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Comprehensive Assessment of Plant and Water Productivity Responses in Negative Pressure Irrigation Technology: A Meta-Analysis

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Abstract: Negative pressure irrigation (NPI) is an important water management strategy that can improve crop yields and water use efficiency (WUE). However, because NPI is affected by vital factors, such as negative pressure values, soil properties, and fertilization dosages, there is a lack of systematic analyses of the application effects of NPI on various crops. Hence, this study collected the results of 44 published studies and established the validity of 142 crop yields, 121 WUEs, 138 crop qualities, and 138 crop nutrient statuses in a database for NPI systems. The meta-analysis method was used to analyze NPI in comparison to conventional irrigation (CI) conditions. The results showed that the NPI yields and WUEs significantly improved by 17% and 63% compared to those of CI, respectively. Meanwhile, the negative pressure values were −2~−5 kPa; the improvement effects on yields were the best; and the WUEs exhibited the highest performance with negative pressure values of −6~−10 kPa. NPI promoted crop quality and plant nutrient uptakes under the appropriate NPI conditions. The synergistic impacts for sandy loam, alkalescent soils, and leafy vegetables were greater than for clay loam, neutral soils, and fruit vegetables under NPI conditions. Simultaneously, it was shown that the soil available phosphorus content and application of P fertilizer have a greater impact on NPI and CI crop yields. Therefore, the meta-analysis demonstrated the impacts of NPI on crop yields, WUEs, quality, and nutrient absorption, and quantified the effects of NPI on crop growth under various conditions, which provides an important water-saving technology for greenhouse production.

Keywords: negative pressure irrigation; yield; quality of plant; water use efficiency; fertilization

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1. Introduction

The growth and development of crops depends on the absorption of large amounts of water, and artificial irrigation is the main source of water to satisfy crop water requirements [1–3]. Conventional irrigation (CI) systems, such as furrows, depressions, and flood irrigation, have relatively low water use efficiencies (WUE), while advanced water-saving technologies, including sprinkler, drip, microspray, and alternate root zone irrigation, provide significantly improved WUEs [4–7]. The introduction of irrigation water into farmland requires human labor and equipment, and the process for water to enter soils depends entirely on human irrigation [3,8]. Crop and soil systems are consistently in a state of passively receiving irrigation water [5,9]. In the past 20 years, negative pressure irrigation (NPI) technology has been developed, which is based on the active absorption of soil water by crops, and water enters the soil under the driving forces of the physiological activities of crop transpiration and water consumption characteristics, which can continuously and smoothly supply crops with water for its absorption and utilization from soil [5,10–12].

NPI is a new type of subsurface irrigation technology, which is also known as active water absorption by crops. The processes by which soil supplies water to crop roots, water supply time, intensity, and water consumption mainly depend on the physiological needs of dryland crops [13–15]. Due to transpiration and the absorption of soil water by root systems, which cause the soil matrix potential to have a gradient between the soil and emitter, the water absorption force spreads out through the soil and attracts water away from the rhizosphere and into root systems [3,10,16]. When the water absorption force of the crops is less than or equal to the external water suction force, crops suspend their absorption of water from the soil, and the outside biotope stops supplying water to the soil [5,15,17]. This ensures that crops can be supplied in a stable manner with suitable water amounts for growth in NPI systems. Since the water supply process is regulated by the controllable negative pressure that is generated in the system, the technology is named "negative pressure" [3,5,18].

At present, NPI has been used in practical research in greenhouse production, which is mainly manifested by the fact that dryland crops have suitable pressure values (e.g., within the range from −2 to −10 kPa) [3,8,19]. For example, the yields of rape, pepper, cucumber, lettuce, tomato, and other crops under suitable negative pressure conditions have shown significant increases from 29% to 77%, and the WUEs have increased from 35% to 166% compared with CI [3,20,21]. NPI also improves the absorption of nutrients and the utilization efficiency of nutrients by crops [15–17]. In addition, NPI affects the soil nutrient availabilities and spatial distributions, soil microbial diversities, and soil and plant enzyme activities [9,11,22,23]. The study also found that NPI increased the microbial diversities in the rhizospheres of rape and tomato (OUT, Chao1, Shannon) and the activities of catalase, urease, and phosphatase in pepper and tomato soils [9,24,25], and it decreased the levels of the superoxide anion, malondialdehyde, proline, catalase, and polyphenol oxidase in maize under NPI conditions [26]. This is proof enough that NPI has emerged as a key potential solution for reducing water extraction in the context of increasing agricultural intensification and climate change. Given its importance, Yang et al. (2022) systematically reviewed the development of NPI in recent years through literature analysis [8]. However, the study lacks a quantitative analysis of the crop yield and WUE by NPI. In addition, although NPI has provided many research achievements, the results occasionally appear to be discrepancies or contradictions, and there is a lack of independent systematic combined analyses of results with common research destinations, analyses of the diversity among studies, and quantitative comprehensive evaluations of research results.

Previous studies have focused on the effects of different negative pressure values on crop growth and WUEs. The results indicated that different crops favor different negative pressure values of NPI. In fact, the efficiency of NPI is also affected by the soil texture, soil property, and water and fertilizer applications, which cannot be ignored. To comprehensively understand the full effect of NPI on crop growth and its relationship with soil physicochemical properties, published experimental data were collected for a synthetic analysis between NPI and crop growth, and these were systematically quantified. The data collection step was carried out by using the published articles related to NPI, and the meta-analysis method was used to systematically analyze the effects of NPI on crop yield and quality, water use efficiency, and nutrient absorption, as well as to clarify the negative pressure values. According to the existing data that were mined, the appropriate fertilization dosages under NPI were quantitatively recommended and would provide a theoretical basis for the development of NPI technology.

2. Materials and Methods

2.1. Data Collection

We collected data from published papers by using the Web of Science (https://www.webofscience.com (accessed on 1 January 2020)) and China National Knowledge Infrastructure (https://www.cnki.net (accessed on 1 January 2020)) databases between 1 January 2000 and 31 December 2021 and used the following 4 search terms: "negative pressure irrigation", "negative emitter irrigation", "negative pressure water supply technology", and "negative emitter water supply". The literature screening was conducted based on the following conditions: (1) the experiment was conducted by using potted and greenhouse experiments; (2) the same experiment must include both an NPI treatment and conventional irrigation treatment and provide yield or water use efficiency or quality or crop nutrient status index data; and (3) the basic physical and chemical indices for the 0~20 cm soil layer are included in the literature. A total of 44 peer-reviewed papers spanning 142 sets of crop yield data, 121 sets of water use efficiency data, 138 sets of crop quality data, and 138 sets of crop nutrient status data were included in this meta-analysis.

A schematic diagram of the negative pressure irrigation system designed by the Chinese Academy of Agricultural Sciences is shown in Figure 1a [5,9,25]. Figure 1b,c show the cultivation of cucumber and rapeseed with NPI in greenhouse production, respectively [3,9].

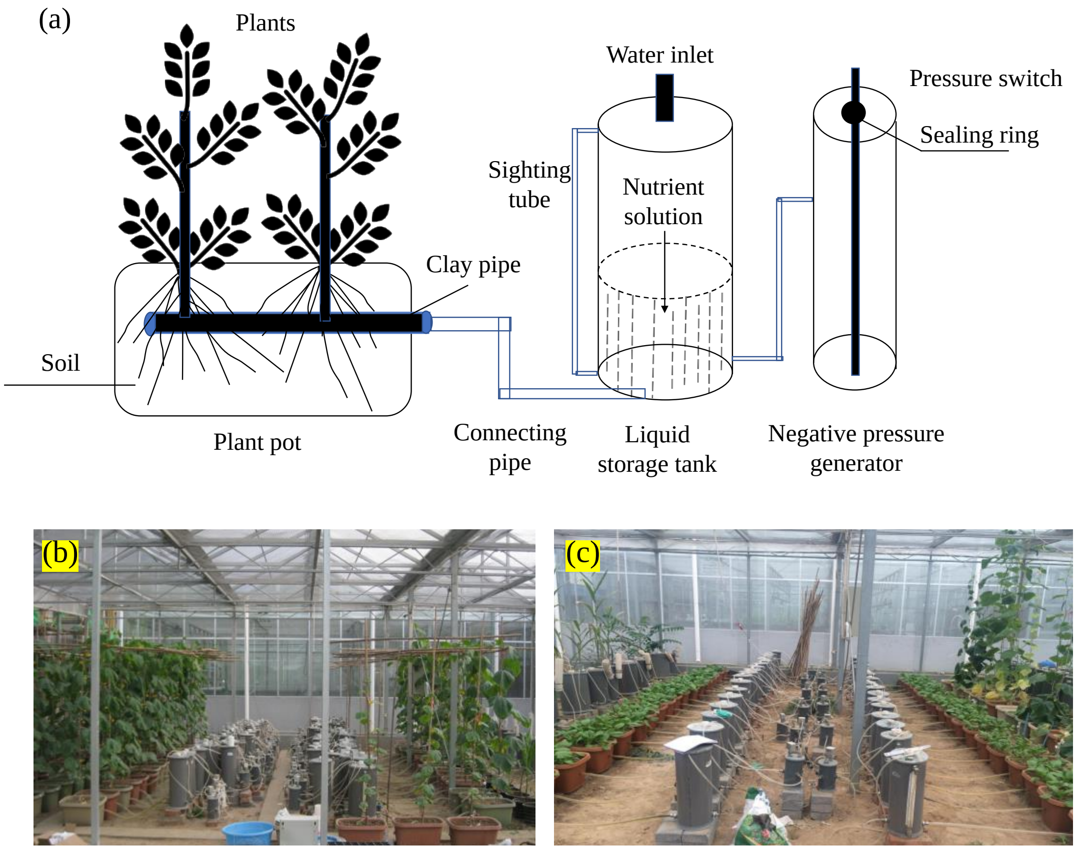

Figure 1. Schematic of plant growth when using a negative pressure irrigation system (**a**). Negative pressure irrigation applied to cucumber [3] (**b**) and rapeseed [9] (**c**) in greenhouse production.

2.2. Data Analysis

In the meta-analysis method, the standard deviations and number of repetitions of the experimental group and control group are very important parameters. If the original literature clearly mentions the sample sizes, mean, and standard deviations (or standard errors), the data were directly extracted. If the standard deviations were not provided directly in the literature, these studies were processed in the following two ways: (1) The data for each treatment are listed. When there were multiple replicates of experimental data, the experimental data were sorted with Excel to obtain the means and standard deviations. (2) The corresponding standard deviations are estimated based on the ratios of the existing standard deviations to the means [27]. If only graphs of the above data parameters are presented in the literature, GetData Graph Digitizer software was used for data extraction.

2.3. Data Calculation

Only the standard error (SE) was provided in the literature, which was converted to the standard deviation (SD) using Formula (1):

$$\mathrm{SD} = \mathrm{SE} \times \sqrt{n} \quad (1)$$

The statistical indicators were expressed as the response ratio (RR) and calculated by Formula (2) and the logarithm of the response ratio (lnRR) to reflect the effect of negative pressure irrigation on conventional irrigation:

$$\mathrm{RR} = \frac{\mathrm{A_t}}{\mathrm{A_c}} \quad (2)$$

$$\mathrm{lnRR} = \frac{\mathrm{lnA_t}}{\mathrm{lnA_c}} = \ln \mathrm{A_t} - \mathrm{lnA_c} \quad (3)$$

The sampling variance for each lnRR was calculated using Formula (4):

$$\mathrm{V} = \frac{\mathrm{SD_t^2}}{\mathrm{A_t^2 n_t}} + \frac{\mathrm{SD_c^2}}{\mathrm{A_c^2 n_c}} \quad (4)$$

In the formula, $\mathrm{SD_t}$, $\mathrm{A_t}$, and $\mathrm{n_t}$ are the standard deviation, mean, and number of samples of the experimental group, respectively; $\mathrm{SD_c}$, $\mathrm{A_c}$, and $\mathrm{n_c}$ are the standard deviation, mean, and number of samples of the control group, respectively.

To facilitate the interpretation, the change percentage of the crop yield, WUE, quality, and nutrient uptake under the NPI treatment compared with the CI treatment was calculated using the following formula:

$$\text{Effect size (\%)} = (\exp(\mathrm{lnRR}) - 1) \times 100 \quad (5)$$

The meta-analysis was performed including the studies as random factors using the rma function in metafor (setting method "REML"), which was necessary to reduce data dispersion due either to the experimental design or the measuring method.

If the 95% confidence interval does not include zero points, this means that NPI has a significant effect as compared to conventional irrigation; otherwise, this means that there was no significant effect. If all values fall on the negative semi-axis, this means that the negative pressure irrigation provided a negative effect; otherwise, this means that there was a positive effect. To evaluate the quality of our meta-analysis, we determined Egger's tests. The results show that there is no publication bias in any of the data ($p > 0.05$, Table 1). We also performed a sensitivity analysis of the meta-analysis results using the Leave1out function in the R software metafor package, and the results showed that the conclusions of this study were reliable.

Table 1. Publication bias test of relevant data—Egger's test.

	Sample Size (n)	Z Value	*p* Value
Crop yields	135	0.5472	0.5842
Water use efficiencies	113	−0.1597	0.8731
Crop quality	132	0.7764	0.4375
Nutrient content	54	1.7533	0.0796
Nutrient concentration	63	−0.9302	0.3523

Note: $p > 0.05$ indicates that there is no publication bias.

The above data processing was performed in R 4.1.0, and Origin 2019b was used for graphing.

3. Results

3.1. Effect Size on Crop Yield under NPI

As shown in Figure 2, NPI significantly improved crop yields by 17.4% compared to conventional irrigation (CI) (all effect sizes and their 95% confidence). However, the crop yield responses showed discrepancies for various levels of negative pressure values, and the crop yields were noticeably improved for the ranges of −2~−5 kPa and −6~−10 kPa. Among these, −2~−5 kPa provided the best yield increase (41.6%), while negative pressure values of −12~−15 kPa remarkably reduced crop yields (−26.2%). The yield-promoting effects of NPI on a variety of crops were different; leafy vegetables had the best yield increase (30.2%), followed by fruit vegetables (8.0%).

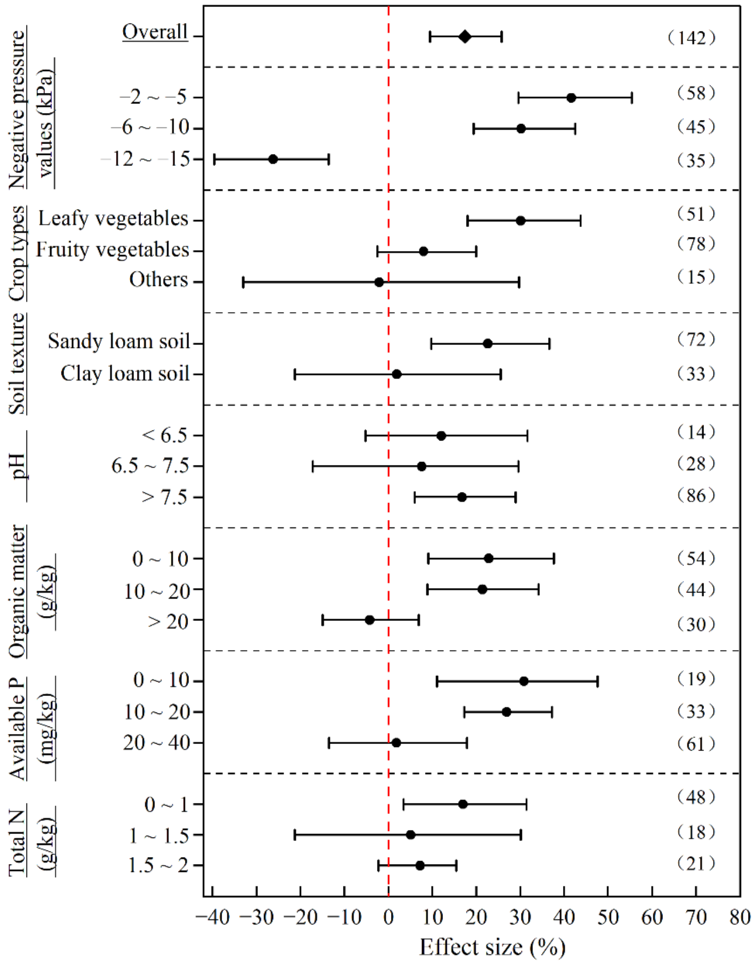

Figure 2. Effect size analysis of various factors on crop yields under negative pressure irrigation compared with conventional irrigation conditions. P, phosphorus; N, nitrogen.

The soil impacts on crop yields vary according to texture (Figure 2). NPI produces a noteworthy yield increase for sandy loam (22.7%) but not for clay loam. Simultaneously, NPI boosts crop yields in alkalescent soils (16.8%), but the effect size was not seen for neutral soils. The effect of NPI on the crop yield was influenced by the soil organic matter content. NPI significantly increased the crop yield at soil organic matter levels below 20 g kg^{-1}. NPI significantly increased the crop yield at soil available phosphorus levels between 0 and 20 mg kg^{-1}, while this effect was not significant at 20~40 mg kg^{-1}. When the soil total nitrogen content was 0~1 g kg^{-1}, NPI significantly increased the crop yield (17.0%).

3.2. Effect Size on Water Use Efficiency under NPI

NPI significantly increased the WUEs of crops under various factors by 62.6% (Figure 3). Differing from the yields, the WUEs are associated with minor differences under various negative pressure values, with the highest WUEs occurring for the range of −6~−10 kPa (75.1%), followed by −12~−15 kPa (67.3%), and then by −2~−5 kPa (53.5%). The WUE results for various crop species were not consistent with the yields, and leafy vegetables (72.8%) were slightly better than fruit vegetables. The WUEs were higher in sandy loam soils than clay loam soils, which were consistent with the yield results. NPI had the greatest impact on the WUEs in alkaline soils (pH > 7.5). The effects of the soil organic matter, available phosphorus, and total N changed significantly with the difference in content under NPI conditions. NPI may significantly increase the WUE under a different organic matter content, and the increase was the best under a low organic matter content (0~10 g kg^{-1}). The subgroups of the available P and total N showed the same trend in the results as organic matter.

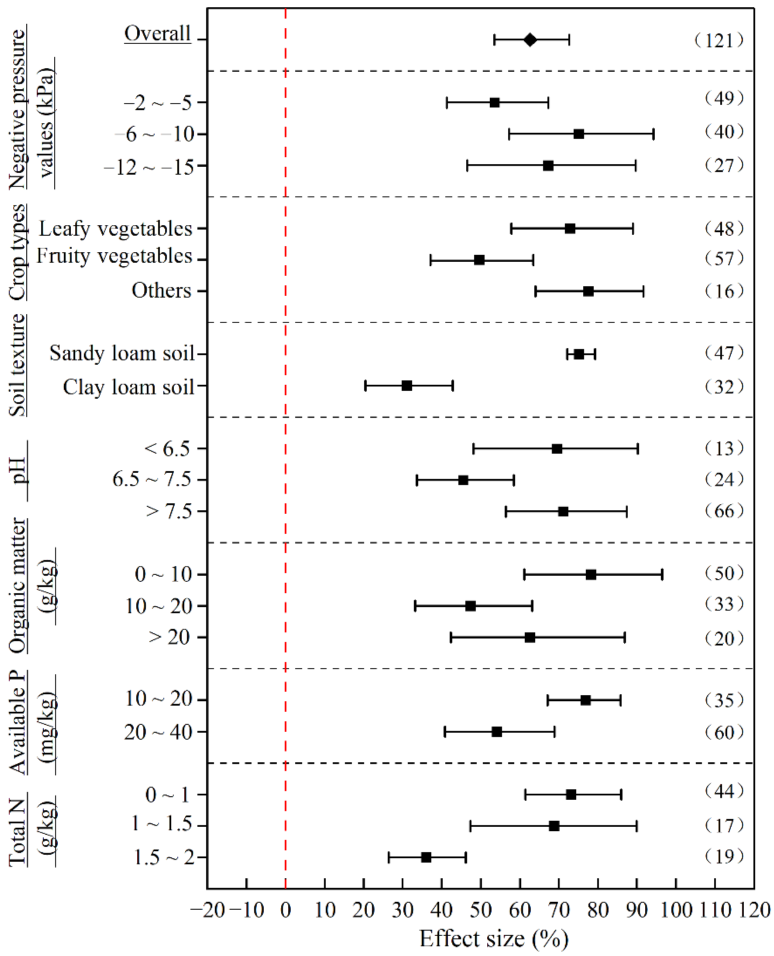

Figure 3. Effect size analysis of various factors on water use efficiencies under negative pressure irrigation compared with conventional irrigation conditions. P, phosphorus; N, nitrogen.

3.3. Crop Quality and Nutrient Uptake on NPI

The quality indicators used in this study were the soluble sugar content, vitamin C (Vc), nitrate, and soluble protein, as shown in Figure 4. NPI markedly increased the crop soluble sugar and Vc contents, and the effect sizes were 15.0% and 16.5%, respectively. The nitrate contents were significantly reduced by 11.7%. However, the effects were not significant for soluble proteins. NPI also significantly promoted the uptakes of the nitrogen (N), phosphorus (P), and potassium (K) contents and concentrations in plants.

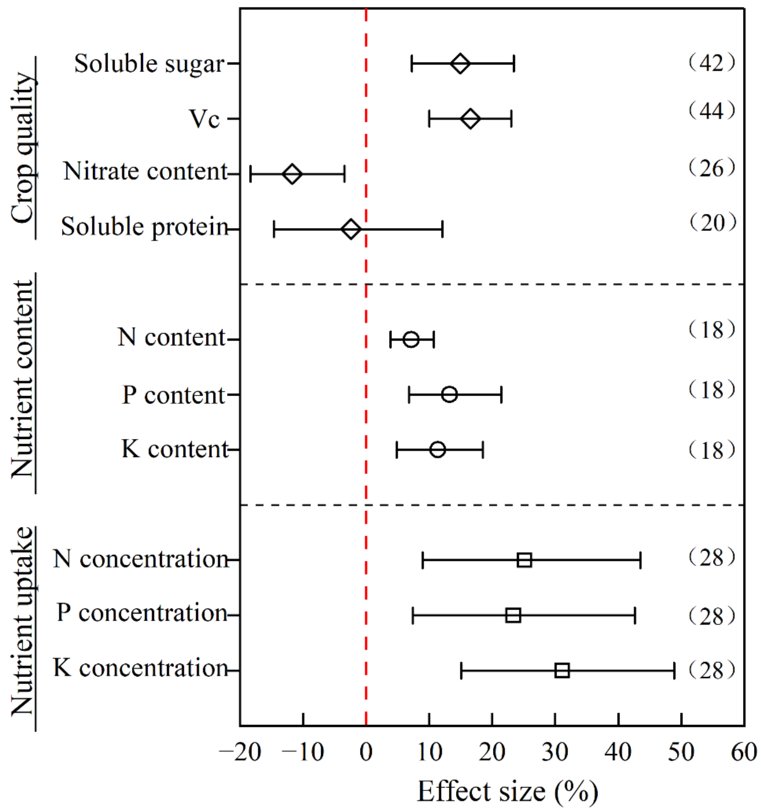

Figure 4. Effect size analysis of various factors on crop quality and nutrient uptake under negative pressure irrigation compared with conventional irrigation conditions. P, phosphorus; N, nitrogen. K, potassium.

3.4. Analysis of Factors Influencing Yield under NPI and CI

In order to evaluate the effect of NPI's application, the random forest model in the R Programming Language was used to analyze the influence of various soil factors on crop yield (Figure 5). The variance explanation degrees of the nine factors included in the analysis of the NPI and CI crop yields were 76.98% and 93.68%, respectively, indicating that these nine factors may well explain the impact on crop yield.

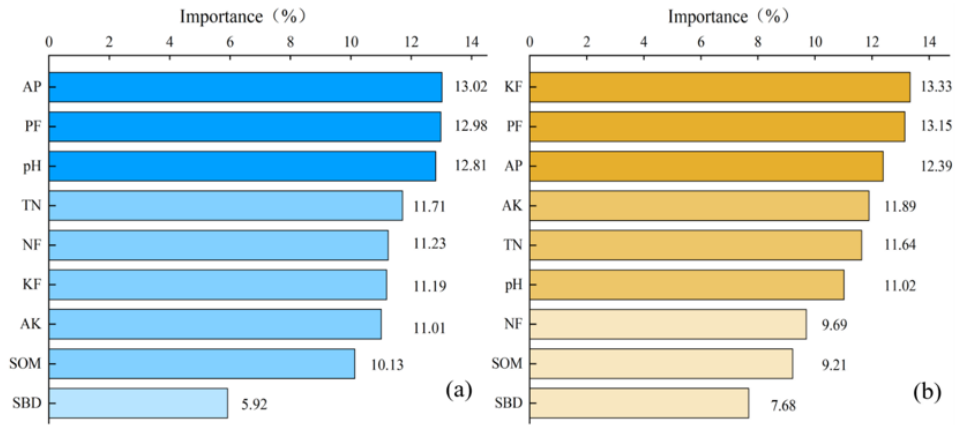

Figure 5. Influencing factors analysis under NPI (**a**) and CI (**b**). AP represents available soil phosphorus, PF represents application amount of phosphorus fertilizer, TN represents total soil nitrogen, NF represents application amount of nitrogen fertilizer, KF represents application amount of potassium fertilizer, AK represents available soil potassium, SOM represents soil organic matter, and SBD represents soil bulk density.

The major factors affecting the yield under NPI were the soil available phosphorus, phosphorus fertilizer application, and soil pH, and the soil organic matter (SBD) had the least effect (Figure 5a). The potassium and phosphorus fertilizer applications were the main factors affecting the CI yield, followed by the soil available phosphorus (Figure 5b).

4. Discussion

4.1. NPI Improves Crop Yields and WUEs

The advantage of NPI is that it can generate a stable water supply, assist the soil water contents to remain within a stable range, and ensure that crops take up water according to their physiological needs [5,21,26]. For example, under NPI, the soil water content remained relatively stable between 9.7 and 11.7%, which was less than 8.6–13.3% of the CI fluctuation range in rapeseed, thereby avoiding the stress of wetting and drought [9]. Determining a suitable water supply pressure value is a basic key approach when applying NPI. Through the meta-analysis, it was found that the crop yields generally showed trends of first increasing and then decreasing with supply pressure reductions (the absolute value of the pressure value increased) on a negative pressure generator (Figure 2). The meta-analysis indicated that negative pressure values of −2~−5 kPa had the best performance with respect to the yields, and negative pressure values of −12~−15 kPa were too low. The crops exhibited symptoms of water shortage, which resulted in reduced yields. This is primarily because the negative pressure water supply devices are buried in the soil without water saturation, and the water supplied pressure of the external water of NPI is lower than the atmospheric pressure, which limits the supply of water [3]. For example, when the negative pressure value was −5 kPa, the cabbage yields increased by 51% compared with a value of −10 kPa [28], and the cucumber yields increased by 45% at −5 kPa compared to 0 kPa [29]. The water and fertilizer supply modes of NPI are conducive to the uptake of water and fertilizer by root systems through the soil, which thereby improve the operation and accumulation of the substances assimilated in plants [14,30]. An appropriate water supply increases the biomass of crops, improves photosynthesis, and improves the ability of roots to absorb soil nutrients [9,25]. Therefore, it is meaningful to discuss crop yields and WUEs under suitable pressure values.

In the 121 sets of data analyzed, the WUEs significantly improved under NPI (Figure 3). For example, tomato and rapeseed decreased their water consumption levels by 20% and 23% compared to CI, respectively, and their WUEs also improved [9,15]. This is due to the crops under NPI absorbing water according to their physiological needs by maintaining unsaturated water in the rhizosphere and by reducing surface evaporation and deep leakage loss of water from the soil [9,12,21]. Simultaneously, NPI is able to transport water directly to the rhizosphere to accurately and constantly supply water to crops [5,19]. Furthermore, negative pressure values in the range from −2 to −15 kPa could improve the WUE, while the range of −6~−10 kPa resulted in the best performance (Figure 3). In addition, considering the differential influences of the NPI values on the crop yield and WUE, it was difficult to achieve a balance of the best effects of the three factors. For example, when the negative pressure of the water supply was −5 kPa, the WUE was 11% higher than that at 0 kPa [29]; simultaneously, for pepper, the WUE was 32% higher at −5 kPa than at −10 kPa [31]. In an experiment conducted on Chinese cabbage, the yields increased by 32% at −5 kPa compared to −10 kPa, but the WUEs decreased by 52% [28]. The fundamental reason is that providing different negative pressure values leads to different soil matrix changes, thereby altering the water requirements of the plants under NPI.

Soil texture is closely related to the distribution and transport of water and nutrients in the soil layer under NPI conditions [32,33]. There are significant positive impacts on sandy loam, alkalescent soils (pH > 7.5), soils with low organic matter contents (e.g., 0~10 g kg^{-1}), and available P levels of 0~20 mg kg^{-1} under NPI conditions (Figures 2 and 3). Mainly, the cumulative infiltration, horizontal and vertical distances, and wet volumes of clay loam soils under NPI were significantly higher than those for sandy loam soils [34]. For the same pressures and water supply times, the same results were also observed [32]. Moreover, soil layers with higher clay contents are prone to salt accumulation at their interfaces [35]. For the same soil matrix potential level, clay loam soils have better water and fertilizer retention capacities than sandy loam soils, and the soil volumetric water contents and water uptake capacities are greater [3,22]. However, NPI that supplies water from the rhizosphere can significantly improve the low infiltration of sandy loam soils and increase the WUEs.

The analysis of the 72 groups of collected data concluded that sandy loam soils exhibit more obvious impacts on increasing yields under NPI conditions (Figure 2). The higher air permeabilities of sandy loam soils are more conducive to microbial activity. NPI significantly increases the numbers and activities of soil microbial populations and promotes the decomposition of organic matter, such as humus [3,9,24]. NPI simultaneously stimulates the growth of rhizosphere soil microorganisms and decomposition of soil humus, which is beneficial to the transformation, absorption, and utilization of nutrients [36]. The pH values of the applied water-soluble fertilizers are approximately 5.5, which makes it easier to neutralize the pH values in alkalescent soils, and the root systems can adjust the soil pH after nutrient uptake, which avoids reductions in pH values in acidic soils. However, soils with low organic matter contents and available P levels can significantly increase crop yields under NPI (Figure 2). This is primarily because NPI directly supplies water and nutrients to the rhizospheres of crops, which can be actively absorbed and utilized by the root systems, and avoids nutrient loss and volatilization caused by traditional irrigation methods [9,21]. Therefore, low-nutrient soil environments are suggested to be more conducive to applications of NPI in greenhouse production.

The root systems of leafy vegetables are not strongly developed, and they can only take up shallow soil water, which is easily lost by evaporation, but NPI mainly supplies water at depths from 15 to 20 cm from the soil surface [9,17,21]. This is just enough to meet the water uptake by the root systems in this area, so the effect of increasing the yields of leaf vegetables is better than that for fruit vegetables, such as cucumber and tomato [28,29]. Another consideration is that leafy vegetables consume less water and nutrition than fruit vegetables, which results in higher yield increase ratios than fruit vegetables.

4.2. NPI Benefits Crop Quality and Nutrient Uptake

Crop quality can be improved by reasonably controlling the soil water contents to provide a suitable water environment for crops under NPI conditions [9,17,19,25]. For example, the soil water contents of rapeseed under NPI were relatively stable, with a range from 9.7% to 11.7%, compared with the soil water contents that appear to vary greatly with CI, with a range from 8.6% to 13.3%, and result in improved quality and N, P, and K contents in rapeseed of 21~57% [9]. Meanwhile, the vitamin C and soluble sugar contents of pak choi, lettuce, and tomato increased by between 23% and 35% with NPI compared to CI [3,15,37]. This is because appropriate water and nutrient contents are beneficial for increasing the stomatal conductances and chlorophyll contents of plants, reducing osmoregulation in the pericarp, promoting vitamin C, and increasing the concentrations of sugar entering the phloem [21,38,39]. In addition, decreasing the application of N fertilizer by 30% with NPI also increased the N uptake of plants by 11% and the nitrogen use efficiency as compared with CI [25]. Meanwhile, increasing the K absorption by crops can promote nitrate metabolism, reduce nitrate contents, and increase the soluble sugar and vitamin C contents in plants [15,29]. Furthermore, the K uptake levels increased by 48%, and the K utilization rates increased by 12% with NPI (-10 kPa value) as compared with CI [40]. However, nutrient applications on the soil surface, especially of N fertilizer, easily cause volatilization and leaching, which not only cause the loss of N but also decrease the quality of crops due to the uptake of excessive nitrate.

4.3. Fertilizer Savings under NPI Conditions

Planting crops decreases the fertilization dosages that are needed with NPI systems compared with CI, but excessive fertilizer applications did not significantly improve the crop yields [3,9,25]. It was found that the NPI application rates of N, P, and K decreased by 30% compared with CI, but the yields were not significantly different in greenhouse production [23]. Meanwhile, the N dosage for lettuce under NPI was 20% lower than that under CI, and its yields still significantly increased by 14% [25]. The primary reason is that the fertilizer dosages that are applied to vegetables are generally high in China's greenhouses [41,42], which mainly rely on furrow and drip irrigation technologies that are applied to the soil surface and easily cause the volatilization and leaching of N fertilizer. However, NPI can solve this shortcoming; the utilization efficiency of N fertilizer in cucumber increased by 52%, and the K utilization efficiency increased by 20%; simultaneously, the uptakes of NPK by tomato, lettuce, and cucumber increased by between 12% and 60% compared with CI [3,20,23].

In addition, using an appropriate fertilizer dosage improves crop yields and fertilizer use efficiencies under NPI conditions [9,23,25]. For example, for rapeseed irrigation with water and fertilization under NPI, the production was highest with a dose of 225 N kg ha^{-1}, compared with other N application treatments, and dosages of excessive amounts of fertilizer resulted in significant production declines [9]. Compared with the same N fertilizer dosage as CI, the N amounts can be reduced by 30% under NPI, but the yields did not decrease; the utilization of ammonium nitrogen can be improved, and the nitrate nitrogen levels can be reduced, which result in the mitigation of N_2O emissions [25]. Excessive applications of N fertilizer pollute rivers and groundwater and lead to high levels of greenhouse gas emissions [43,44].

This study found that NPI yields increased by 17% compared to a uniform dosage with CI, it provides guidance on fertilizer dosages for future research of NPI by using the meta-analysis, which would be helpful for fertilization management. The analysis of the yield influencing factors also showed that phosphorus fertilizer and potassium fertilizer had greater influences on the crop yield under negative pressure and conventional irrigation (Figure 5). Therefore, while considering reductions in the fertilizer applications under NPI, their impact on the environment can also be studied, especially large-scale N fertilizer applications and the mechanisms of soil and greenhouse gas emissions, which deserve further investigation.

At present, the research on NPI mainly applies to vegetables, especially those with shallow root systems, such as rapeseed, spinach, and lettuce [9,24,25]; it has been less frequently applied to cereals and fruits, and there are also few experimental studies in the field [3]. In addition, it is necessary to use NPI technology in water-deficient areas to solve water shortage problems. Moreover, most of the water emitters used for NPI consist of ceramic heads, which are expensive and only have a service life from approximately 1 to 2 years, and the phenomenon of micropore blockage will occur, which is also one of the technologies that needs improvement [3,8]. In short, the combination of the water and fertilizer integration technologies of NPI can save water and nutrients and improve the yields and quality of crops. Negative pressure irrigation is an important strategy to solve the water resource shortage in China.

5. Conclusions

Overall, NPI significantly promoted crop yields, water use efficiencies, quality, and nutrient uptakes when compared to conventional irrigation. Negative pressure values of $-2\sim-5$ kPa were the best indicator of the crop yields, followed by the values of $-6\sim-10$ kPa and $-12\sim-15$ kPa, which decreased yields, while the WUEs exhibited the highest performance at $-6\sim-10$ kPa. The yield increases of leafy vegetables were significantly higher than those of fruit vegetables, and the WUEs were slightly higher for fruit vegetables. There was a dominance of sandy loam over clay soils and of alkalescent soils over neutral soils under NPI conditions. The soil available phosphorus (P) content and application of P fertilizer have a greater impact on the NPI and CI crop yields.

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