition of nitrogen, phosphorus and potassium deficiency. *Guangdong Agric. Sci.* **2018**, *45*, 7–13, (In Chinese with English abstract). [CrossRef]
80. Huang, Z.; Shi, Y.; Song, S.; Zhao, Y.; Bao, Z.; Liu, L.; Ma, B. Effects of nitrogen, phosphorus and potassium deficiency on water and fertilizer utilization efficiency of winter wheat under different irrigation methods. *Water Sav. Irrig.* **2022**, *11*, 79–85, (In Chinese with English abstract). [CrossRef]
81. Sun, Y.; Hu, K.; Qiu, J.; Jiang, L.; Xu, Y. Simulation and analysis of nitrogen loss, water and nitrogen use efficiencies of greenhouse cucumber under different water and fertilizer managements. *Sci. Agric. Sin.* **2013**, *46*, 1635–1645, (In Chinese with English abstract). [CrossRef]
82. Liu, J.; Qiu, H.; Zhang, W.; Cai, J.; Wang, X.; Lv, M. The effects of irrigation and biochar amendment on yield and water and nitrogen use efficiency of winter wheat. *J. Irrig. Drain.* **2021**, *40*, 59–65, (In Chinese with English abstract). [CrossRef]
83. Fan, J. Effects of different irrigation methods on pepper growth. *Hydro Sci. Cold Zone Eng.* **2022**, *5*, 41–45. (In Chinese)
84. Gao, L.; Li, J.; Huang, H.; Xiang, B.; Li, S. Effects of aerated irrigation on soil habitat factors and yield of winter potato under drip irrigation in Yunnan. *Agric. Res. Arid Areas.* **2022**, *40*, 108–115, (In Chinese with English abstract). [CrossRef]
85. Pan, N.; Shen, H.; Wu, D.; Deng, L.; Tu, P.; Gan, H.; Liang, Y. Mechanism of improved phosphate uptake efficiency in banana seedlings on acidic soils using fertigation. *Agric. Water Manag.* **2011**, *98*, 632–638. [CrossRef]
86. Singandhupe, R.; Rao, G.; Patil, N.; Brahmanand, P. Fertigation studies and irrigation scheduling in drip irrigation system in tomato crop (*Lycopersicon esculentum* L.). *Eur. J. Agron.* **2003**, *19*, 327–340. [CrossRef]
87. Mahajan, G.; Singh, K. Response of greenhouse tomato to irrigation and fertigation. *Agric. Water Manag.* **2006**, *84*, 202–206. [CrossRef]
88. Ma, T.; Gao, F.; Liu, C.; Hu, C.; Cui, B.; Cui, E.; Hao, Y. Spatial distribution of added selenium in soil as affected by different irrigations using reclaimed water. *J. Irrig. Drain.* **2022**, *41*, 58–64, (In Chinese with English abstract). [CrossRef]
89. Yang, W.; Liu, F.; Liu, T.; Wang, D.; Zhang, Q. Effects of different fertilization levels on greenhouse tomato under aerated irrigation. *Water Sav Irrig.* **2019**, *7*, 49–55, (In Chinese with English abstract).
90. Liang, B.; Tang, Y.; Wang, Q.; Li, F.; Li, J. Drip irrigation and application of straw reducing nitrogen leaching loss in tomato greenhouse. *Trans. Chin. Soc. Agric. Eng.* **2019**, *35*, 78–85, (In Chinese with English abstract). [CrossRef]
91. Guo, L.; Li, J.; Li, Y.; Xu, D. The Availability of Nitrogen in Sewage Effluent to Maize Compared to Synthetic Fertilizers under Drip Irrigation. Master's Thesis, China Institute of Water Resources and Hydropower Research, Beijing, China, 2017. [CrossRef]
92. Surendran, U.; Chandran, K.M. Development and evaluation of drip irrigation and fertigation scheduling to improve water productivity and sustainable crop production using HYDRUS. *Agric. Water Manag.* **2022**, *269*, 107668. [CrossRef]
93. Good, A.G.; Beattyg, P.H. Fertilizing nature: A tragedy of excess in the commons. *PLoS Biol.* **2011**, *9*, e1001124. [CrossRef]
94. Su, L.; Lin, S.; Wang, Q.; Wang, K. Influence of soil hydraulic parameters on soil wetting pattern shape of point source infiltration. *Trans. Chin. Soc. Agric. Mach.* **2020**, *51*, 264–274, (In Chinese with English abstract). [CrossRef]
95. Shi, W. Factors Affecting the Application of Micro-Irrigation Integrated with Water and Medicine and Optimization of the Applicator. Master's Thesis, Northwest A&F Universit, Xi'an, China, 2020.
96. Wei, Q.; Xie, J.; Liu, S.; Wu, W.; Hu, Y. Effects of lower limit of drip irrigation and rain shelter cultivation on nitrogen leaching and grape yield and quality. *Water Sav. Irrig.* **2022**, *9*, 17–23, (In Chinese with English abstract).
97. Sun, X.; Xie, Z.; Yang, X.; Hu, Z. Effects of biochar application and water saving drip irrigation on phosphorus leaching in farmland fluvo-aquic soil. *J. Univ. Chin. Acad. Sci.* **2021**, *38*, 772–781, (In Chinese with English abstract). [CrossRef]
98. Luo, X.; Lv, H.; Kou, C. Effects of mineral nitrogen substitution by organic fertilizer nitrogen and water saving on nitrogen leaching in tomato and pepper greenhouse vegetable fields. *China Soils Fert.* **2021**, *2*, 96–101, (In Chinese with English abstract). [CrossRef]

99. Lei, H.; Li, G.; Ding, W.; Xu, C.; Wang, H.; Li, H. Modeling nitrogen transport and leaching process in a greenhouse vegetable filed. *Chin. J. Eco Agric.* **2021**, *29*, 38–52. [CrossRef]
100. Tang, Y.; Li, L.; Liu, P.; Bai, G. Effects of irrigation and fertilization on nutrient absorption and yield of cucumber and soil quality in greenhouse. *China Soils Fert.* **2018**, *1*, 77–82, (In Chinese with English abstract). [CrossRef]
101. Zhang, X.; Li, H.; Zhang, T.; Ma, S. Effects of different water and nitrogen levels on nitrogen use efficiency under drip irrigation. *J. Irrig. Drain.* **2017**, *37*, 45–50, (In Chinese with English abstract). [CrossRef]
102. Zhang, Z.; Zhao, W.; Li, J. Effects of drip irrigation frequency and nitrogen fertilizer on nitrate leaching and tomato growth. *J. China Inst. Water Res. Hydropower Res.* **2015**, *13*, 81–90, (In Chinese with English abstract). [CrossRef]
103. Yin, G.; Hu, K.; Li, P.; Liu, R. Nitrogen loss and use efficiency in greenhouse vegetable soil under different water and fertilizer managements. *J. Agro-Environ. Sci.* **2013**, *32*, 2403–2412, (In Chinese with English abstract). [CrossRef]
104. Zhai, Y.; Ma, K.; Jia, B.; Wei, X.; Yun, B.; Ma, J.; Zhang, H.; Ji, L.; Li, J. Effects of different precipitation years on soil nitrate distribution, leaching loss and nitrogen uptake and utilization under drip irrigation of maize. *Chin. J. Eco-Agric.* **2022**, *30*, 1–11, (In Chinese with English abstract). [CrossRef]
105. Li, J. Microirrigation in China: History, current situation and future. *Irrig. Drain.* **2020**, *69*, 88–96. [CrossRef]
106. Wang, Z.; Fan, B.; Guo, L. Soil salinization after long-term mulched drip irrigation poses a potential risk to agricultural sustainability. *Eur. J. Soil Sci.* **2019**, *70*, 20–24. [CrossRef]
107. Ning, S.; Zhou, B.; Shi, J.; Wang, Q. Soil water/salt balance and water productivity of typical irrigation schedules for cotton under film mulched drip irrigation in northern Xinjiang. *Agric. Water Manag.* **2021**, *245*, 106651. [CrossRef]
108. Fan, W.; Xuan, J.; Li, B.; Shi, J.; Liu, Y.; Sheng, J. The impact of long-term drip irrigation on spatiotemporal variation in salt in the proximity of soil surface in a cotton field. *J. Irrig. Drain.* **2020**, *39*, 83–89, (In Chinese with English abstract). [CrossRef]
109. Yang, Z.; Ma, Z.; Chen, Y. Effects of nitrogen and phosphorus transport on nutrient utilization and yield of maize under film drip irrigation. *Water Sav. Irrig.* **2019**, *4*, 1–6, 11, (In Chinese with English abstract).
110. Wu, K.; Xiao, R.; Zhang, Y.; Yu, H. Effect of drip irrigation under film on soil environment in Hexi Corridor irrigation area. *Agric. Sci.-technol. Inf.* **2020**, *6*, 14–15. (In Chinese)
111. Wu, J.; Tao, W.; Zhao, W.; Wang, Q. Impact of different irrigation amount of light saline water drip irrigation under mulch on water-salt transport and cotton growth. *J. Soil. Water Conserv.* **2015**, *29*, 272–276, 329, (In Chinese with English abstract). [CrossRef]
112. Ma, D.; Wang, Q.; Lai, J. Field experimental studies on the effects of water quality and drip rate on soil salt distribution in drip irrigation under film. *Trans. Chin. Soc. Agric. Eng.* **2005**, *21*, 42–46, (In Chinese with English abstract). [CrossRef]