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Review

A Review of Drip Irrigation's Effect on Water, Carbon Fluxes, and Crop Growth in Farmland

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Abstract: The substantial depletion of freshwater reserves in many pivotal agricultural regions, attributable to the dual pressures of global climate change and the excessive extraction of water resources, has sparked considerable apprehension regarding the sustainability of future food and water security. Drip irrigation, as an efficient and precise irrigation method, reduces water loss caused by deep percolation, soil evaporation, and runoff by controlling the irrigation dosage and frequency, thus improving the efficiency of water resource utilization. Studies have shown that compared with traditional irrigation methods, drip irrigation can significantly decrease water consumption, optimize the water–energy relationship by reducing soil evaporation, increase the leaf area index, and promote crop growth, thereby enhancing plant transpiration. Although more wet and dry soil cycles from drip irrigation may increase soil CO_2 emissions, it also enhances crop photosynthesis and improves crop net ecosystem productivity (NEP) by creating more favorable soil moisture conditions, indicating greater carbon sequestration potential. The advantages of drip irrigation, such as a short irrigation cycle, moderate soil moisture, and obvious dry and wet interfaces, can improve a crop's leaf area index and biomass accumulation, improve root dynamics, promote the distribution of photosynthetic products to the aboveground parts, and thus enhance crop yields. This study highlights the potential for the application of drip irrigation in arid regions where resource optimization is sought, providing strong technical support for the achievement of sustainable agricultural development. Future research needs to consider specific agricultural practices, soil types, and environmental conditions to further optimize the implementation and effectiveness of drip irrigation.

Keywords: drip irrigation; carbon sequestration; crop growth; sustainable agricultural development

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1. Introduction

Global climate change and the overexploitation of water resources have led to a significant decline in freshwater storage in many important agricultural areas, causing concerns about future food and water security [1,2]. Irrigation is the largest consumer of freshwater resources globally [3,4], accounting for roughly 70% of global freshwater consumption [5]. Irrigated areas account for 24% of croplands, and roughly 40% of global food production is from irrigated croplands [6]. As the population grows, many regions need to maintain high yields while reducing agricultural water use to ensure sustainable food and water supplies [7]. Although irrigation plays a key role in food production [8], water scarcity is emerging as a major constraint on the sustainable development of agriculture. Concurrently, rapid urbanization is exacerbating the competition for water resources between industrial and agricultural use. Therefore, it may be necessary to reduce the allocation of freshwater resources to agriculture to meet the freshwater demands of other areas of economic growth. In light of these challenges, developing efficient water-saving irrigation technologies and improving the water efficiency of crop production have become paramount objectives for contemporary agriculture [9]. Drip irrigation is considered to be one of the most water-efficient forms of irrigation to date. Drip irrigation is a localized water application technique. Its characteristic is the delivery of water under pressure through a drip irrigation pipeline system to lateral pipes, and then the water is emitted in a controlled manner as droplets through emitters, orifices, or drip tape installed on the lateral pipes. This method of irrigation uniformly and slowly drips water into the soil to meet the growth requirements of crops. Although many studies have explored the positive effects of drip irrigation on reducing irrigation water use and promoting yield growth, there are few studies on water carbon crop growth in drip-irrigated farmland. A comprehensive study of the effects of drip irrigation technology in the soil-crop system, the analysis of the impact of drip irrigation technology on farmland water carbon flux and crop growth, and the evaluation of the effect of drip irrigation technology on water saving and emission reduction is the scientific basis for large-scale promotion of drip irrigation technology in the future.

Since the beginning of the 21st century, the Chinese government has put forward policies to promote water conservation, vigorously develop water-saving agriculture, and promote water-saving irrigation as a revolutionary measure, which has become a major policy guarantee for water conservation in China. In the past two decades, the adoption area of water-saving irrigation has been steadily on the rise. By 2020, water-saving irrigation covered half of the total farmland irrigation area (75.69 million hectares) in China (Figure 1). Among various methods, drip irrigation is globally recognized as one of the most efficient precision irrigation methods, with a long and rich developmental history [10]. As early as the mid-19th century, Germany initiated experiments with clay pipes for both drainage and irrigation purposes. Entering the 20th century, a man first adopted a drip irrigation system. Shortly thereafter, in 1920, Charle pioneered a method of irrigation by drilling holes in ceramic pots, which is now recognized as the earliest form of drip irrigation technology [11]. In the same year, Germany achieved a technological milestone with the development of perforated tape irrigation, which facilitates water transport through pipes with water exiting through strategically placed holes. In 1934, Robey conducted research on canvas tube seepage irrigation, adding a new form of drip irrigation technology. With the advent of the plastics industry, plastic pipes began to be widely used in drip irrigation systems [12]. By the late 1950s, Israel had successfully developed long-path emitters, establishing drip irrigation as a significant method of irrigation in the country during the 1960s [13]. Since the 1970s, drip irrigation technology has developed rapidly worldwide, and by the 1990s, the technology began to be applied to the irrigation of field crops. China introduced drip irrigation technology from Mexico in 1974 and then combined it with mulch film covering technology to innovatively develop drip irrigation under film mulch technology and successfully conducted field tests. Since then, based on the imported drip irrigation equipment, Chinese domestic researchers have continuously transformed and innovated, gradually achieving the localization of drip irrigation equipment, making breakthrough progress, and laying the foundation for the application of drip irrigation technology in crops [14]. Since 2000, drip irrigation technology has begun to be widely promoted in the field and has achieved significant results, promoting the development and application of drip irrigation technology in China's large fields [15]. Today, China currently has the largest coverage area of drip irrigation systems in the world. In 2017, the coverage area of water-saving irrigation systems reached a total of 34,319 thousands of hectares [14]. Over time, drip irrigation technology has developed from local pilot demonstrations to large-scale promotion and application, and its coverage has expanded from the north to the arid northwest, the cold northeast, and the subtropical south.

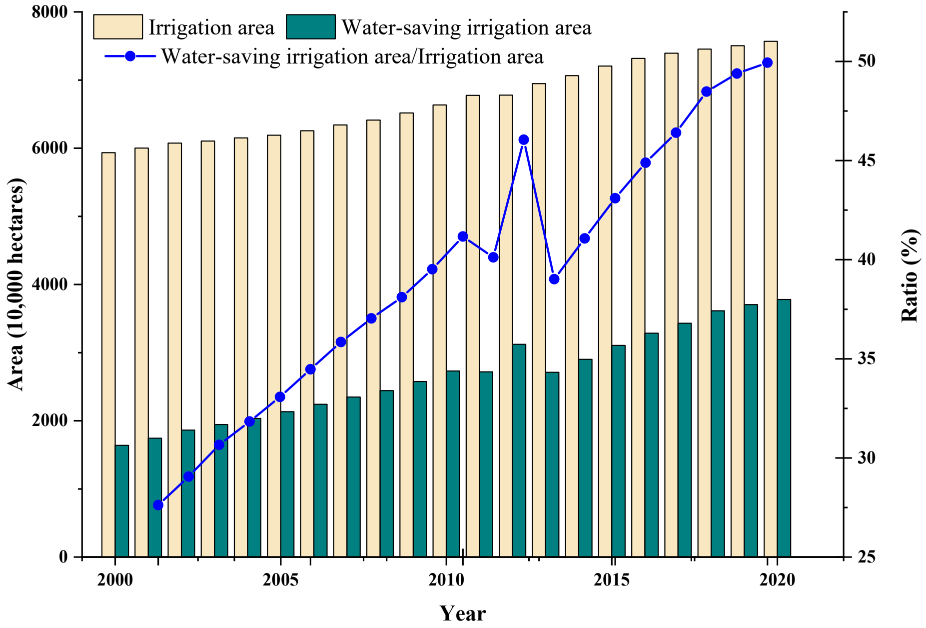

Figure 1. The growth of irrigated farmland area and water-saving irrigation area in China [16].

Traditional surface irrigation is a common irrigation method in Chinese irrigation agriculture which relies on natural terrain and artificial channels to transfer and distribute water. Its irrigation feature is to direct water from high to low fields using gravity. Due to the lack of effective water resource management, traditional surface irrigation often has a large amount of water waste and a low utilization rate of water resources. At the same time, due to the limitations of terrain and channels, the irrigation conditions of different fields may be greatly different, resulting in uneven irrigation and affecting the growth of crops. The traditional surface irrigation method has poor adaptability when dealing with the changeable agricultural demand and environmental change, and it is difficult to meet the development needs of modern agriculture. These irrigation methods mainly include (1) flood irrigation, which is one of the oldest methods of irrigation, where water is spread over the field in a thin layer, covering the soil surface. It is simple and inexpensive but can be inefficient, as a significant amount of water can be lost to evaporation and runoff. (2) Furrow irrigation sees water channeled into long, narrow trenches (furrows) between crop rows. The water slowly infiltrates the soil, providing moisture to the plants. It is more efficient than flood irrigation but still loses water to evaporation and requires careful management to prevent waterlogging. Finally, (3) border irrigation, also known as banded or furrow irrigation, is a method where water is applied to long, uniformly graded strips of land separated by earth bunds or dikes. Water is diverted from a channel to the upper end of the border, and it flows down the slope. The flow is stopped when the desired amount of water has been delivered, which may be before the water reaches the end of the border.

Compared with traditional irrigation systems, drip irrigation has the potential to conserve water resources, enhance crop quality, and increase crop yields, which are achieved through the use of controlled irrigation dosages and frequencies [17]. By reducing water loss due to deep percolation, soil evaporation, and runoff, drip irrigation improves the efficiency of water resource utilization. It can also reduce weed growth, regulate salinity and alkalinity issues, and optimize the use of fertilizers [18]. However, drip irrigation also has some limitations, with the main constraints being the high initial installation costs and the intensive maintenance requirements, such as clogging of emitters. Additionally, drip irrigation can limit the development of plant root systems, lead to the accumulation of salt near the root zone of plants, and decrease the soil's ability to absorb carbon dioxide [18]. Therefore, the aim of this study is to summarize the role of drip irrigation technology within the soil-crop system and to evaluate the water-saving and emission reduction effects of drip irrigation technology by analyzing its impact on agricultural field water carbon fluxes and crop growth. Additionally, this study will highlight the critical role that drip irrigation technology plays in promoting environmental sustainability, which is an aspect that should not be overlooked.

2. Methodology

In order to summarize the effects of drip irrigation on water flux, we searched the papers collected by Web of Science using the keywords "drip irrigation" and "water" or "evapotranspiration". Based on the collected data, this paper summarizes the research on water flux in drip irrigation. Similarly, for the study of carbon flux, our search keywords were "drip irrigation" and "carbon" or "it has to" or "respiration" or "GPP" or "RE" or "NEE". Our search keywords for crop growth were "drip irrigation" and "growth" or "biomass" or "yield". Since the development of drip irrigation technology accelerated significantly after 2000, the time range of the literature search was 2000–2024 to ensure the timeliness and relevance of the review.

3. Drip Irrigation and Water Balance in Farmland

In arid regions, irrigation serves as the primary means of replenishing soil moisture in farmlands. Different irrigation methods significantly influence the spatial distribution of soil water content [19]. Studies have shown that there are distinct differences in the spatial distribution of soil moisture between traditional flood irrigation and drip irrigation. Horizontally, soil moisture distribution under traditional flood irrigation exhibits a certain degree of uniformity [20]. However, under drip irrigation conditions, water slowly and uniformly infiltrates the soil of the crop root zone through emitters, creating a moist area with a high soil water content (SWC) within a 0–20 cm range on either side of the drip line. As the distance from the drip line increases, the soil water content gradually decreases, forming a relatively drier area in regions further away from the drip line [21]. Consequently, there is a clear division between moist and dry zones in drip-irrigated farmlands. Vertically, drip irrigation also presents significant differences in the vertical distribution of soil moisture compared with traditional flood irrigation. Drip irrigation technology can significantly enhance the SWC in the shallow (0–40 cm) and middle layers (40–60 cm) of farmland soil and reduce the fluctuation amplitude of the moisture content [21]. This implies that drip irrigation systems can provide a more stable and suitable moisture environment for the crop root system, which is beneficial for the growth and development of crops. Overall, drip irrigation technology, through refined water management, creates more favorable soil moisture conditions for the absorption and growth of crop roots. It not only improves the efficiency of soil moisture utilization but also contributes to increasing crop yields and water use efficiency. Therefore, for farmland management in arid regions, drip irrigation technology is an effective irrigation strategy which can achieve sustainable use of water resources while ensuring the moisture required for crop growth.

Drip irrigation can effectively reduce the waste of water resources caused by irrigation. Compared with traditional surface irrigation, drip irrigation can reduce field water consumption by 30–50%. For instance, the research conducted by Tiwari et al. demonstrated that drip irrigation can lead to a reduction of approximately 40% in water consumption for cabbage fields [22]. The application of drip irrigation to maize fields in Northeast China saved 37~52% of their water [23]. In Baggio, Mexico, drip irrigation could save about 40% of the irrigation water for barley and maize [24]. In the Indian state of Punjab, replacing gravity-fed irrigation with drip irrigation could reduce crop water demand by 32–39% [25]. The implementation of drip irrigation in upland rice had the potential to save water (50%) without compromising grain yields [26]. Drip irrigation technology significantly impacts regional ecohydrological processes by optimizing the water–energy relationship. Numerous studies have delved into the differences in evapotranspiration (ET) between drip and traditional irrigation methods. Because drip irrigation reduced water stress, the crop canopy was better developed, resulting in more radiation absorption by the canopy and a higher transpiration rate [27]. This is consistent with the results of Wang et al., which showed that the transpiration rate of maize increased after drip irrigation was applied [28]. Although the transpiration rate of crops increased under drip irrigation during the growing period, Qin et al. compared the total evapotranspiration of drip irrigation with that of border irrigation under sufficient irrigated conditions and found that drip irrigation could reduce the total evapotranspiration of maize by about 10% [29]. This is quite close to the findings of Han et al. in 2023, which showed that drip irrigation reduced ET by 11.2% compared with flood irrigation [30]. This was due to the shortening of the crop growing season length under drip irrigation. The simulated results are consistent with the observed results; that is, the cumulative water flux under flood irrigation is significantly greater than that under drip irrigation [31]. The water-saving effect of drip irrigation is smaller at the watershed scale than at the field scale, and Nouri et al. found that the combination of drip irrigation and mulching can reduce the evapotranspiration of crops by about 5%, which is less than 10% at field scale [32]. Compared with different irrigation methods, drip irrigation has great differences in saving irrigation water. For example, compared with flood irrigation, the irrigation amount of drip irrigation is reduced by 20~50%, while compared with spray irrigation, it is only reduced by 5~32% (Table 1). Similarly, the same irrigation method has great differences in its water-saving effect in different regions.

Table 1. Irrigation amount and evapotranspiration of crops under drip irrigation in different regions.

Site	Latitude and Longitude	Annual Rainfall (mm)	Crop	Irrigation Method	Control Group	Irrigation (Drip Irrigation) (mm)	Irrigation (Control) (mm)	ET (Drip Irrigation) (mm)	ET (Control) (mm)	Irrigation Amount Variation (%)	ET Variation (%)	Sources
Hebei, China	-	-	Winter wheat	Drip irrigation	Flood irrigation	148	188	260	300	−21.28	−13.55	[33]
Henan, China	35°08′ N, 113°45′ E		Wheat	Drip irrigation	Flood irrigation	210	300	299	341	−30.00	−12.32	[34]
Henan, China	35°08′ N, 113°45′ E		Wheat	Drip irrigation	Flood irrigation	180	240	310	319	−25.00	−2.82	[34]
Hebei, China	37.90° N, 115.70° E	555.0	Maize	Drip irrigation	Flood irrigation	146	205	400	429	−28.78	−6.76	[35]
Kafr El-Sheikh Governorate, Egypt	31°6′ N, 30°56′ E	-	Maize	Drip irrigation	Flood irrigation	3600	5300	-	-	−32.08	-	[36]
Kafr El-Sheikh Governorate, Egypt	31°6′ N, 30°56′ E	-	Cabbage	Drip irrigation	Flood irrigation	3900	5950	-	-	−34.45	-	[36]
Kafr El-Sheikh Governorate, Egypt	31°6′ N, 30°56′ E	-	Sunflower	Drip irrigation	Flood irrigation	2700	4000	-	-	−32.50	-	[36]
Kafr El-Sheikh Governorate, Egypt	31°6′ N, 30°56′ E	-	sugar beet	Drip irrigation	Flood irrigation	3500	4900	-	-	−28.57	-	[36]
Kafr El-Sheikh Governorate, Egypt	31°6′ N, 30°56′ E	-	Garlic	Drip irrigation	Flood irrigation	2200	4000	-	-	−45.00	-	[36]
Kafr El-Sheikh Governorate, Egypt	31°6′ N, 30°56′ E	-	Barley	Drip irrigation	Flood irrigation	1800	2800	-	-	−35.71	-	[36]
Kafr El-Sheikh Governorate, Egypt	31°6′ N, 30°56′ E	-	onion	Drip irrigation	Flood irrigation	2000	4300	-	-	−53.49	-	[36]
Maharashtra, India	19°57′ N, 74°42′ E	450.0	Cabbage	Drip irrigation	Flood irrigation	319	600	-	-	−46.83	-	[37]
Kayeshpur, India	23°5.4′ N, 83°5.4′ E	1600.0	Strawberry	Drip irrigation	Flood irrigation	160	233	169	247	−31.33	−31.78	[38]
Qinghai, China	36°22′ N, 96°27′ E	57.1	Barley	Drip irrigation	Border irrigation	573	584	474	501	−1.88	−5.39	[39]
Qinghai, China	36°22′ N, 96°27′ E	57.1	Barley	Drip irrigation	Border irrigation	534	554	432	480	−3.61	−10.00	[39]
Qinghai, China	36°22′ N, 96°27′ E	57.1	Barley	Drip irrigation	Border irrigation	404	453	276	361	−10.82	−23.55	[39]
Qinghai, China	36°22′ N, 96°27′ E	57.1	Barley	Drip irrigation	Border irrigation	361	405	241	281	−10.86	−14.23	[39]

Table 1. *Cont.*

Site	Latitude and Longitude	Annual Rainfall (mm)	Crop	Irrigation Method	Control Group	Irrigation (Drip Irrigation) (mm)	Irrigation (Control) (mm)	ET (Drip Irrigation) (mm)	ET (Control) (mm)	Irrigation Amount Variation (%)	ET Variation (%)	Sources
Bayannur of Inner Mongolia, China	40°46″ N, 107°24″ E	135.0	Maize	Drip irrigation	Border irrigation	340	525	332	553	−35.24	−39.89	[40]
Bayannur of Inner Mongolia, China	40°46″ N, 107°24″ E	135.0	Maize	Drip irrigation	Border irrigation	340	525	361	526	−35.24	−31.33	[40]
Bayannur of Inner Mongolia, China	40°46″ N, 107°24″ E	135.0	Maize	Drip irrigation	Border irrigation	340	525	421	533	−35.24	−21.09	[40]
Ludhiana	30°56′ N, 75°48′ E	600.0	Sunflower	Drip irrigation	Furrow irrigation	-	-	504	567	-	−11.11	[41]
Shandong, China	36°50′ N, 118°52′ E	550.0	Tomato	Drip irrigation	Furrow irrigation	364	535	185	199	−31.96	−7.04	[42]
Shandong, China	36°50′ N, 118°52′ E	550.0	Tomato	Drip irrigation	Furrow irrigation	296	581	234	234	−49.05	0.00	[42]
Shibin El-Kom, Egypt	30°30′ N, 31°18′ E	-	tomato	Drip irrigation	Furrow irrigation	-	-	314	600	-	−47.67	[43]
Henan, China	34°27′ N, 113°31′ E	542.0	Cucumber	Drip irrigation	Furrow irrigation	468	909	-	-	−48.58	-	[44]
Bayannur of Inner Mongolia, China	40°46″ N, 107°24″ E	135.0	Maize	Drip irrigation	Furrow irrigation	340	450	332	464	−24.44	−28.36	[40]
Bayannur of Inner Mongolia, China	40°46″ N, 107°24″ E	135.0	Maize	Drip irrigation	Furrow irrigation	340	450	361	437	−24.44	−17.35	[40]
Bayannur of Inner Mongolia, China	40°46″ N, 107°24″ E	135.0	Maize	Drip irrigation	Furrow irrigation	340	450	421	439	−24.44	−4.19	[40]
Southeast Spain	39°03′ N, 2°05′ W,	314.0	Maize	drip irrigation	Sprinkler irrigation	703	743	510	590	−5.38	−13.56	[45]
Southeast Spain	39°03′ N, 2°05′ W,	314.0	Maize	drip irrigation	Sprinkler irrigation	642	722	480	620	−11.08	−22.58	[45]
Henan, China	35°08′ N, 113°45′ E	-	Wheat	Drip irrigation	Sprinkler irrigation	210	240	299	302	−12.50	−0.99	[34]
Henan, China	35°08′ N, 113°45′ E	-	Wheat	Drip irrigation	Sprinkler irrigation	180	210	310	307	−14.29	0.98	[34]
Maharashtra, India		-	Cabbage	Drip irrigation	Sprinkler irrigation	319	471	-	-	−32.27	-	[37]
Heilongjiang, China	45°22′ N, 125°45′ E	-	Maize	Drip irrigation	Rainfed	-	-	519	521	-	−0.38	[46]

Under drip irrigation, soil evaporation (E) and plant transpiration (T) decreased by 19.5% and 1.5%, respectively, indicating that drip irrigation primarily conserves water by significantly reducing soil evaporation [46,47]. This is closely related to the characteristics of irrigation methods. Under traditional irrigation practices, a larger amount of water is applied at once, resulting in extensive wetted areas where irrigation water easily penetrates the exposed soil surface, which is the primary site for soil evaporation. In contrast, drip irrigation directly delivers water to the crop root zone, reducing the opportunity for water to penetrate the exposed soil surface and thereby lowering the soil evaporation rate. When the irrigation method shifts to drip irrigation, it not only effectively reduces soil evaporation but also promotes crop growth. By accelerating crop growth, drip irrigation enables crops to achieve a higher leaf area index (LAI), which in turn promotes an increase in the rate of plant transpiration [28]. An increase in the LAI implies an increase in the coverage of the ground canopy, which can also be attributed to the reduction in evaporation. Thus, drip irrigation alters the ratio of soil evaporation to total evapotranspiration. Under traditional irrigation, the E/ET ratio typically ranges from 30% to 60% [48–50], but with drip irrigation, this ratio can be reduced to 18–23% [51]. Overall, drip irrigation reduces the seasonal average E/ET ratio and increases the seasonal average T/ET ratio [52]. Thus, when the irrigation method shifts to drip irrigation, it not only effectively reduces soil evaporation but also promotes crop growth. Consequently, drip irrigation technology not only excels in water conservation but also plays a positive role in improving crop growth quality and promoting ecohydrological processes. Through these integrated benefits, drip irrigation provides an effective irrigation management strategy for sustainable agricultural development.

4. Drip Irrigation and Carbon Fluxes in Farmland

Agricultural ecosystems, as both carbon sources and carbon sinks, have become a hot spot. The photosynthetic uptake of CO_2 by crops endows agricultural ecosystems with a robust carbon sequestration effect [53]. Concurrently, soil respiration and plant autotrophic respiration directly lead to carbon emissions [54]. Thus, agroecosystems are endowed with the dual characteristics of carbon uptake and carbon emission. Photosynthesis is highly sensitive to fluctuations in soil moisture through stomatal and biochemical reactions, which significantly impacts crop growth [55]. Compared with traditional flood irrigation, drip-irrigated crops under sufficient irrigation conditions exhibit markedly increased photosynthetic rates and stomatal conductance [56]. The net photosynthesis is higher (about 15%) in drip irrigation in comparison with flood irrigation [34]. Drip irrigation has an effect on the physiological characteristics of spring maize, and the photosynthetic area of the lower leaf and the photosynthetic capacity of the upper middle leaf are increased [57]. Additionally, the maximum photosynthetic rate and maximum carboxylation rate of crops are significantly enhanced by 21.1% and 10.7%, respectively [58]. Due to the amplified carboxylation efficiency under drip irrigation conditions, the rate of photosynthesis in leaves is further increased, thereby enhancing canopy photosynthesis by 42.1–48.1% [27]. Increasing the frequency of drip irrigation fertilization could prolong the time of high-level photosynthesis [59], which is beneficial for increasing the accumulation of photosynthetic products. In addition, drip irrigation increases the leaf area index of crops, as it determines the photosynthetic area [60], which may also explain why drip irrigation can fix more CO_2 than flood irrigation. The promotion effect of drip irrigation on the photosynthetic rate is more prominent in arid farmland. If the frequency of drip irrigation is low, then it is easy to cause a crop water deficit, which has an adverse effect on the photosynthetic rate [61]. Analyzed through the carbon sequestration potential of farmland, drip-irrigated fields have a higher net ecosystem production (NEP) compared with traditional flood irrigation, indicating greater carbon sequestration potential [61]. This is predominantly achieved by diminishing soil heterotrophic respiration and concurrently enhancing the net primary production (NPP) [62,63]. In summary, the environment created by drip irrigation is more conducive to the absorption of atmospheric CO_2 when it is conducive to the growth and development of crops.

Irrigation is a significant factor influencing CO_2 emissions from farmlands [64]. Drip irrigation, when compared with traditional flood irrigation, uses less water per application and maintains a more regular interval between irrigations, leading to a slower infiltration rate. This results in less disturbance of the soil, which can contribute to increased CO_2 emissions due to reduced disruption of the soil structure and microbial activity. The frequent alternation between wet and dry conditions in drip-irrigated soils can also enhance soil carbon mineralization, microbial activity, and respiration, thereby promoting CO_2 emissions [65]. Research on maize fields in the arid northwest region of China confirmed these effects [61]. Compared with flood irrigation, the soil respiration rate in drip irrigation fields was higher at both daytime and nighttime hours, indicating that the soil carbon emissions in the drip irrigation fields were higher [61]. The observations by Andrews et al., however, were quite the opposite, indicating that drip irrigation can reduce soil CO_2 emissions [66]. The lower emissions observed here were primarily driven by the application of nutrients and water, which are dependent on the crops [67]. Irrigation and fertilization are influenced by management decisions, and the differences in field management strategies can have a significant impact on emissions [68]. For example, the frequency of irrigation also affects the soil CO_2 emissions. Research by Wei in 2021 highlighted that when drip irrigation is applied more frequently, leading to more stable soil moisture conditions than flood irrigation, there are fewer wet and dry cycles [69]. This can effectively reduce the amount of soil CO_2 emissions [69]. Additionally, irrigation methods significantly affect soil carbon leaching. Under drip irrigation, the dissolved organic carbon (DOC) content of soil is higher than under flood irrigation, as the dissolution rate of soluble organic and inorganic carbon increases with the volume of water applied, leading to greater leaching losses. This is primarily because irrigation methods greatly influence the soil solute transport process [70]. However, in the case of excessive water in and out, long-term high frequency irrigation is the main factor affecting carbon leaching [71]. Therefore, the process of the influence of drip irrigation on farmland carbon flux is limited by regional and climatic conditions, and often shows different change characteristics (Table 2).

Table 2. Carbon flux of crops under drip irrigation in different regions.

Site	Latitude and Longitude	Annual Rainfall (mm)	Crop	Irrigation Method	Control Group	Pn Variation	NPP	NEE	Rs	DOC	SOC	Sources
Hebei, China	-	-	Winter Wheat	Drip irrigation	Flood irrigation	15%	-	-	-	-	-	[33]
Liaoning, China	-	-	Tomato	Drip irrigation	Furrow irrigation	-	-	-	-	−7%	-	[72]
Southern Arizona, USA	-	230		Drip irrigation	Flood irrigation	-	-	-	-	-	+	[73]
Inner Mongolia, China	41°05′ N, 108°03′ E		Maize	Drip irrigation	Flood irrigation	-	+	+	+	-	-	[61]
Bhubaneswar	20° N, 85°38′ E		Capsicum	Drip irrigation	Flood irrigation	24%	-	-	-	-	-	[55]
HID, China	41°09′ N, 107°39′ E	180	Maize	Drip irrigation	Border irrigation	-	-	-	17%	-	-	[74]
Heilongjiang, China	45°22′ N, 125°45′ E	600	Maize	Drip irrigation	Rainfed	13%	-	-	-	-	-	[56]
Heilongjiang, China	45°22′ N, 125°45′ E	600	Maize	Drip irrigation	Rainfed	42%	-	-	-	-	-	[56]
Imperial County, CA	-	-	Sudangrass	Drip irrigation	Flood irrigation	-	-	-	1%	-	-	[66]
Imperial County, CA	-	-	Alfalfa	Drip irrigation	Flood irrigation	-	-	-	−50%	-	-	[66]
Xinjiang, China	44°17′ N, 85°49′ E	211	Cotton	Drip irrigation	Flood irrigation	-	-	-	5%	-	0.40%	[75]
Xinjiang, China	44°17′ N, 85°49′ E	211	Cotton	Drip irrigation	Flood irrigation	-	-	-	-	-	−2%	[75]
Hebei, China	37°41′ N, 116°38′ E	-	Maize	Drip irrigation	Flood irrigation	-	-	-	10%	-	-	[76]
Hebei, China	37°41′ N, 116°38′ E	-	Maize	Drip irrigatHion	Rainfed	-	-	-	25%	-	-	[76]
Bahia, Brazil	12°40′ S, 39°06′ W	1143	Banana	Drip irrigation	Sprinkler Irrigation	-	-	-	-	-	−21%	[77]
Xinjing, China	87°56′ E, 44°17′ N	-	Cotton	Drip irrigation	Flood irrigation	-	65%	-	34%	-	-	[63]

Notes: - indicates that relevant information is not mentioned in the text. Pn is the net photosunthesis, NPP is the net primary productivity, NEE is the net ecosystem exchange, Rs is the soil respiration, DOC is the dissolved organic carbon, and SOC is the soil organic carbon.

5. Effect of Drip Irrigation on Crop Growth

Water and nutrient management, in addition to the climate and soil characteristics, are critical factors which influence crop growth and the physiological status [78,79]. Drip irrigation, compared with traditional surface irrigation methods such as furrow and flood irrigation, offers several advantages which are beneficial for crop growth, including shorter irrigation cycles [80], moderate soil moisture levels, and distinct wet and dry interfaces [81], which are advantageous for the growth of crops like maize. By employing a scientifically managed supply of water and nutrients, drip irrigation can not only improve a crop's leaf area index (LAI) and photosynthetic efficiency but also promote the accumulation and effective transfer of biomass [82], thus accelerating the growth and development of crops [83]. In recent years, much research has been conducted on the effects of drip irrigation on crop growth. For instance, Wang et al. confirmed that drip irrigation, by increasing the soil's surface temperature, shortens the growth period of maize [51]. Long-term observational experiments by Liu et al. demonstrated that under drip irrigation, maize exhibited higher canopy height, LAI, and SPAD values compared with furrow irrigation. Additionally, the dry matter transport rate, efficiency, and contribution to grain were significantly improved by 27.44%, 13.97%, and 7.85%, respectively, over furrow irrigation, leading to a 14.39% increase in yield [84]. Different irrigation methods also have varying impacts on the physiological characteristics of crops. Throughout the entire growth period, drip-irrigated wheat showed a significantly taller plant height, greater leaf area, and more tillers compared with traditional irrigation [85]. The experimental results on an oasis cotton field confirmed that the plant height, leaf area index, and stem diameter increased by 30–65%, 24–145%, and 25–30%, respectively, under drip irrigation [86].

The integrated water and nutrient management of drip systems increases the availability of nitrogen and water in the topsoil layer, which is a significant reason for the increased biomass and yields with drip irrigation [87]. Zhang et al. reported that mulched drip irrigation notably boosted the biomass of maize, with a significant 6.90% increase at maturity in contrast to conventional irrigation practices [88]. Furthermore, Li et al. discovered that drip irrigation enhanced the dry matter accumulation during the growth period, which translated to a 4.9~11.1% increase in biomass at maturity [89]. Drip irrigation not only alters the accumulation of crop biomass but also influences the distribution of photosynthetic products. By changing the distribution characteristics of soil water and nutrients, drip irrigation also impacts the physiological and ecological traits of the root system. Compared with traditional irrigation, wheat irrigated with drip methods had a lower total root weight and higher aboveground biomass, with a significantly reduced root-to-shoot ratio [90]. Drip irrigation under film mulch, with its higher soil moisture content, reduced the root-to-shoot ratio, favoring the allocation of biomass to reproductive organs [90].

Drip irrigation has shown incomparable advantages in increasing crop yields. Sandhu et al. observed that under drip irrigation, the grain yields of maize and wheat increased by 13.7% and 23.1% when compared with furrow irrigation, respectively [91]. Xu et al. noted that the implementation of drip irrigation techniques resulted in a 14% increase in grain yield and a remarkable water savings value of 40% compared with furrow irrigation [92]. Liu et al. also found that drip irrigation not only improved cucumber yields by 4.3% but also increased economic benefits by 3.1% in comparison with furrow irrigation [46]. For a single crop (for example, maize), the influence of drip irrigation on the yield varies greatly in different regions (Table 3). This is mainly related to the local climate conditions, and drip irrigation is a promising irrigation technology in areas with limited water resources. In addition to this, Assefa et al. identified that the integration of drip irrigation technology with conservation tillage practices holds significant potential for bolstering crop yields while simultaneously enhancing the ecological environment [93]. These findings underscore the multifaceted benefits of drip irrigation in enhancing crop growth, yields, and water use efficiency, as well as its potential for improving soil and root system dynamics. The adoption of drip irrigation can lead to more sustainable yield increases, particularly in regions facing water scarcity or seeking to optimize resource use.

Table 3. Yield changes of maize under drip irrigation in different regions.

Site	Latitude and Longitude	Annual Rainfall (mm)	Soil Type	Crop	Irrigation Method	Control Group	Yield (t ha^{-1}) (Drip Irrigation)	Yield (t ha^{-1}) (Control)	Amplitude of Variation	Sources
Henan province, China	38°1′ N, 115°5′ E	555	Sandy loam	Summer maize	Drip irrigation	Flood irrigation	11.32	8.84	28%	[93]
Hebei province, China	37°41′ N, 116°38′ E	600	Silt loam	Summer maize	Drip irrigation	Flood irrigation	11.25	10.12	11%	[77]
Henan province, China	35°18′ N, 113°54′ E,	555	Sandy loam	Summer maize	Drip irrigation	Flood irrigation	8.69	7.50	16%	[94]
Hebie province, China	38°1′ N, 115°5′ E	519	Sandy Sandy loam	Summer maize	Drip irrigation	Flood irrigation	8.03	7.22	11%	[95]
Henan province, China	35°11′30″ N, 113°48′ E	-	Sandy loam	Summer maize	Drip irrigation	Flood irrigation	8.40	7.48	12%	[96]
Henan province, China	35°11′30″ N, 113°48′ E	573	Sandy loam	Summer maize	Drip irrigation	Flood irrigation	9.00	7.88	14%	[97]

Table 3. *Cont.*

Site	Latitude and Longitude	Annual Rainfall (mm)	Soil Type	Crop	Irrigation Method	Control Group	Yield (t ha^{-1}) (Drip Irrigation)	Yield (t ha^{-1}) (Control)	Amplitude of Variation	Sources
Henan province, China	34°47′ N, 113°38′ E	480	Sandy loam	Spring maize	Drip irrigation	Flood irrigation	22.45	20.43	10%	[60]
Shaanxi Province, China	34°17′ N, 108°4′ E	560	Silty clay loam	Summer maize	Drip irrigation	Flood irrigation	11.05	8.45	31%	[98]
Xinjiang, China	80°14′ E, 41°16′ N	42.4–94.4	Loam	Summer maize	Drip irrigation	Flood irrigation	12.63	11.50	10%	[99]
Egypt	31°02′ N,30°28′ E	-	Sandy	-	Drip irrigation	Flood irrigation	7.98	7.49	7%	[100]
Inner Mongolia, China	40°46′ N, 107°24′ E	105	Silty loam	Spring maize	Drip irrigation	Flood irrigation	16.06	14.25	13%	[70]
Jilin province, China	45°33′ N, 122°78′ E	419.7	Clay	Spring maize	Drip irrigation	Furrow irrigation	12.90	9.39	37%	[101]
Bayannur of Inner Mongolia, China	40°46″ N, 107°24″ E	135	Sandy loam	Spring maize	Drip irrigation	Furrow irrigation	16.00	13.00	23%	[41]
Faisalabad, Pakistan	31.25° N, 73.09° E	-	Clay loam	-	Drip irrigation	Furrow irrigation	10.02	4.58	119%	[102]
Marvdasht, Iran	29°47′ N, 52°42′ E	340	Clay loam	-	Subsurface drip irrigation	Furrow irrigation	11.91	10.02	19%	[103]
					Drip irrigation	Furrow irrigation	11.49	10.02	15%	
Coimbatore, India	11°8′ N, 77°8′ E	648	Sandy Clay	Summer maize	Drip irrigation	Furrow irrigation	7.57	5.31	43%	[104]
Guanajuato, Mexico	20°45 ′ N, 101°20′ W	700	-	-	Drip irrigation	Furrow irrigation	13.15	12.45	6%	[25]
Colorado State, USA	38°2′23″ N, 103°41′ 43″ W	-	Clay loam	-	Subsurface drip irrigation	Furrow irrigation	13.20	12.70	4%	[105]
Van, Turkey	38.576° N, 43.29° E	393.8	Sandy clay loam	-	Drip irrigation	Furrow irrigation	13.92	12.71	10%	[106]
Southern Mozambique	25°19′13″ S; 32°15′53″ E,	580	Sandy laom	-	Drip irrigation	Furrow irrigation	5.81	5.50	6%	[107]
Ludhiana, India	30°54′ N; 75°48′ E	-	Sandy loam	-	Drip irrigation	Furrow irrigation	8.00	6.62	21%	[108]
Nebraska, USA	44.6° N, 98.1° W;	680	Silt loam	-	Subsurface drip irrigation	Furrow irrigation	16.25	14.45	12%	[109]
Ladhowal, India	30.99° N, 75.44° E	680	Sandy loam	Summer maize	Drip irrigation	Furrow irrigation	5.18	4.63	12%	[90]
Bayannur of Inner Mongolia, China	40°46″ N, 107°24″ E	135	Sandy loam	Spring maize	Drip irrigation	Border irrigation	16.00	13.20	21%	[41]
Inner Mongolia, China	41°09′ N, 107°39′ E	160	Loam	Spring maize	Drip irrigation	Border irrigation	14.25	13.70	4%	[110]
Inner Mongolia, China	40°43 ′ N, 107°13′ E	135	Silty loam	Spring maize	Fully mulched drip irrigation	Border irrigation	14.41	10.28	40%	[111]
Inner Mongolia, China	40°43 ′ N, 107°13 ′ E	135	Silty loam	Spring maize	Partially mulched drip irrigation	Border irrigation	11.36	10.28	11%	[111]
León, Spain	5°31′18″ W, 42°19′9″ N,	-	Sandy loam	-	Drip irrigation	Sprinkler irrigation	17.68	17.01	4%	[112]
Heilongjiang province, China	45°22′ N, 125°45′ E	400–650	Silty loam	Spring maize	Mulched drip irrigation	Rain-fed	12.48	10.16	23%	[58]
					Non-mulched drip irrigation	Rain-fed	11.66	10.16	15%	
Jilin province, China	43°21′ N, 124°05′ E	540	Loam sandy	Spring maize	Drip irrigation	Rain-fed	13.45	11.34	19%	[113]

Table 3. *Cont.*

Site	Latitude and Longitude	Annual Rainfall (mm)	Soil Type	Crop	Irrigation Method	Control Group	Yield (t ha^{-1}) (Drip Irrigation)	Yield (t ha^{-1}) (Control)	Amplitude of Variation	Sources
Heilongjiang province, China	45°22′ N, 125°45′ E	400–650	-	Spring maize	Mulched drip irrigation	Rain-fed	11.50	9.45	22%	[57]
					Non-mulched drip irrigation	Rain-fed	11.00	9.45	16%	
Shaanxi Province, China	34°17′ N, 108°4′ E	560	Silty clay loam	Summer maize	Drip irrigation	Rain-fed	11.10	10.20	9%	[114]

Notes: - indicates that relevant information is not mentioned in the text. Rain-fed is clarified to denote agricultural systems which rely on natural precipitation without any supplementary irrigation. The potential disadvantages of drip irrigation systems.

Through a review of the literature, we have summarized the impact of drip irrigation on the water, carbon, and yield values of farmland ecosystems (Figure 2). Overall, there is a consistent conclusion for the suppression effect of drip irrigation on soil evaporation, but there are different conclusions in the research for crop transpiration. Although many studies have pointed out that drip irrigation increases the soil moisture and promotes stomatal opening, thereby enhancing crop transpiration, it is unquestionable that drip irrigation reduces evapotranspiration from the perspective of the entire farmland. However, there is still much uncertainty in the research on carbon fluxes. Drip irrigation can promote the photosynthetic rate of crops, but soil respiration is affected by the frequency and amount of irrigation, and there is a large difference between different regions. There is also a consensus among researchers that drip irrigation is beneficial to the accumulation of biomass, thereby increasing crop yields.

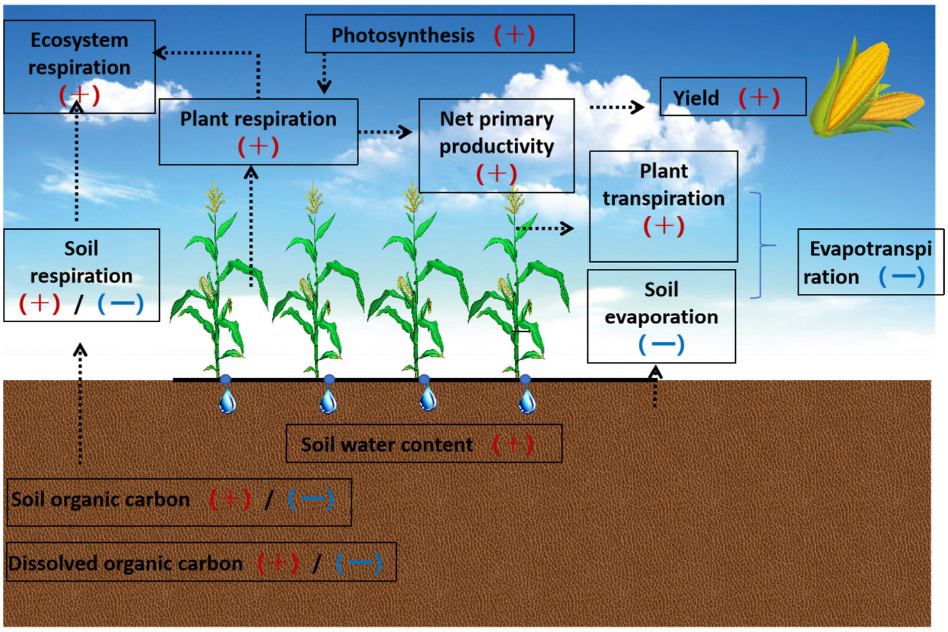

Figure 2. The effects of drip irrigation on water, carbon, and yield. Note: + means that drip irrigation has a promoting effect on this variable, and − means that it has an inhibiting effect.

Although many studies have confirmed the advantages of drip irrigation in saving water and increasing production, many problems have also appeared in the actual application process on farmland. (1) Clogging: one of the main problems with drip irrigation systems is the clogging problem of the irrigator, which can be caused by physical factors (such as sediment), biological factors (such as microorganisms), or chemical factors (such as chemical condensate) [115]. (2) Salt accumulation: when drip irrigation is performed on soil with a high salt content or with saline water drip irrigation, salt may accumulate at the edges of wet areas, leading to the risk of salt damage to crops [116]. (3) Limiting root development: since drip irrigation only moistens part of the soil, the root system of the crop may be concentrated in the wet area, which may limit the full development of the root system [117]. (4) High set-up costs: the initial set-up costs of a drip irrigation system are relatively high, including components such as drip belts, drip pipes, hoses, flexible PVC pipes, and timers, as well as the time and skilled labor required for installation [118]. (5) Maintenance requires more attention: drip irrigation systems require constant monitoring and maintenance to ensure an even distribution of water and prevent clogging, which may require regular filter changes and inspection of the filtration system. (6) Difficult rotations: moving and reinstalling drip irrigation systems during rotations can require additional labor and costs [119]. (7) External problems: equipment in drip irrigation systems can be affected by environmental factors such as ultraviolet light and heat, resulting in deterioration of the plumbing system while also being vulnerable to damage from human or animal intervention. (8) Finally, the application of drip irrigation technology improves the efficiency of irrigation water, but field-scale water saving does not necessarily translate into watershed scale water saving. This is due to the fact that "lost" water (e.g., runoff) which was previously not consumed at the field scale is often recycled and reused at the watershed scale. There are even data to support that the increased efficiency of irrigation water has increased the amount of groundwater extracted [120]. With the improvement in irrigation efficiency, farmers may tend to plant more water-intensive but economically valuable crops, which will lead to higher water consumption per unit area. At the same time, a government's economic subsidies for farmers who use drip irrigation technology will lead to an increase in the irrigated area, which has been proven in New Mexico [121]. The agricultural water saved through drip irrigation technology is also redistributed to other water users, suppressing the recovery of freshwater resources [122]. All of this can lead to a reduction in the flow returning to aquifers and spatially and temporally offset the negative impacts of apparent local water savings on regional water availability [123,124].

In addition, when the irrigation method is changed from traditional surface irrigation to drip irrigation, energy consumption is also a link which cannot be ignored. Compared with traditional irrigation, drip irrigation requires a certain amount of working pressure to deliver water to the roots of the crop, and thus the same amount of irrigation water inevitably leads to an increase in energy consumption [125]. However, considering the total amount of irrigation water, drip irrigation improves the efficiency of irrigation water utilization, thus reducing the total amount of irrigation water. Therefore, in areas which rely on groundwater for irrigation, the use of drip irrigation can reduce energy consumption in the process of pumping water [126].

6. Conclusions and Future Perspectives

This study explored the role of drip irrigation technology within the soil-crop system and evaluated its water-saving and emission reduction effects by analyzing its impact on agricultural field water carbon fluxes and crop growth. Firstly, this study provides empirical evidence of the impact of drip irrigation technology on water balance. The results show that drip irrigation technology, through refined water management, provides a more stable and suitable moisture environment for the crop root system, which not only improves the efficiency of soil moisture utilization but also helps to reduce soil evaporation. Secondly, this study analyzed the impact of drip irrigation technology on carbon fluxes in farmland. The characteristics of drip irrigation technology caused frequent dry and wet soil alternation, which promoted soil carbon dioxide emission but, at the same time, enhanced the carbon sequestration capacity of farmland by improving the photosynthetic rate and stomatal conductance of crops. Thirdly, a wealth of research indicates that drip irrigation contributes to promoting crop growth. Drip irrigation technology, through scientific management of the water and nutrient supplies, can not only improve a crop's leaf area index and photosynthetic efficiency but also promote the accumulation and effective transfer of biomass, thus accelerating the growth and development of crops. Drip irrigation can increase a crop's biomass and yield and improve soil and root system dynamics, thereby enhancing crop growth and yields.

Drip irrigation technology, as an effective water-saving irrigation management strategy, is of great significance for sustainable agricultural development. Drip irrigation plays a pivotal role in advancing several of the United Nations' Sustainable Development Goals (SDGs), which are a universal call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030. It not only excels in water conservation but also plays an active role in improving the quality of crop growth and promoting ecohydrological processes. Through these integrated benefits, drip irrigation technology provides strong support for sustainable agricultural practices in arid regions and areas seeking to optimize resource utilization. Future research should consider specific agricultural practices, soil types, and environmental conditions to further optimize the implementation and benefits of drip irrigation technology.

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