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Meta-Analysis of the Effect of Subsurface Irrigation on Crop Yield and Water Productivity

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Abstract: Problems such as population growth and climate change have led to a reduction in the use of water for irrigated agriculture, constraining the growth of crops. Subsurface irrigation, as a widely used and efficient water-saving irrigation technology, varies in its effect on increasing yields and saving water under different environmental, management, and other conditions. To investigate the effects of subsurface irrigation on yield, water productivity (WP), and irrigation water productivity (IWP) of three typical crops (wheat, maize, and cotton), this paper conducted a meta-analysis of 528 pairs of studies from 64 papers worldwide to quantify the response of crop yield, WP, and IWP to subsurface irrigation. Overall, the yield, WP and IWP increased by 5.96%, 21.62%, and 27.72%, respectively, with subsurface irrigation compared with surface irrigation. Compared with other conditions, the greatest rate of change was observed at around 200–500 m above sea level, 10–15 °C average annual temperature, 1.45–1.55 g/cm^3 soil bulk density, alkaline soil, and when the crops were planted with equal row spacing. Meanwhile, the amount of irrigation water, as well as the subsurface pipeline arrangement and burial depth, had significant effects on crop yield, WP, and IWP. The maximum increase in crop yield, WP, and IWP was favored when the irrigation volume of the subsurface irrigation was reduced by 50–100% compared with surface irrigation or when both had the same volume of irrigation but a mild water deficit. In addition, the yield, WP, and IWP were also affected by fertilization factors. The recommended fertilizer application rates were ≤90 kg P ha^{-1} (phosphorus) and <150 kg N ha^{-1} (nitrogen). Compared with surface irrigation, subsurface irrigation showed the greatest yield increase when fertilizer was applied in a one-time application, and the WP and IWP increased significantly when the number of fertilizer applications was <3.

Keywords: subsurface irrigation; yield; water productivity; irrigation water productivity

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1. Introduction

On about 20% of the global farmland area, irrigated agriculture contributes about 40% of crop production [1–3] and is the largest water-using sector globally [4]. In response to the increased demand for agricultural production due to population growth and socio-economic development [5], as well as land degradation and reduced crop yields due to climate change [6,7], the irrigated area has continued to expand globally. In the last 100 years or so, the global irrigated area has increased from 50 million ha to 300 million ha, a nearly sixfold increase [8,9]. The expansion of irrigated areas has led to a surge in irrigation water use, which in some regions has even exceeded their resource-carrying capacity. In parts of Asia and Africa, over-abstraction of irrigation water has caused problems such as stream and groundwater depletion, soil degradation, mineralization of organic matter, and reduction in biodiversity [3]. In addition, with the occurrence of climate extremes, the problem of water scarcity is exacerbated by the reduced availability of water for agricultural irrigation and elevated evapotranspiration from agricultural lands [10]. Therefore, there is an urgent need to select suitable irrigation technologies to increase crop yields and improve water productivity.

Currently, more than 90% of the total irrigated area worldwide is irrigated using conventional surface irrigation [11]. However, this irrigation method has high soil evaporation and low irrigation efficiency, which are not conducive to crop root uptake. Subsurface irrigation is a water-saving irrigation technique that delivers water directly to the root zone of crops in the soil through a network of percolation pipes or pipe pores buried below the ground, using soil capillary action to provide water for crop growth [12,13]. Many scholars have conducted studies on crop growth under different subsurface irrigation methods, including subsurface drip irrigation [14], infiltration irrigation [15], micro-irrigation [16], water storage pit irrigation [17], trace irrigation [18], and vertical line source irrigation [19]. The results showed that subsurface irrigation can effectively reduce soil evaporation and surrounding weed growth [20], decrease deep seepage [21], improve root activity [22], induce deep root penetration [23], and thus improve water productivity. However, the effect of subsurface irrigation on crop yield is still controversial, and the extent of the effect varies with soil texture, field management practices, climatic conditions, and crop type. It has been shown that subsurface drip irrigation can improve both crop yield and water productivity compared with surface irrigation, but the optimum depth of pipe burial varies between crops [24,25]. Wang et al. [26] found that the extent of yield increase by subsurface drip irrigation is related to the degree of water stress through continuous field trials across many years, with greater water stress resulting in a more significant yield increase in subsurface drip irrigation, while without water stress, subsurface drip irrigation might cause yield reduction. Umair et al. [27] used an evapotranspiration meter and the water balance principle to irrigate winter wheat and found that the water productivity (WP) and irrigation water productivity (IWP) of subsurface drip irrigation are higher than surface irrigation, while the yield is higher than surface drip irrigation but lower than diffuse irrigation. Ardenti et al. [28] found that subsurface drip irrigation increases maize yield and reduces NO_2 emissions compared with sprinkler irrigation and that a 70 cm drip tape spacing is optimal.

With the increasing attention paid to subsurface irrigation technology by scholars at home and abroad in recent years, various irrigation methods based on the theory of subsurface irrigation have emerged, but there has not yet been a comprehensive evaluation of the effects of subsurface irrigation. In addition, previous studies on the effects of subsurface irrigation on yield and water productivity have mostly focused on fixed locations and a single subsurface irrigation method. However, different experimental sites and irrigation methods may lead to different results due to differences in climate and soil properties, and it is not possible to accurately evaluate the combined effects of subsurface irrigation at a macroscopic scale.

Meta-analysis provides a comprehensive statistical approach that can integrate the results of several independent studies to reveal effect size and influencing factors [29–31]. Therefore, to explore the advantages of subsurface irrigation in saving water and increasing yield, this study used meta-analysis to (1) assess the effects of subsurface irrigation on crop yield, WP, and IWP; and (2) analyze how these effects vary by environment, soil properties, field management, irrigation, and fertilization factors.

2. Materials and Methods

2.1. Data Search and Collection

The English data for this study were obtained from Web of Science (http://apps.webofknowledge.com/) and Science Direct (https://www.sciencedirect.com/), while the Chinese data were obtained from China National Knowledge Infrastructure (http://www.cnki.net/) and Wanfang Data Knowledge Service Platform (https://www.wanfangdata.com.cn/) (accessed on August–October 2022). The keywords "subsurface irrigation" and various subsurface irrigation methods, such as "subsurface drip irrigation", "infiltration irrigation", "trace irrigation", "micro-irrigation", and "wheat", "maize", "cotton", "water productivity" and "yield" are used as search terms in English and Chinese. The selection of literature needed to meet the following criteria: (1) appropriate surface irrigation as a control group; (2) sample size ≥2; (3) the experiment was conducted in the field (open or sheltered); (4) the yield and WP and/or IWP were detailed for the experimental observations. Meanwhile, literature with overlapping results in terms of experiment location, year, and data was excluded.

A total of 64 publications published from 2000 to 2022 were searched and screened, containing 528 pairs of field observations (525 for yield, 292 for IWP, and 409 for WP) from 10 countries (Details of the publications are shown in Supplementary Materials). However, not all publications included both yield and IWP/WP, with the number of pairs studied for yield and IWP/WP varying. The majority of the data were from Asia (81.63% for yield, 80.89% for WP, and 86.17% for IWP), followed by North America (13.83% for yield, 12.97% for WP, and 10.44% for IWP), Europe (2.65% for yield, 2.73% for WP, and 3.40% for IWP), Africa (1.14% for yield, 2.05% for WP, and 0.00% for IWP), and South America (0.76% for yield, 1.37% for WP, and 0.00% for IWP).

2.2. Meta-Analysis

The natural logarithm of the effect ratio (R) was used as a scale for evaluating effect sizes (lnR) in the meta-analysis [32] to characterize the effect of subsurface irrigation on crop yield, WP, and IWP.

$$\ln R = \ln(X_e/X_c) = \ln X_e - \ln X_c \tag{1}$$

where X_e and X_c represent the arithmetic mean of the yield/WP/IWP for subsurface irrigation and surface irrigation (control), respectively; lnR represents the logarithmic response ratio, which is a dimensionless quantity with positive or negative values and represents the rate of increase or decrease in the yield, WP or IWP, respectively, for subsurface irrigation compared with surface irrigation. As the majority of the included studies did not provide a standard deviation (SD), the unweighted method proposed by Rosenberg [33,34] was used to address this issue. Effect sizes and 95% confidence intervals (95% CI) were calculated using the Bootstrap method in Metawin software [35–37]. To better reflect the effect of subsurface irrigation on the yield, WP, and IWP, lnR was converted to a rate of change (CR, %) [34].

$$CR = (\exp(\ln R) - 1) \times 100\% \tag{2}$$

If the 95% CI of the CR contains 0, it means that there is no significant difference between the treatment and control groups ($p < 0.05$); otherwise, there is a significant difference. If the 95% CI of the CR are larger than 0, then there is a significant positive effect. Meanwhile, if all 95% CI of CR are smaller than 0, then there is a significant negative effect.

A mixed-effects model was used to combine lnR across studies, and the within-group heterogeneity of this model consisted of both sampling error and random variation [38,39]. In the meta-analysis of the collected data, the hypotheses of the mixed model are more easily met than those of the fixed-effects model, making the mixed model superior [32,36].

Resampling tests were completed in 64,999 iterations, and Rosenthal's method [40,41] was used to detect publication bias [42]. When the Fail-safe N > 5n + 10 (where n is the number of treatment groups), publication bias was considered not to exist and the results were reliable; conversely, when the Fail-safe N < 5n + 10, publication bias was considered to exist. As shown in Table 1, no publication bias was found to exist in the included studies, indicating that the study results are reliable.

Table 1. Tests for publication bias.

Indicators	Number of Study Articles (n)	Fail-Safe N	5n + 10	Whether Bias Exists
Yield	525	16,937	2635	No
WP	292	6897.9	1470	No
IWP	409	14,639.5	2055	No

2.3. Data Classification

To further clarify the effects of different factors on the yield, WP, and IWP under subsurface irrigation conditions, we combined the classification criteria and methods from different meta-analyses [43,44] and analyzed the factors in subgroups. The specific groups and their criteria are shown in Table 2.

Table 2. Data grouping factors and their criteria.

Factor Classification	Factors	Subgroups and Criteria
Environmental factors	Altitude (m)	<200, 200–500, 500–1000, >1000
	Mean annual Temperature (°C)	<10, 10–15, >15
	Mean annual precipitation (mm)	<200 (arid zones), 200–400 (semi-arid zones), 400–800 (semi-humid zones)
Soil factors	Soil texture [45]	Coarse soils (sandy loam, sandy clay loam, loamy sandy loam, sandy clay loam), medium soils (loamy loam, chalky loam, chalky loam), fine soils (clay, clay loam, chalky loam, chalky clay loam)
	Soil pH	Acidic (pH < 6.5), alkaline (pH = 7.5–8.5), strongly alkaline (pH > 8.5)
	Soil bulk density (g/cm^3)	≤1.25, 1.25–1.35, 1.35–1.45, 1.45–1.55, >1.55
Field management factors	Planting pattern	Equally spaced planting, wide and narrow rows
	Underground pipeline layout	1 pipe for 1 row, 1 pipe for 2 rows, 1 pipe for 3 rows
	Burial depth of underground pipeline (cm)	<10, 10–20, 20–30, 30–40, ≥40
Irrigation factors	Tr/CK irrigation volume	≤50%, 50–100%, 100%, >100%
	Level of water deficit in both with equal irrigation	Severe (<40% FC [1]/40% ETc [2]), moderate (40–50% FC/40–60% ETc), mild (50–60% FC/60–80% ETc), full (60–80% FC/80–105% ETc), excess (≥90–100%FC/120%ETc)
Fertilization factors	Frequency of fertilization	1, 2, 3, 4, ≥5
	Nitrogen application (kg/ha)	<150, 150–200, 200–250, 250–300, ≥300
	Phosphorus application (kg/ha)	≤90, 90–150, >150

[1] FC indicates the field water-holding capacity; [2] ETc indicates crop water consumption.

2.4. Data Processing

We used Excel 2021 for data merging and classification, GetData 2.20 for graphical data extraction from the literature, Metwin 2.1 for analyzing the relevant data, and GraphPad Prism 9.3.0 software for graph drawing.

3. Results

3.1. Comprehensive Effects of Subsurface Irrigation on Crop Yield, WP, IWP, and Tests of Publication Bias

A total of 525 pairs of the yield, 292 pairs of WP, and 409 pairs of IWP observations were included in this study, with total effect values of 0.0579, 0.1957, and 0.2447, respectively. The yield, WP, and IWP for the three typical crops (wheat, maize, and cotton) under subsurface irrigation showed an overall positive effect (Figure 1). The average growth rate of the yield was 5.96%, WP was 21.62%, and IWP was 27.72%.

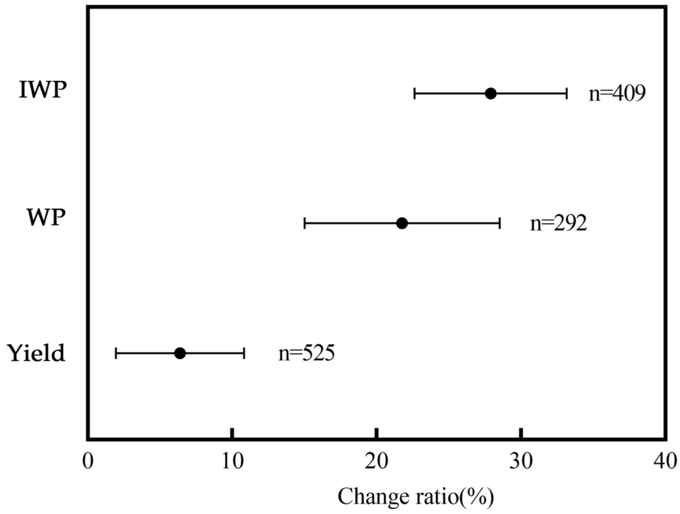

Figure 1. Effect of subsurface irrigation on the yield, irrigation water productivity (IWP), and water productivity (WP). Mean effects and 95% confidence intervals are shown. Sample size (n) is listed next to each bar. Error bars indicate 95% confidence intervals. Same as below.

For the yield and WP, increasing yield and efficiency accounted for 56.96%, increasing yield and reducing efficiency accounted for 5.06%, reducing yield and increasing efficiency accounted for 21.84%, and reducing yield and efficiency accounted for 15.82%. For the yield and IWP, increasing yield and efficiency accounted for 51.63%, increasing yield and reducing efficiency accounted for 5.93%, reducing yield and increasing efficiency accounted for 24.28%, and reducing yield and efficiency accounted for 18.16% (Figure 2). Crop growth and development are influenced by factors such as environment, soil, field management, irrigation, and fertilizer application, which consequently influence crop yield, WP, and IWP, so the degree of influence of each factor needs to be further analyzed in subgroups.

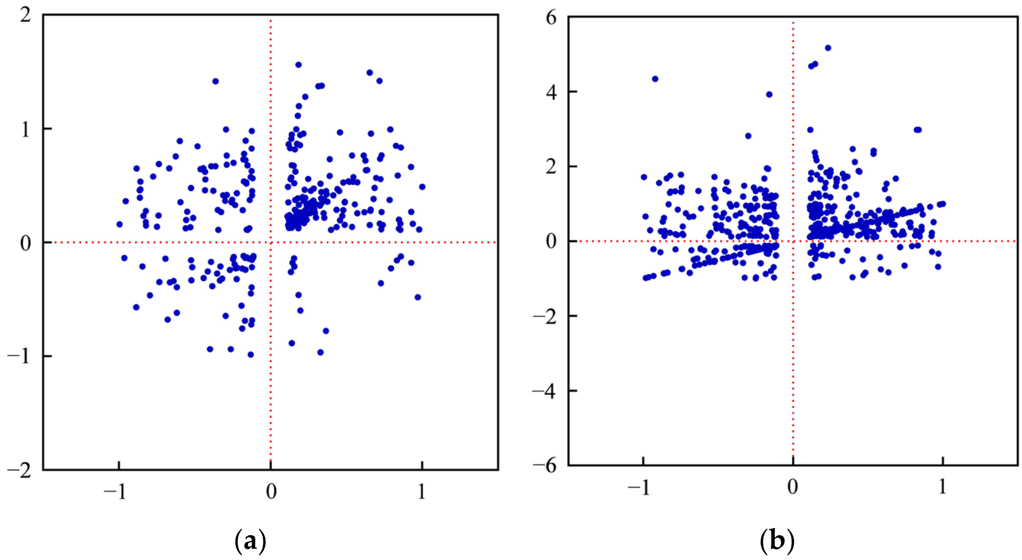

Figure 2. Distribution of the rates of change of subsurface irrigation compared with surface irrigation: (**a**) yield vs. WP; (**b**) yield vs. IWP.

3.2. *Response of Crop Yield, WP, and IWP to Subsurface Irrigation as Influenced by Environmental Factors*

In terms of overall mean values (Figure 3), subsurface irrigation increased the crop yield, WP, and IWP for all environmental factors (altitude, mean annual precipitation, and mean annual temperature). Additionally, the crop yield increase rate under subsurface irrigation showed a trend of increasing and then decreasing with increasing altitude. The most significant advantage of subsurface irrigation was found at an altitude of 200–500 m, where the rates of change in the yield, WP, and IWP reached 9.91%, 26.36%, and 228.25%, respectively.

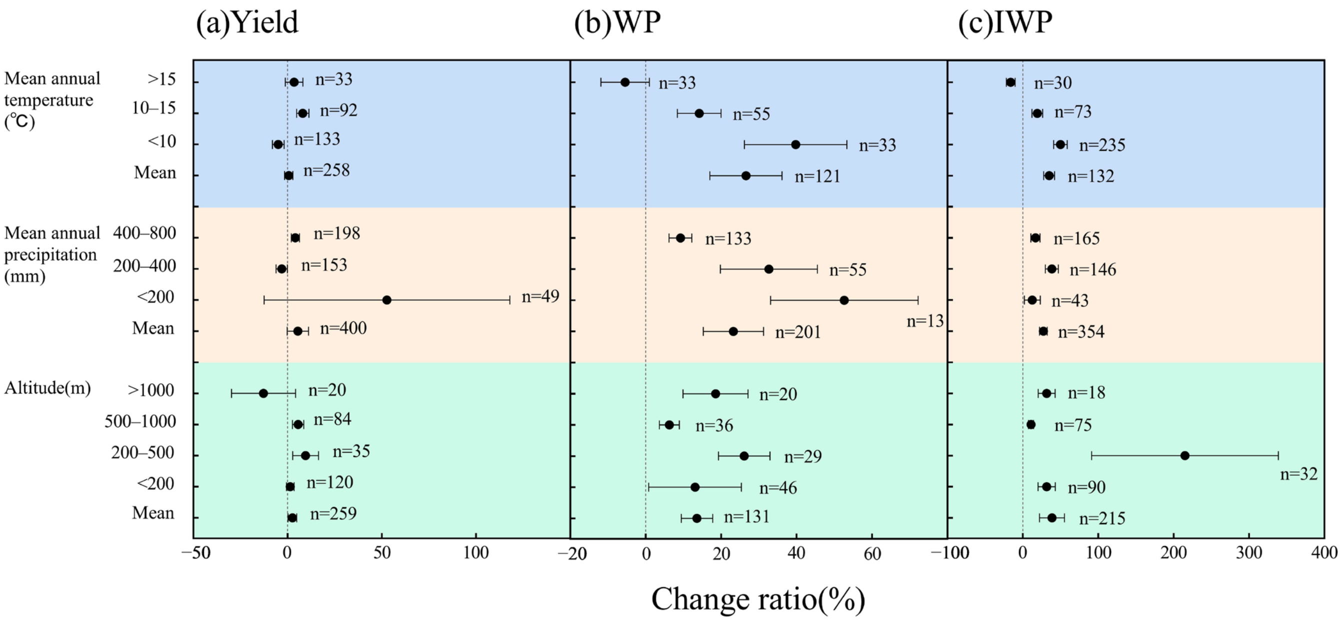

Figure 3. Response of crop yield, WP, and IWP to subsurface irrigation under different environmental factors.

Subsurface irrigation had the greatest yield increase (38.57%) compared with surface irrigation when the mean annual precipitation was <200 mm, but the effect was not significant. The largest increase in WP was 38.14% and in IWP was 32.72% for a mean annual precipitation of 200–400 mm. IWP reached its maximum (56.22%) for a mean annual precipitation of 400–800 mm.

Crop yields increased and then decreased with an increasing mean annual temperature, while the rates of change of WP and IWP were significantly negatively correlated with the mean annual temperature. Crop yields increased significantly by 8.05% at a mean annual temperature of 10–15 °C, while a significant negative effect was observed at <10 °C. WP and IWP reached their maximum at a mean annual temperature of <10 °C, with 39.53% and 49.60%, respectively. In summary, the average effect values of subsurface irrigation on crop yield, WP, and IWP increased by 0.60%, 26.53%, and 34.72%, respectively, at different temperatures.

3.3. Response of Crop Yield, WP, and IWP to Subsurface Irrigation as Influenced by Soil Factors

Differences in soil factors (including soil pH, soil bulk density, and soil texture) lead to differences in the crop yield, WP, and IWP (Figure 4). As soil pH increased, crop yield, WP, and IWP tended to increase and then decrease. The crop yield, WP, and IWP responded significantly to subsurface irrigation conditions at different soil pH, with an average increase of 12.76%, 27.72%, and 14.91%, respectively, but there was no significant difference between crop yield groups. The alkaline soils had a significant effect on the increase in crop WP and IWP, with a 39.84% and 42.75% increase, respectively.

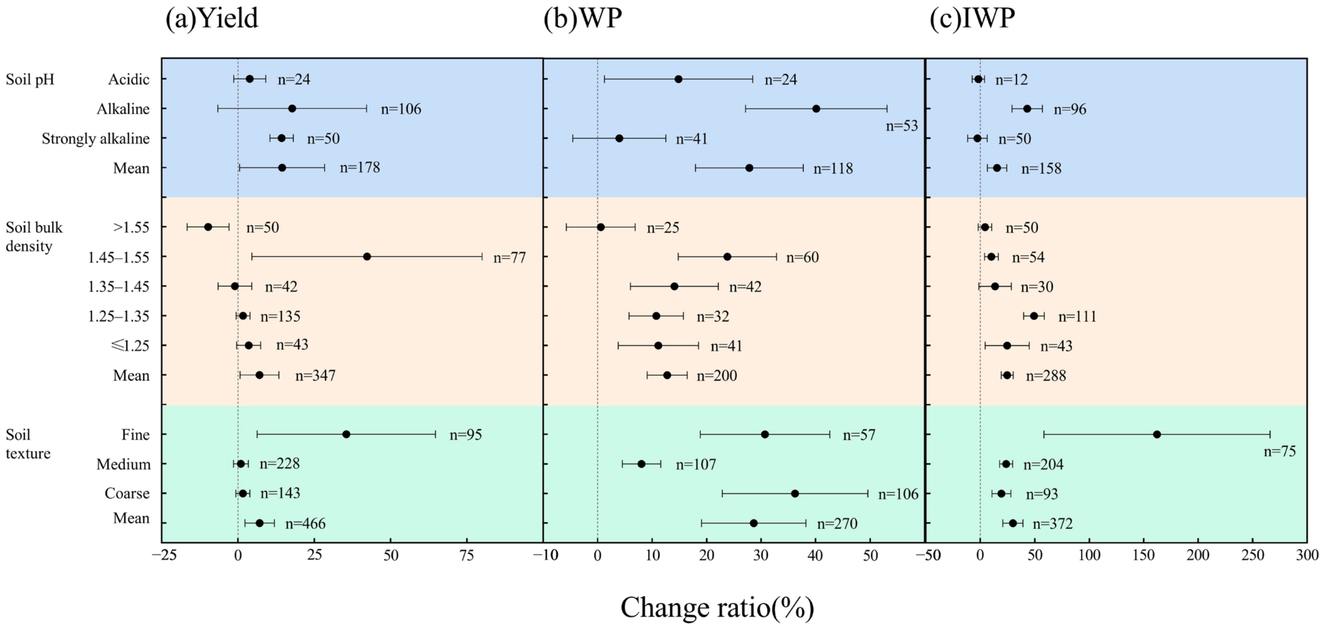

Figure 4. Response of crop yield, WP, and IWP to subsurface irrigation under different soil factors.

Subsurface irrigation was more favorable for crop yield and WP at relatively high soil bulking weights. The greatest increase in crop yield and WP was seen in the range of 1.45–1.5 g/cm^3, with 35.69% and 23.33%, respectively. The greatest increase in IWP occurred at a soil bulk density of 1.25–1.35 g/cm^3, with 48.97%. The use of subsurface irrigation at a too-high bulk density (>1.5 g/cm^3) was not conducive to the improvement of crop yield and water productivity.

In terms of soil texture, fine-textured soils had the greatest effect on yield change for subsurface irrigation, at 30.85%, at which point the rate of increase in WP was 29.33% and the rate of increase in IWP was 167.43%. At the mean value of change, soil texture had a significant positive effect on the yield, WP, and IWP, with mean rates of change of 6.65%, 28.45%, and 29.30%, respectively. Meanwhile, as for WP, coarse-textured soils had the highest rate of change, at 35.53%.

3.4. Response of Crop Yield, WP, and IWP to Subsurface Irrigation as Influenced by Field Management Factors

Overall, different field management conditions (planting pattern, underground pipe layout, and burial depth of underground pipes) had significant effects on crop yield, WP, and IWP under subsurface irrigation (Figure 5). Equally spaced planting significantly improved the crop yield and WP under subsurface irrigation, and the improvement effect was significantly better than that of planting in wide and narrow rows, with an improvement rate of 3.99% and 31.73%, respectively. As for IWP, the rate of change was 27.92% under equally spaced planting and 45.03% under planting in wide and narrow rows.

The comprehensive effects of each underground pipe layout on the crop yield, WP, and IWP were obtained with a mean rate of change of 5.98%, 21.49%, and 28.25%, respectively. All of the pipe layout conditions had a significant positive effect on the crop yield, WP, and IWP effects of subsurface irrigation, and the change first decreased and then increased as the number of control rows of pipes increased, reaching a maximum of 10.05%, 39.89%, and 47.18% with one pipe per row, respectively.

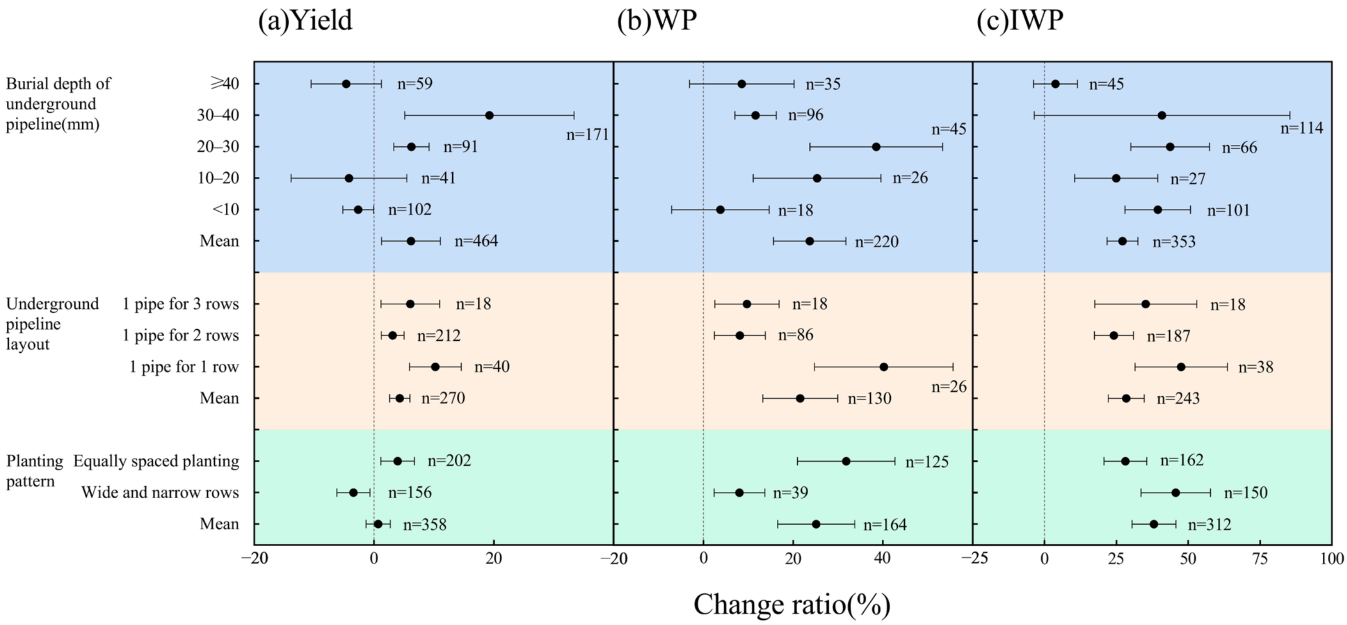

Figure 5. Response of crop yield, WP, and IWP to subsurface irrigation under different field management factors.

As the burial depth of the underground irrigation pipes increased, the rate of change of the yield, WP, and IWP for subsurface irrigation compared with surface irrigation showed a general trend of increasing and then decreasing. The crop yield achieved a maximum value of 17.50% at a pipe depth of 30–40 cm; the WP and IWP achieved a maximum value of 38.09% and 43.65% at a pipe depth of 20–30 cm, respectively.

3.5. Response of Crop Yield, WP, and IWP to Subsurface Irrigation as Influenced by Irrigation Factors

It can be found that when the ratio of subsurface irrigation amount to surface irrigation amount was >100%, the yield increased significantly by 8.89%, WP decreased insignificantly by 3.37%, and IWP decreased significantly by 10.3% (Figure 6). When the ratio of subsurface irrigation amount to surface irrigation amount was $\leq$50%, the yield was significantly reduced by 14.3%, WP was significantly increased by 12.45%, and IWP was significantly increased by 167.01%. The crop yield, WP, and IWP increased significantly at irrigation amount ratios of 50–100%, by 16.42%, 35.45%, and 35.76%, respectively.

With the same amount of irrigation water for both irrigation methods, adequate and mild water deficits had significant positive effects on the crop yield, WP, and IWP under subsurface irrigation conditions, with the mild water deficit case being the most suitable. The increases in crop yield, WP, and IWP were 7.03%, 8.05%, and 4.78% for adequate irrigation and 8.44%, 10.57%, and 15.26% for mild water deficits, respectively. Excessive irrigation had a non-significant effect on yield, WP, and IWP, while moderate water deficits had a non-significant effect on yield improvement but a significant increase in WP and IWP, with increases of 13.77% and 32.7%, respectively. Overall, subsurface irrigation increased the mean yield, WP, and IWP at all levels of water deficit by 4.07%, 8.58%, and 23.48%, respectively, relative to surface irrigation.

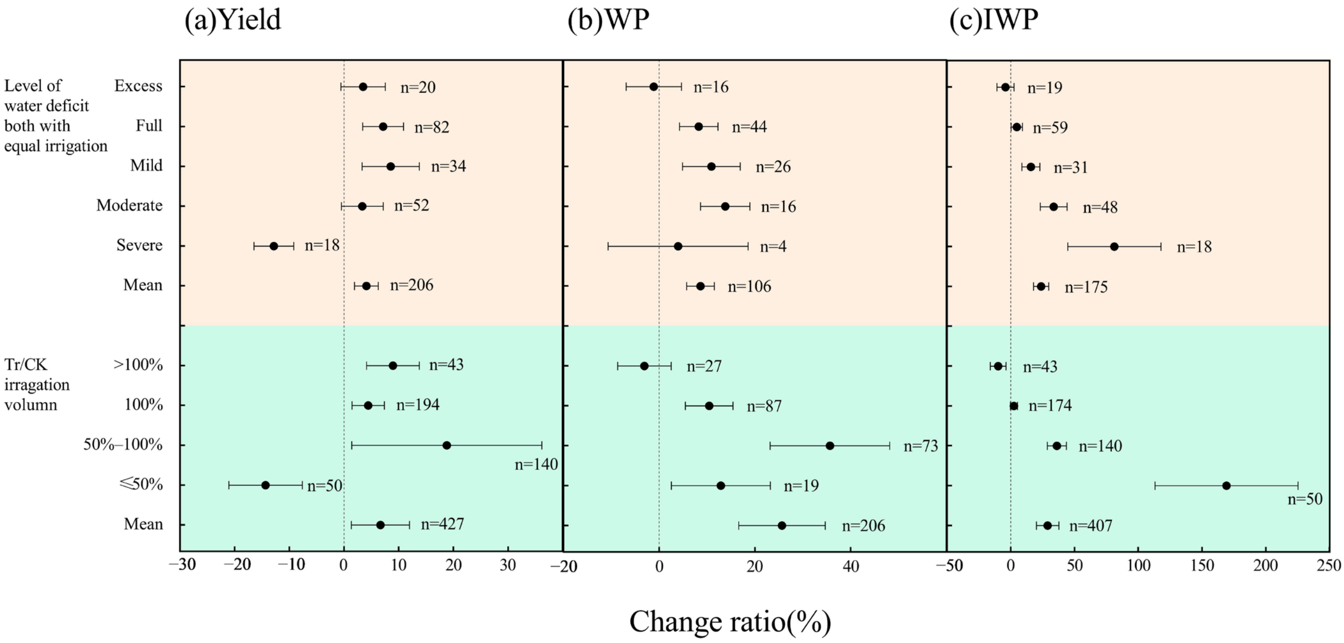

Figure 6. Response of crop yield, WP, and IWP to subsurface irrigation under different irrigation factors.

3.6. Response of Crop Yield, WP, and IWP to Subsurface Irrigation as Influenced by Fertilization Factors

Compared with surface irrigation, subsurface irrigation significantly increased the crop yield, WP, and IWP overall under different fertilizer applications (Figure 7). The yield increase rate of subsurface irrigation compared with surface irrigation gradually decreased as the number of fertilizer applications increased. For one-time fertilization, the yield increase rate reached 4.77%. When N fertilization was <150 kg/ha, the yield increase rate of subsurface irrigation (8.36%) was significantly higher than the other four N fertilization rates. While the yield increase rate of P fertilization ≤90 kg/ha (5.59%) was significantly higher than the other two P fertilization rates (Figure 7).

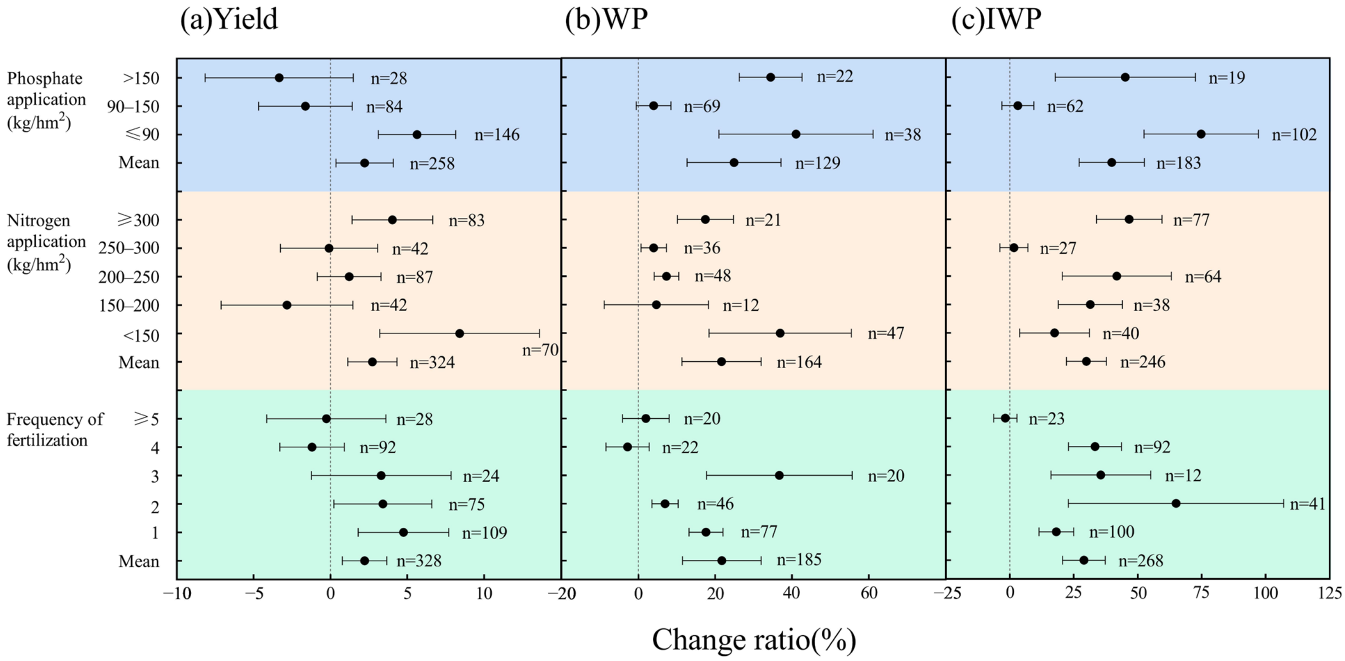

Figure 7. Response of crop yield, WP, and IWP to subsurface irrigation under different fertilization factors.

As for WP, the maximum increase (35.65%) was obtained when the number of fertilizer applications was three. The rate of change in WP was 35.95% when N fertilization was <150 kg/ha and 17.55% when N fertilization was ≥300 kg/ha. The increase in WP for subsurface irrigation relative to surface irrigation first decreased and then increased as P fertilization increased, with the greatest growth rate of 39.06% at ≤90 kg/ha.

The trend in IWP is largely consistent with WP across fertilizer applications, reaching a maximum of 60.54%, 46.32%, and 73.31% at ≥300 kg/ha of N, ≤90 kg/ha of P, and two applications of fertilizer, respectively.

4. Discussion

4.1. Crop Yield, WP, and IWP Response to Subsurface Irrigation under Different Environmental Factors

Environmental resources are essential for agricultural production and are an important factor affecting the effectiveness of subsurface irrigation. As the altitude of the experimental site increases, it directly leads to enhanced solar radiation, lower temperatures, and increased diurnal temperature differences, thus affecting crop growth and leading to changes in the crop yield, WP, and IWP [46]. In this meta-analysis, the crop yield first showed an increase and then a decrease with elevation, which is consistent with the results of Chuma et al. [47]. Subsurface irrigation significantly increased the yield compared with surface irrigation at altitudes of 200–500 m. At altitudes >1000 m, the yield was reduced, but both WP and IWP increased significantly. This may be due to the moderate light, temperature, and rainfall conditions at a medium altitude, which are suitable for crop growth. However, at high altitudes, there is low temperature and cold damage, and crops do not have an effective enough temperature, which limits the yield growth [48].

Crops in areas with mean annual precipitation <200 mm suffer from severe water shortages and are more dependent on irrigation water. Subsurface irrigation promotes crop growth and reduces inefficient crop water evaporation by direct irrigation to the root zone of the crop. In this meta-analysis, the maximum yield, WP, and IWP increase rates of subsurface irrigation occurred in areas with a mean annual precipitation <200 mm or 200–400 mm, and the WP and IWP increase rates were significantly different from those in areas with a mean annual precipitation of 400–800 mm. In contrast, the rate of yield increase was not significantly different between areas with mean annual precipitation <200 mm and 400–800 mm, which may be due to the small number of samples with mean annual precipitation <200 mm and the large confidence interval.

In addition, temperature directly affects soil temperature and thus the crop–soil system water and nutrient cycle [49,50]. High temperatures lead to increased crop evapotranspiration [51] and excessive water loss from leaves, which is detrimental to crop growth. Low temperatures lead to soil freezing, which reduces the rate of water and nutrient uptake by crop root cells and slows crop metabolism. This meta-analysis found that the mean annual temperature between 10 and 15 °C significantly increases the yield. At a mean annual temperature of <10 °C, yield significantly decreased, but the greatest increase in WP and IWP was observed at this point. This may be related to the reduced survival rate of crops caused by low temperatures. In low-temperature periods and areas, the depth of crop roots is mostly shallower than the depth of subsurface irrigation, meaning that the water is not easily absorbed and used by crops. Therefore, in order to make crops emerge smoothly through the winter period, the first water should be irrigated on the surface to ensure crop survival, and subsurface irrigation treatments should start after the winter period. In the case of the same yield reduction, subsurface irrigation improves crop water productivity by flooding the soil at a deeper level, which acts as a moisture retainer and reduces water consumption and temperature loss.

4.2. Crop Yield, WP, and IWP Response to Subsurface Irrigation under Different Soil Factors

The effect of soil pH, bulk density, and texture factors on subsurface irrigation was analyzed and it was found that alkaline soils (pH = 7.5–8.5) had an increased effect on the crop yield, WP, and IWP under subsurface irrigation, as well as a significant effect on WP and IWP. Soil pH is one of the main factors regulating the structure of the microbial community and the chemical transformation processes between substances in the soil. When the soil is too acidic, metal cations are released from oxides or silicates and poison the crop roots, thus affecting crop growth and yield [52,53]. Alkaline soils usually have greater ammonia volatilization and high nitrogen losses, which are also detrimental to crop growth. A suitable soil pH for wheat, maize, and cotton is neutral or weakly acidic. In alkaline soils, subsurface irrigation exerts dilution and leaching effects to reduce soil alkalinity; at the same time, it reduces water evaporation. According to the "salt follows water" principle, subsurface irrigation can inhibit nitrogen loss, thus widening the difference with surface irrigation [54]. Soil bulk density is positively correlated with soil firmness, and a suitable soil bulk density can provide a favorable growing environment for crops [55,56]. This meta-analysis showed that the maximum crop yield and WP can be achieved at soil bulking weights of 1.45–1.55 g/cm^3. For soil texture, fine-textured soils had the greatest effectiveness in increasing yield and differed significantly from coarse- and medium-textured soils, while coarse-textured soils had the highest rate of change in WP. This may be because when the soil bulk density is 1.45–1.55 g/cm^3 or the soil texture is fine-textured, the soil has a high clay particle content, high compactness, and poor soil aeration and water conductivity. This inhibits the infiltration of surface irrigation water into the root zone, at which time the advantage of subsurface irrigation in transporting water directly to the vicinity of the crop root zone becomes more obvious and more conducive to water uptake and use by the root system. The highest WP variability in coarse-textured soils may be due to the high sand content of the soil, the high number of large pores, and the poor water and fertilizer retention properties of this soil [57], which can be alleviated by subsurface irrigation.

4.3. Crop Yield, WP, and IWP Response to Subsurface Irrigation under Different Field Management Factors

In this study, the crop planting pattern, underground pipe layout, and burial depth of the underground pipes all had significant positive effects on crop yield, WP, and IWP. This is because equally spaced planting provides the plants with sufficient space to develop their root systems, which leads to a significant increase in individual plant dominance and consistent plant population growth and development, whereas the productivity level of the individual plants directly affects the quality and efficiency of the crop population [58,59]. As for IWP, the results showed that it increased at a greater rate under wide and narrow row planting than equally spaced planting. This may be explained by the fact that in wide and narrow row planting, underground irrigation pipes are mostly laid in the middle of the narrow rows and arranged in two rows with one pipe, so that the irrigation water is closer to the crop, allowing the crop to make better use of the irrigation water and thus increasing IWP. Studies on pipe layout are now mostly focused on the comparison of the effects of different pipe-to-row ratios on surface drip irrigation [60,61], while few studies have been conducted on subsurface irrigation. In this meta-analysis, a comprehensive analysis of different pipe layout methods in the literature revealed a significant positive effect on crop yield, WP, and IWP, with an effect of one pipe for one row > one pipe for three rows > one pipe for two rows. This may be due to the fact that in the one pipe for one row case, the crop is closest to the irrigation water, and the water reaches the root system directly below the plant, meaning that it can be absorbed and used directly by the crop. The difference between the two irrigation methods is increased by the fact that in the case of multiple rows of pipes, the crop root system is also dependent on the lateral movement of soil water, and in the case of subsurface irrigation, the water from the one pipe for three rows is closer to the crop root system than in the case of the one pipe for two rows treatment. In the case of subsurface irrigation, the choice of pipe burial depth is a key factor in determining the depth of irrigation and thus the initial infiltration location of water, which affects the moisture content and its distribution in the soil, and therefore the growth and development of the crop. The appropriate burial depth of subsurface pipes depends on the type of crop and the nature of the soil [62,63]. For coarse soil with good hydraulic conductivity, subsurface pipes can be buried shallowly, while for fine soil with poor hydraulic conductivity and high soil water-holding capacity, subsurface pipes should be buried deeper, not only to avoid deep seepage but also to avoid wetting of the topsoil and reduce ineffective soil evaporation. The root growth range of different crop species is different, so the ability to absorb soil nutrients and water at different depths is different, and the appropriate burial depth of the capillary pipe also differs [64,65]. Mo et al. [66] concluded that the appropriate depth of burial for subsurface drip irrigation strips for summer maize in the northeast on loamy soils is 30–35 cm. Duan et al. [67] compared the growth of unmulched cotton at three underground pipe burial depths (10, 15, and 20 cm) and found that maximum combined benefits were obtained at a 15 cm depth and maximum yields at a 20 cm depth. For winter wheat, the optimum burial depth for subsurface irrigation is 40 cm in heavy loam soils [68].

4.4. Crop Yield, WP, and IWP Response to Subsurface Irrigation under Different Irrigation Factors

The volume of irrigation directly affects crop growth. In general, crop yield and water productivity tend to increase and then decrease with increasing irrigation water, with negative effects when certain limits are exceeded [69,70]. The findings of this meta-analysis showed that the yield, WP, and IWP change more significantly when the irrigation volume is different between subsurface and surface irrigation. When the ratio of irrigation volume between subsurface and surface irrigation is $\leq$50%, the yield is significantly lower, while WP and IWP are significantly higher. However, when the ratio is 50–100%, the crop yield, WP, and IWP are significantly higher, and this effect is more pronounced than when the irrigation volume is the same. The reason for this is that in the first case, the amount of water under subsurface irrigation is severely inadequate, limiting crop growth and maturity, resulting in a reduction in yield. Meanwhile, the reduction in irrigation water under subsurface irrigation is much higher than the reduction in crop yield, which results in an increase in crop water productivity. In the second case, the amount of irrigation water under subsurface irrigation is lower than that under surface irrigation, and there is slight water stress compared with surface irrigation, but subsurface irrigation can still give full play to its role of increasing yield and efficiency. Additionally, appropriate water stress can effectively stimulate the crop root system to take in water and nutrients under subsurface irrigation, improving crop yield and water absorption performance. This is similar to the finding of Yang [71], in that moderate deficit irrigation can increase the amount and rate of water uptake by the lower root system, which is more conducive to crop growth under subsurface irrigation conditions. The analysis by Ma et al. [72] also showed that direct root zone irrigation, a subsurface irrigation method, can improve root distribution patterns under reduced irrigation (moderate water deficit) to optimize production water use. In contrast, when subsurface irrigation was >100% of irrigation water than surface irrigation, the yield increased by 8.89%, but the increase was lower than when the irrigation water ratio was 50–100%, and the WP and IWP decreased. This also illustrates the water-saving advantages of subsurface irrigation, where over-irrigation can cause yield reduction as well as ineffective water evaporation and leakage.

When both irrigation methods have the same volume of irrigation water, if both have a severe water deficit and the crop is severely undersupplied with water, the crop yield decreases with subsurface irrigation compared with surface irrigation at this time, while WP and IWP increase. This is because subsurface irrigation delivers water directly to the root zone, which greatly reduces water losses and thus increases water productivity, but does not have a significant effect on increasing WP, which may be due to the large confidence interval in this case. In contrast, the crop yield, WP, and IWP are substantially increased under adequate and mild water deficit conditions with subsurface irrigation, again indicating that subsurface irrigation can alleviate the adverse effects of mild water stress on crops, enhance the adaptive capacity of crops under water stress, stimulate compensatory root growth [73], improve crop root shape, enhance root vigor, and regulate roots to distribute them evenly in the soil layer, which is consistent with the findings of Cao et al. and Al-Ghobari et al. [74,75]. In the case of moderate water deficits, the effect of subsurface irrigation on yield is not obvious, but it can significantly increase crop WP and IWP. This conclusion is supported by the view of Zou et al. [76], who demonstrated that mild water deficit treatment can obtain a higher yield and moderate water deficit treatment can improve water productivity.

4.5. Crop Yield, WP, and IWP Response to Subsurface Irrigation under Different Fertilization Factors

Crop nutrient uptake is mainly dependent on soil residues and additional fertilizer applications. Deng et al. [77] found that splitting fertilizer applications improves photosynthetic efficiency during the reproductive growth period compared with a single application and synergistically improves N fertilizer efficiency and seed yield by optimizing the source-library relationship during the filling period and reducing N fertilizer inputs. A study by Hamad et al. [78] and Tanaskovik et al. [79] also showed that a high number of fertilizer applications reduces N losses and increases chard yields. However, Fu et al. [80] reported that the number of fertilizer applications affects soil pH and thus nutrient uptake by plants, with more frequent applications resulting in greater nitrogen losses and a lower crop yield and biomass. Our study showed that the yield of subsurface-irrigated crops is significantly higher than that of surface-irrigated crops in the case of one-time fertilization. When the number of crop fertilizer applications increases, the yield difference between surface and subsurface irrigation diminishes. This may be because in this study, fertilizer was basically applied with water, and the water–fertilizer coupling increased the fertilizer fixation rate of surface irrigation and increased water utilization, which led to an increase in surface irrigation yield and a decrease in the difference between the two. In general, the crop yield gradually increases with increasing fertilizer applications until a certain threshold is reached and the yield begins to show a decreasing trend again. However, this meta-analysis found that the crop yield, WP, and IWP are significantly increased by subsurface irrigation over surface irrigation when P fertilization is $\leq$90 kg ha^{-1} and N fertilization is <150 kg ha^{-1}, with the largest increase being observed. This may be attributed to the fact that subsurface irrigation mitigates the problem of low fertilizer application rates affecting crop growth and development, thus increasing yields. In contrast, at higher fertilizer application rates, the difference between the two irrigation methods diminishes due to soil fertility, which also reflects the fertilizer-saving effect of subsurface irrigation.

4.6. Advantages and Disadvantages of Subsurface Irrigation

This meta-analysis showed that, compared with surface irrigation, subsurface irrigation can reduce deep soil bulk, increase the deep soil water content [81], reduce soil water evaporation after irrigation [82], and improve the nutrient status of the soil [83]. The water from subsurface irrigation penetrates deep into the soil of the active layer of the root system, which makes it easy for the root system to absorb water and grow [84], maintain the ground temperature, and ensure a suitable water, heat, air, and fertilizer environment, thus improving soil productivity and water conditions and realizing the yield and efficiency-increasing effect of subsurface irrigation.

5. Conclusions

The results of our global meta-analysis showed that the use of subsurface irrigation had a significant effect on the yield, WP, and IWP for all three typical crops (wheat, maize, and cotton). The effects are closely related to factors such as environment, soil, field management, irrigation, and fertilization, and it is recommended to work with these indicators when guiding irrigation. Subsurface irrigation should be controlled at 50–100% of surface irrigation, and when both irrigation volumes are the same, mild water deficits are more favorable to the subsurface irrigation method. In arid areas with altitudes of 200–500 m, moderate mean annual temperatures (10–15 °C), or annual precipitation

<200 mm, it is recommended that subsurface irrigation techniques be given priority. In high-altitude (>1000 m) and low-temperature (average annual temperature < 10 °C) areas, it is recommended to combine subsurface irrigation and surface irrigation, using surface irrigation in the early stage to ensure safe overwintering of the crop and improve the survival rate, while subsurface irrigation can be used in the mid- and late stages to save water and increase production. In humid areas (average annual rainfall > 400 mm), surface irrigation can be used, and the amount of irrigation water can be appropriately reduced. Subsurface irrigation performs best in the following conditions: soil capacity of 1.45–1.55 g/cm^3, alkaline soil, one-time application of fertilizer, phosphorus application ≤90 kg/ha, nitrogen application <150 kg/ha, suitable depth of pipe burying (20–40 cm), planting in one pipe of one pipe, and equidistant row spacing, which is more conducive to subsurface irrigation to save water and increase production.

This meta-analysis is a comprehensive analysis of the yield, water productivity, and irrigation water productivity for three typical crops of wheat, corn, and cotton under subsurface irrigation. Factors affecting subsurface irrigation were analyzed, and some suggestions were given; however, the cost of installation and maintenance of subsurface irrigation and other costs were not considered in this study, so the practical application should be considered in combination with yield, water productivity, economic benefits, and ecological benefits. Secondly, the suitable subsurface irrigation methods may be different for different crops, and the frequency of irrigation and soil nutrients may also affect the results, which can be further studied in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su152215716/s1, Table S1: Details of the publications.

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References

1. Zohaib, M.; Kim, H.; Choi, M. Detecting global irrigated areas by using satellite and reanalysis products. *Sci. Total Environ.* **2019**, *677*, 679–691. [CrossRef] [PubMed]
2. Wang, L.; Wu, W.; Xiao, J.; Huang, Q.; Hu, Y. Effects of different drip irrigation modes on water use efficiency of pear trees in northern China. *Agric. Water Manag.* **2021**, *245*, 106660. [CrossRef]
3. Nagaraj, D.; Proust, E.; Todeschini, A.; Rulli, M.C.; D'Odorico, P. A new dataset of global irrigation areas from 2001 to 2015. *Adv. Water Resour.* **2021**, *152*, 103910. [CrossRef]
4. Intrigliolo, D.S.; Ballester, C.; Castel, J.R. Carry-over effects of deficit irrigation applied over seven seasons in a developing Japanese plum orchard. *Agric. Water Manag.* **2013**, *128*, 13–18. [CrossRef]
5. FAO AQUASTAT. Food and Agriculture Organization of the United Nations (FAO), Roma, Italy. 2018. Available online: http://www.fao.org/aquastat/en/ (accessed on 2 March 2021).
6. Bai, H.; Tao, F.; Xiao, D.; Liu, F.; Zhang, H. Attribution of yield change for rice-wheat rotation system in China to climate change, cultivars and agronomic management in the past three decades. *Clim. Chang.* **2016**, *135*, 539–553. [CrossRef]
7. Rahman, A.; Mojid, M.A.; Banu, S. Climate change impact assessment on three major crops in the north-central region of Bangladesh using DSSAT. *Int. J. Agric. Biol. Eng.* **2018**, *11*, 135–143. [CrossRef]

8. Wada, Y.; de Graaf, I.E.M.; van Beek, L.P.H. High-resolution modeling of human and climate impacts on global water resources. *J. Adv. Model. Earth Syst.* **2016**, *8*, 735–763. [CrossRef]
9. FAO AQUASTAT-Database. Food and Agriculture Organization of the United Nations (FAO), Roma, Italy. 2018. Available online: https://www.fao.org/aquastat/statistics/query/index.html;jsessionid=9D762F03F7A25EDCAAA00EBB7DD8383F (accessed on 20 March 2020).
10. Abrahão, R.; García-Garizábal, I.; Merchán, D.; Causapé, J. Climate change and the water cycle in newly irrigated areas. *Environ. Monit. Assess.* **2015**, *187*, 22. [CrossRef]
11. Allen, R.G.; Pereira, L.S.; Raes, D. *FAO Irrigation and Drainage Paper No. 56*; FAO: Roma, Italy, 1998.
12. Zhang, L.; Wu, P.; Fan, X. Numerical simulation of soil water movement with drip irrigation of multiple point source. *Trans. Chin. Soc. Agric. Eng.* **2010**, *26*, 40–45. [CrossRef]
13. Jin, Y.; Gao, X.; Zhang, R.; Wu, X.; Long, H.; Sun, Z.; Zhang, S. Comprehensive Assessment of Plant and Water Productivity Responses in Negative Pressure Irrigation Technology: A Meta-Analysis. *Agronomy* **2022**, *12*, 1925. [CrossRef]
14. Gao, Y.; Yang, L.; Shen, X.; Li, X.; Sun, J.; Duan, A.; Wu, L. Winter wheat with subsurface drip irrigation (SDI): Crop coefficients, water-use estimates, and effects of SDI on grain yield and water use efficiency. *Agric. Water Manag.* **2014**, *146*, 1–10. [CrossRef]
15. Zhang, Y.; Song, S.; Yang, H.; Xu, W.; Guo, P.; Yu, Y. Water-use efficiency of potted pakchoi in Yunnan laterite with root infiltration irrigation and anticlogging emitter. *J. Irrig. Drain. Eng.* **2019**, *145*, 04018038. [CrossRef]
16. Zou, X.; Quan, T.; Zhou, M.; Yang, Q.; Shi, Y. Progress and prospects of moistube irrigation technology research. *Bull. Soil Water Conserv.* **2017**, *37*, 150–155. [CrossRef]
17. Su, Y.; Guo, X.; Lei, T.; Zheng, L.; Ma, J.; Sun, X.; Hao, L.; Hu, F. Three-Dimensional Model of Soil Water and Heat Transfer in Orchard Root Zone under Water Storage Pit Irrigation. *Water* **2022**, *14*, 1813. [CrossRef]
18. Chen, L.; Zhang, L.; Lu, Z.; Xian, F.; Zhang, J.; Cheng, Y.; Zhang, X.; Liu, Y. Effects of Trace Irrigation at Different Depths on Transcriptome Expression Pattern in Cotton (*G. hirsutum* L.) Leaves. *BioMed Res. Int.* **2020**, *2020*, 7248513. [CrossRef]
19. Fan, Y.; Huang, N.; Gong, J.; Shao, X.; Zhang, J.; Zhao, T. A simplified infiltration model for predicting cumulative infiltration during vertical line source irrigation. *Water* **2018**, *10*, 89. [CrossRef]
20. Kanda, E.K.; Niu, W.; Mabhaudhi, T.; Senzanje, A. Moistube irrigation technology: A review. *Agric. Res.* **2019**, *9*, 139–147. [CrossRef]
21. Yao, J.; Qi, Y.; Li, H.; Shen, Y. Water saving potential and mechanisms of subsurface drip irrigation: A review. *Chin. J. Eco-Agric.* **2021**, *29*, 1076–1084. [CrossRef]
22. Guo, F.; Ma, J.; Zheng, L.; Sun, X.; Guo, X.; Zhang, X. Estimating distribution of water uptake with depth of winter wheat by hydrogen and oxygen stable isotopes under different irrigation depths. *J. Integr. Agric.* **2016**, *15*, 891–906. [CrossRef]
23. Guo, X.; Sun, X.; Ma, J.; Lei, T.; Zheng, L.; Wang, P. Simulation of the water dynamics and root water uptake of winter wheat in irrigation at different soil depths. *Water* **2018**, *10*, 1033. [CrossRef]
24. Cai, Y.; Wu, P.; Zhu, D.; Zhang, L.; Zhao, X.; Gao, X.; Ge, M.; Song, X.; Wu, Y.; Dai, Z. Subsurface irrigation with ceramic emitters: An effective method to improve apple yield and irrigation water use efficiency in the semiarid Loess Plateau. *Agric. Ecosyst. Environ.* **2021**, *313*, 107404. [CrossRef]
25. Thamer, T.; Nassif, N.; Almaeini, A.; Al-Ansari, N.; Hassan, D. Modeling of Different Irrigation Methods for Maize Using AquaCrop Model: Case Study. *Engineering* **2021**, *13*, 472–492. [CrossRef]
26. Wang, J.; Gong, S.; Xu, D.; Yu, Y. Effects of irrigation models on the space distribution of root system andyield of winter wheat. *J. Hydraul. Eng.* **2011**, *42*, 1239–1246. [CrossRef]
27. Umair, M.; Hussain, T.; Jiang, H.; Ahmad, A.; Yao, J.; Qi, Y.; Zhang, Y.; Min, L.; Shen, Y. Water-saving potential of subsurface drip irrigation for winter wheat. *Sustainability* **2019**, *11*, 2978. [CrossRef]
28. Ardenti, F.; Abalos, D.; Capra, F.; Lommi, M.; Maris, S.C.; Perego, A.; Bertora, C.; Tabaglio, V.; Fiorini, A. Matching crop row and dripline distance in subsurface drip irrigation increases yield and mitigates N2O emissions. *Field Crop Res.* **2022**, *289*, 108732. [CrossRef]
29. Mitchell-McCallister, D.; Cano, A.; West, C. Meta-analysis of crop water use efficiency by irrigation system in the Texas High Plains. *Irrig. Sci.* **2020**, *38*, 535–546. [CrossRef]
30. Cheng, M.; Wang, H.; Fan, J.; Zhang, S.; Liao, Z.; Zhang, F.; Wang, Y. A global meta-analysis of yield and water use efficiency of crops, vegetables and fruits under full, deficit and alternate partial root-zone irrigation. *Agric. Water Manag.* **2021**, *248*, 106771. [CrossRef]
31. Tong, X.; Wu, P.; Liu, X.; Zhang, L.; Zhou, W.; Wang, Z. A global meta-analysis of fruit tree yield and water use efficiency under deficit irrigation. *Agric. Water Manag.* **2022**, *260*, 107321. [CrossRef]
32. Hedges, L.V.; Gurevitch, J.; Curtis, P.S. The meta-analysis of response ratios in experimental ecology. *Ecology* **1999**, *80*, 1150–1156. [CrossRef]
33. Rosenberg, M.S.; Adams, D.C.; Gurevitch, J. *MetaWin: Statistical Software for Meta-Analysis with Resampling Tests*, 1st ed.; Sinauer Associates: Sunderland, MA, USA, 1997.
34. Chen, H.; Li, X.; Hu, F.; Shi, W. Soil nitrous oxide emissions following crop residue addition: A meta-analysis. *Glob. Chang. Biol.* **2013**, *19*, 2956–2964. [CrossRef]
35. Adams, D.C.; Gurevitch, J.; Rosenberg, M.S. Resampling tests for meta-analysis of ecological data. *Ecology* **1997**, *78*, 1277–1283. [CrossRef]

36. Gurevitch, J.; Hedges, L.V. Statistical issues in ecological meta-analyses. *Ecology* **1999**, *80*, 1142–1149. [CrossRef]
37. Morgan, P.B.; Ainsworth, E.A.; Long, S.P. How does elevated ozone impact soybean? A meta-analysis of photosynthesis, growth and yield. *Plant Cell Environ.* **2003**, *26*, 1317–1328. [CrossRef]
38. Valkama, E.; Koricheva, J.; Oksanen, E. Effects of elevated O3, alone and in combination with elevated CO2, on tree leaf chemistry and insect herbivore performance: A meta-analysis. *Glob. Chang. Biol.* **2007**, *13*, 184–201. [CrossRef]
39. Ainsworth, E.A. Rice production in a changing climate: A meta-analysis of responses to elevated carbon dioxide and elevated ozone concentration. *Glob. Chang. Biol.* **2008**, *14*, 1642–1650. [CrossRef]
40. LeBauer, D.S.; Treseder, K.K. Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. *Ecology* **2008**, *89*, 371–379. [CrossRef]
41. Rosenthal, R. The file drawer problem and tolerance for null results. *Psychol. Bull.* **1979**, *86*, 638. [CrossRef]
42. Rosenberg, M.S.; Adams, D.C.; Gurevitch, J. MetaWin (Version2.1). 2000. Available online: http://www.metawinsoft.com/ (accessed on 21 May 2022).
43. Li, Q.; Chen, Y.; Sun, S.; Zhu, M.; Xue, J.; Gao, Z.; Zhao, J.; Tang, Y. Research on Crop Irrigation Schedules Under Deficit Irrigation—A Meta-analysis. *Water Resour. Manag.* **2022**, *36*, 4799–4817. [CrossRef]
44. Yang, Z.; Hu, Y.; Zhang, S.; Raza, S.; Wei, X.; Zhao, X. The Thresholds and Management of Irrigation and Fertilization Earning Yields and Water Use Efficiency in Maize, Wheat, and Rice in China: A Meta-Analysis (1990–2020). *Agronomy* **2022**, *12*, 709. [CrossRef]
45. Soil Survey Staff. *Key to Soil Taxonomy*, 12th ed.; USDA-Natural Resources Conservation Service: Washington, DC, USA, 2014; p. 360.
46. Ginbo, T. Heterogeneous impacts of climate change on crop yields across altitudes in Ethiopia. *Clim. Chang.* **2022**, *170*, 12. [CrossRef]
47. Chuma, B.A.; Cotter, M.; Kalisa, A.; Rajaona, A.; Senthilkumar, K.; Stuerz, S.; Vincent, I.; Asch, F. Altitude, temperature, and N Management effects on yield and yield components of contrasting lowland rice cultivars. *J. Agron. Crop Sci.* **2020**, *206*, 456–465. [CrossRef]
48. Xiao, G.; Zhang, Q.; Li, Y.; Wang, R.; Yao, Y.; Zhao, H.; Bai, H. Impact of temperature increase on the yield of winter wheat at low and high altitudes in semiarid northwestern China. *Agric. Water Manag.* **2010**, *97*, 1360–1364. [CrossRef]
49. Zhou, C.; Ge, X.; Huang, W.; Li, D.; Liu, Z. Effects of Aqua-Dispersing Nano-Binder on Clay Conductivity at Different Temperatures. *Sustainability* **2019**, *11*, 4859. [CrossRef]
50. Sabziparvar, A.; Khoshhal Jahromi, F. Evaluating the most effective climatic parameters affecting the monthly mean soil temperature estimates using the PLS method. *Arab. J. Geosci.* **2022**, *15*, 1044. [CrossRef]
51. Yu, L.; Zhao, X.; Gao, X.; Siddique, K.H. Improving/maintaining water-use efficiency and yield of wheat by deficit irrigation: A global meta-analysis. *Agric. Water Manag.* **2020**, *228*, 105906. [CrossRef]
52. Faria, J.M.S.; Conceição, T.A.; Teixeira, D.M.; Brito, I.; Barrulas, P.; Pinto, A.P.; Vaz, M.; Carvalho, M. Arbuscular Mycorrhiza Extraradical Mycelium Promotes Si and Mn Subcellular Redistribution in Wheat Grown under Mn Toxicity. *Int. J. Plant Biol.* **2022**, *13*, 82–94. [CrossRef]
53. Huang, L.; Liu, X.; Wang, Z.; Liang, Z.; Wang, M.; Liu, M.; Suarez, D.L. Interactive effects of pH, EC and nitrogen on yields and nutrient absorption of rice (*Oryza sativa* L.). *Agric. Water Manag.* **2017**, *194*, 48–57. [CrossRef]
54. Wang, H.; Wang, N.; Quan, H.; Zhang, F.; Fan, J.; Feng, H.; Cheng, M.; Liao, Z.; Wang, X.; Xiang, Y. Yield and water productivity of crops, vegetables and fruits under subsurface drip irrigation: A global meta-analysis. *Agric. Water Manag.* **2022**, *269*, 107645. [CrossRef]
55. Abdo, I.A.; Xu, Y.; Shi, D.; Li, J.; Li, H.; El-Sappah, A.H.; Elrys, S.A.; Alharbi, A.S.; Zhou, C.; Wang, L.; et al. Nitrogen transformation genes and ammonia emission from soil under biochar and urease inhibitor application. *Soil Tillage Res.* **2022**, *223*, 105491. [CrossRef]
56. Wang, X.; He, J.; Bai, M.; Liu, L.; Gao, S.; Chen, K.; Zhuang, H. The Impact of Traffic-Induced Compaction on Soil Bulk Density, Soil Stress Distribution and Key Growth Indicators of Maize in North China Plain. *Agriculture* **2022**, *12*, 1220. [CrossRef]
57. Asghari, S.; Abbasi, F.; Neyshabouri, M.R. Effects of soil conditioners on physical quality and bromide transport properties in a sandy loam soil. *Biosyst. Eng.* **2011**, *109*, 90–97. [CrossRef]
58. Liu, J. Effects of Density and Row Spacing Configuration on Growth Development and Yield Quality of Cotton. Master's Thesis, Tarim University, Alar, China, 2022. [CrossRef]
59. Hu, L.; Pan, X.; Wang, X.; Hu, Q.; Wang, X.; Zhang, H.; Xue, Q.; Song, M. Cotton photosynthetic productivity enhancement through uniform row-spacing with optimal plant density in Xinjiang, China. *Crop Sci.* **2021**, *61*, 2745–2758. [CrossRef] [PubMed]
60. Wan, W.; Li, L.; Jing, J.; Diao, M.; Lv, Z.; Li, W.; Wang, J.; Li, Z.; Wang, X.; Jiang, D. Narrowing row space improves productivity and profit of enlarged lateral space drip irrigated spring wheat system in Xinjiang, China. *Field Crop. Res.* **2022**, *280*, 108474. [CrossRef]
61. Wan, W.; Zhao, Y.; Wang, Z.; Li, L.; Jing, J.; Lv, Z.; Diao, M.; Li, W.; Jiang, G.; Wang, X.; et al. Mitigation fluctuations of inter-row water use efficiency of spring wheat via narrowing row space in enlarged lateral space drip irrigation systems. *Agric. Water Manag.* **2022**, *274*, 107958. [CrossRef]
62. Afzal, M.S.; Cheema, M.J.M.; Shahid, M.A.; Arshad, M.; Khaliq, T. Optimization of subsurface drip lateral depths and irrigation levels for best yield response of onion (*Allium cepa* L.). *J. Anim. Plant Sci.* **2020**, *30*, 702–712. [CrossRef]

63. Arbat, G.; Cufí, S.; Duran-Ros, M.; Pinsach, J.; Puig-Bargués, J.; Pujol, J.; Ramírez de Cartagena, F. Modeling Approaches for Determining Dripline Depth and Irrigation Frequency of Subsurface Drip Irrigated Rice on Different Soil Textures. *Water* **2020**, *12*, 1724. [CrossRef]
64. Bhattarai, S.P.; Midmore, D.J.; Pendergast, L. Yield, water-use efficiencies and root distribution of soybean, chickpea and pumpkin under different subsurface drip irrigation depths and oxygation treatments in vertisols. *Irrig. Sci.* **2008**, *26*, 439–450. [CrossRef]
65. Patel, N.; Rajput, T.B.S. Effect of drip tape placement depth and irrigation level on yield of potato. *Agric. Water Manag.* **2007**, *88*, 209–223. [CrossRef]
66. Mo, Y.; Li, G.; Wang, D. A sowing method for subsurface drip irrigation that increases the emergence rate, yield, and water use efficiency in spring corn. *Agric. Water Manag.* **2017**, *179*, 288–295. [CrossRef]
67. Duan, J.; Wang, G.; Wang, J.; Hao, X.; Luo, H.; Yang, G. Appropriate subsurface drip irrigation depth can improve the photosynthetic capacity and increase the economic coefficient of cotton without plastic mulching. *Appl. Ecol. Environ. Res.* **2022**, *20*, 3763–3777. [CrossRef]
68. He, H.; Kang, S.; Cao, H. Effect of Lateral Depth on Root and Seedling Growth and Water Use Efficiency of Winter Wheat. *Trans. Chin. Soc. Agric. Eng.* **2001**, *17*, 31–33. [CrossRef]
69. Yan, F.; Zhang, F.; Fan, X.; Fan, J.; Wang, Y.; Zou, H.; Wang, H.; Li, G. Determining irrigation amount and fertilization rate to simultaneously optimize grain yield, grain nitrogen accumulation and economic benefit of drip-fertigated spring maize in northwest China. *Agric. Water Manag.* **2021**, *243*, 106440. [CrossRef]
70. Gebremariam, H.L.; Welde, K.; Kahsay, K.D. Optimizing yield and water use efficiency of furrow-irrigated potato under different depth of irrigation water levels. *Sustain. Water Resour. Manag.* **2018**, *4*, 1043–1049. [CrossRef]
71. Yang, M.; Leghari, S.; Guan, X.; Ma, S.; Ding, C.; Mei, F.; Wei, L.; Wang, T. Deficit subsurface drip irrigation improves water use efficiency and stabilizes yield by enhancing subsoil water extraction in winter wheat. *Front. Plant Sci.* **2020**, *11*, 508. [CrossRef]
72. Ma, X.; Han, F.; Wu, J.; Ma, Y.; Jacoby, P.W. Optimizing crop water productivity and altering root distribution of Chardonnay grapevine (*Vitis vinifera* L.) in a silt loam soil through direct root-zone deficit irrigation. *Agric. Water Manag.* **2023**, *277*, 108072. [CrossRef]
73. Aydinsakir, K.; Dinc, N.; Isik, M.; Yegin, A.B.; Ozbek, O.; Bayram, S.; Bastug, R. Determining the Effect of Deficit Irrigation Applications on Yield and Quality Parameters in Grapefruit and Economical Assessment. *J. Irrig. Drain. Eng.* **2022**, *148*, 04022018. [CrossRef]
74. Cao, Y.; Cai, H.; Sun, S.; Gu, X.; Mu, Q.; Duan, W.; Zhao, Z. Effects of drip irrigation methods on yield and water productivity of maize in Northwest China. *Agric. Water Manag.* **2022**, *259*, 107227. [CrossRef]
75. Al-Ghobari, H.M.; Dewidar, A.Z. Integrating deficit irrigation into surface and subsurface drip irrigation as a strategy to save water in arid regions. *Agric. Water Manag.* **2018**, *209*, 55–61. [CrossRef]
76. Zou, H.; Huang, X.; Gong, S. Effects of water deficit on soil moisture and temperature regimes in subsurface drip irrigated summer corn field. *Trans. Chin. Soc. Agric. Mach.* **2012**, *43*, 72–77. [CrossRef]
77. Deng, T.; Wang, J.-H.; Gao, Z.; Shen, S.; Liang, X.-G.; Zhao, X.; Chen, X.-M.; Wu, G.; Wang, X.; Zhou, S.-L. Late split-application with reduced nitrogen fertilizer increases yield by mediating source–sink relations during the grain filling stage in summer maize. *Plants* **2023**, *12*, 625. [CrossRef]
78. Hamad, A.A.A.; Wei, Q.; Xu, J.; Hamoud, Y.A.; He, M.; Shaghaleh, H.; Wei, Q.; Li, X.; Qi, Z. Managing Fertigation Frequency and Level to Mitigate N2O and CO2 Emissions and NH3 Volatilization from Subsurface Drip-Fertigated Field in a Greenhouse. *Agronomy* **2022**, *12*, 1414. [CrossRef]
79. Tanaskovik, V.; Cukaliev, O.; Kanwar, R.S.; Heng, L.K.; Markoski, M.; Spalevic, V. Nitrogen fertilizer use efficiency of pepper as affected by irrigation and fertilization regime. *Not. Bot. Horti Agrobot.* **2016**, *44*, 525–532. [CrossRef]
80. Fu, P.; Ji, H.; He, Q.; Tang, S.; Wang, H.; Wu, Y.; Meng, L. Effects of Nitrogen Fertilizer Application Times and Nitrification Inhibitor on N2O Emission from Potted Maize. *Chin. J. Environ. Sci.* **2021**, *42*, 4538–4547. [CrossRef]
81. Fu, B.; Li, Z.; Gao, X.; Wu, L.; Lan, J.; Peng, W. Effects of subsurface drip irrigation on alfalfa (*Medicago sativa* L.) growth and soil microbial community structures in arid and semi-arid areas of northern China. *Appl. Soil Ecol.* **2021**, *159*, 103859. [CrossRef]
82. Kim, J.; Kim, P.; Kim, S.; Kim, J.; Eum, D.; Lee, S. Pressure drop analysis of subsurface irrigation dripper system and its flow rate uniformity. *J. Mech. Sci. Technol.* **2023**, *37*, 203–208. [CrossRef]
83. Wang, J.; Niu, W.; Li, Y.; Lv, W. Subsurface drip irrigation enhances soil nitrogen and phosphorus metabolism in tomato root zones and promotes tomato growth. *Appl. Soil Ecol.* **2018**, *124*, 240–251. [CrossRef]
84. Lamm, F.R.; Colaizzi, P.D.; Sorensen, R.B.; Bordovsky, J.P.; Dougherty, M.; Balkcom, K.; Zaccaria, D.; Bali, K.M.; Rudnick, D.R.; Peters, R.T. A 2020 vision of subsurface drip irrigation in the US. *Trans. ASABE* **2021**, *64*, 1319–1343. [CrossRef]