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Gravel Mulching Significantly Improves Crop Yield and Water Productivity in Arid and Semi-Arid Regions of Northwest China: Evidence from a Meta-Analysis

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Abstract: In the arid and semi-arid regions of Northwest China, periodic rainfall deficits, high field evaporation, limited freshwater resources, and high irrigation costs restrict crop yield and water productivity (WP). Gravel mulching (GM), a traditional agricultural tillage management practice widely used in arid and semi-arid regions, improves crop yield and WP. However, the combined impacts of GM on crop yield and WP are unclear. This study aimed to examine the effects of GM on crop yield and WP under different factors and to find the most critical regional factors and gravel characteristics that affect crop yield and WP. To quantitatively assess the impact of GM on crop yield and WP, this study performed a meta-analysis, a regression analysis, and a path analysis of 185 yield comparisons and 130 WP comparisons from 30 peer-reviewed scientific reports. This study found that GM significantly increased crop yield and WP by an average of 29.47% and 28.03%, respectively. GM was reported with the highest response percentages (I) of crop yield and WP in regions whose average annual precipitation (AAP) was 200–400 mm, average annual temperature (AAT) was 0–9 °C, and altitude (A) was >1000 m. Overall, AAP, AAT, and A had significant effects on the I of crop yield ($p < 0.001$), but AAT and A had an insignificant impact on the I of crop WP ($p > 0.05$). Gravel size (GS), the amount of gravel mulching (AGM), the degree of gravel mulching (DGM), and the gravel mulching thickness (GMT) had a significantly positive impact on crop yield and WP ($p < 0.05$). The stepwise multiple linear regression analysis results indicated that the primary regional factors influencing yield were AAT and A, contributing 43.14% and 53.09%, respectively. GMT and GS were identified as significant gravel characterization factors impacting yield, contributing 82.63% and 17.37%, respectively. AAP and GMT were the main regional factors and gravel characterization factors affecting WP. Furthermore, the I values for cash crop yield and WP were higher than that for food crops, and moderate fertilization and irrigation would increase the I values of yield and WP. The benefits of GM are strongly correlated with the planting year. This study's results show that GM generally improves crop yield and WP, although the extent of this impact varies based on different conditions. These findings are not only useful in relation to their direct applicability to other countries worldwide but also due to their potential to provide new ideas for agricultural practices in similar crop-growing environments.

Keywords: gravel mulching; climatic condition; gravel characteristics; management practice; statistical analysis; crop productivity

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Citation: Wu, Y.; Jia, Z.; Li, W.; Gao, S.; Zhang, X.; Niu, X.; Huang, Y. Gravel Mulching Significantly Improves Crop Yield and Water Productivity in Arid and Semi-Arid Regions of Northwest China: Evidence from a Meta-Analysis. *Agronomy* **2024**, *14*, 1717. https://doi.org/10.3390/agronomy14081717

Academic Editor: Paula Paredes

Received: 27 June 2024
Revised: 16 July 2024
Accepted: 2 August 2024
Published: 4 August 2024

1. Introduction

Dryness is one of the most severe constraints limiting global crop production, and global warming is expected to make dryness events more severe and frequent [1]. Approximately 45% of the Earth's land surface consists of arid regions, also known as drylands [2]. The availability of soil water primarily influences the growth of crops in arid areas. Water resource scarcity in arid and semi-arid regions is the critical factor restricting the efficient utilization of cultivable land and agricultural production. With the increasing global demand for food, adequate water and nutrient resources are crucial determinants of food production. As a result, human water resource utilization is facing serious challenges [3]. Particularly in the arid and semi-arid regions of Northwest China, harsh natural environments restrict crop yields and water productivity (WP, i.e., the ratio of yield to evapotranspiration (ET)) [4–6]. In the context of water and food scarcity, managing water resources in agriculture has become critical as water is one of the major inputs affecting crop yields. Producing more food with limited water resources by adopting a range of water management practices and agronomic technologies has become one of the core objectives for achieving sustainable agricultural development [7,8].

The scarcity of water resources have prompted the adoption of various agronomic techniques, which include rainwater harvesting, farmland mulching, no-tillage farming, intelligent agricultural system, etc., in order to conserve water for utilization in crop production in arid and semi-arid regions [9–11]. Among these, farmland mulching is a global agronomic technique, especially in arid and semi-arid regions. Organic materials (e.g., agricultural wastes and animal manures), inorganic materials (e.g., polyethylene plastic films and synthetic polymers), and specialty materials (e.g., sand, gravel, and concrete) are the three typical types of farmland mulching materials [12,13]. Farmland mulching has been widely used in arid and semi-arid regions due to the advantages it brings by improving soil properties, hydrological processes, and crop productivity [14,15]. Therefore, mulching materials significantly impact agricultural water conservation and crop yield by altering soil's physical, chemical, and biological properties [16]. Farmland mulching has the advantages of retaining soil moisture, regulating temperature, and reducing soil erosion [17]. Still, residual film from the film mulching process can contaminate the environment [18], straw mulching may increase pest infestation [19], and the benefits of GM diminish with each year of continuous cropping [20]. However, each mulching method presents distinct advantages and drawbacks, making it appropriate for specific conditions while less optimal for others [17].

Gravel mulching (GM) has a history of more than 300 years of being used as a conservation tillage method in the arid and semi-arid regions of Northwest China [21,22]; it originated in Gansu and its use is mainly distributed in Gansu, Ningxia, and parts of Qinghai to provide favorable conditions for crop growth [23]. Besides China, soils with gravel on their surface are widespread worldwide and may be found in areas near the Mediterranean Sea, the USA, and Western Europe [24]. GM is also found in several other arid and semi-arid regions of the world, such as in Northern New Mexico in the United States of America [25], Chamoson in Switzerland [26], and some parts of South Africa [27]. GM significantly impacts soil physical properties, particularly in regulating critical hydrological processes such as soil moisture evaporation, infiltration, and run-off [28,29]. GM has also been shown to reduce soil erosion, prevent the loss of nutrients and organic matter from the soil, and favorably reduce soil temperature fluctuation between day and night [30–32]. Additionally, GM impacts soil pH and elemental composition [33,34], modifying soil enzyme activity and microbial biomass [35]. Many scholars have proven GM to be a practical, effective technique for studying and realizing better water-saving, high-yield, and high-efficiency unification [36–38]. Thus, GM can mitigate the effects of water scarcity on crops and plays an essential role in soil moisturization, temperature regulation, wind erosion reduction, and soil environment improvement. Factors affecting the effectiveness of GM are complex, and current research on GM is not comprehensive. So, more factors need to be considered to study the combined effects of GM on crop yield and WP in order to assess its applicability in different regions. As a typical traditional agronomic technique still common in the Loess Plateau region of China, the value of GM research lies not only in its direct applicability to other countries around the world but also in its potential to provide new ideas for agricultural practices in similar crop-growing environments.

A meta-analysis involves a more systematic, objective, and quantitative synthesis of multiple independent research results with the same purpose [39]. Unlike individual studies with limited sample sizes, which may cause insignificant statistical results concerning crop yield, a meta-analysis consolidates data from multiple independent studies with similar experiments, thereby increasing the sample size and enhancing the statistical accuracy of the analysis. Crucially, conducting a meta-analysis on contentious or conflicting studies allows for more apparent conclusions and a more precise estimation of the effect of a specific treatment. By synthesizing data from such studies, a meta-analysis can provide greater clarity and accuracy in determining the overall impact of the treatment under investigation. Therefore, it is of great practical significance in guiding and solving complex agricultural production problems. So far, the effects of farmland mulching on the production of potatoes [40], the impact of irrigation on crop yield [41], the crop WP response to potassium fertilization [42], and changes in soil salinity under wastewater irrigation treatment [43] have been reported using meta-analyses.

In summary, such a quantitative analysis may help us to develop reasonable GM strategies, thereby improving the efficient use of water resources and crop yield. In this study, we performed a meta-analysis, a regression analysis, and a path analysis to assess the impact of GM on crop yield and WP in the arid and semi-arid regions of Northwest China using 185 yield comparisons and 130 WP comparisons from 30 peer-reviewed scientific reports. This study's objectives were to (1) identify an agricultural management practice for arid and semi-arid regions based on the combined effects of GM on crop yield and WP and (2) propose suggestions on the use of GM based on the critical regional factors and gravel characteristics.

2. Materials and Methods

2.1. Data Collection

A comprehensive search was conducted in the China National Knowledge Infrastructure (CNKI, http://www.cnki.net/, accessed on 5 November 2023) and Web of Science (WoS, http://apps.webofknowledge.com/, accessed on 5 November 2023) databases for primary research papers reporting the effects of GM on crop yield and WP in arid and semi-arid regions of Northwest China with a cut-off date of 5 November 2023. The search and screening process is shown in Figure 1. During the literature retrieval process, the search terms used included gravel, gravel mulch, gravel–sand mulch, rock fragment, rock weathering, crop, yield, water use efficiency, and water productivity, and the search was limited to the title, abstract, and keywords of the papers. Non-English publications, reports, and conference proceedings were excluded. Articles without the required keywords in the title or abstract were also excluded. The literature included in this study had to meet the following criteria: (1) The experimental region had to be located in the arid and semi-arid regions of Northwest China, specifically in Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang Provinces. (2) The experiment had to have been conducted in the field (year $\geq$ 1) and consisted of a treatment group (GM) and a control group (non-mulching), with all other experiment conditions kept consistent, including irrigation, fertilization, crop type, etc., and with each experimental treatment having at least three replications. (3) The average crop yield or WP, the standard deviation, and the sample sizes of GM and non-mulching treatments had to be provided in the paper or else could be calculated. When a study only provided yield and ET data without WP data, WP was calculated using the following formula: WP = yield/ET. ET was calculated using the formula ET = $P_e + I - i \pm R \pm \Delta S \pm F_B \pm F_L$, where P_e = effective precipitation, I = irrigation, i = water intercepted by the canopy, R = run-off, ΔS = difference in water stored in the soil between the beginning and the end of the considered period, F_B = fluxes of water at the bottom of the root zone, and F_L = fluxes of water at the laterals of the root zone. Due to the difficulty that arises in quantifying some components of this equation, many authors have utilized simplified versions of the ET formula, such as ET = $P_e + I$ [6]. These data were derived from text, tables, and figures (using the image digitizing tools in OriginPro 2018 software). (4) The experimental operation steps had to be clearly described, including information about the experimental regions, experimental year, gravel characteristics, crop type, and farmland management measures. (5) Duplicate experimental data from different studies were excluded, and the paper with the most information was selected. Based on these criteria, this study collected 30 publications from three provinces (Figure 2), totaling 185 yield comparisons and 130 WP comparisons.

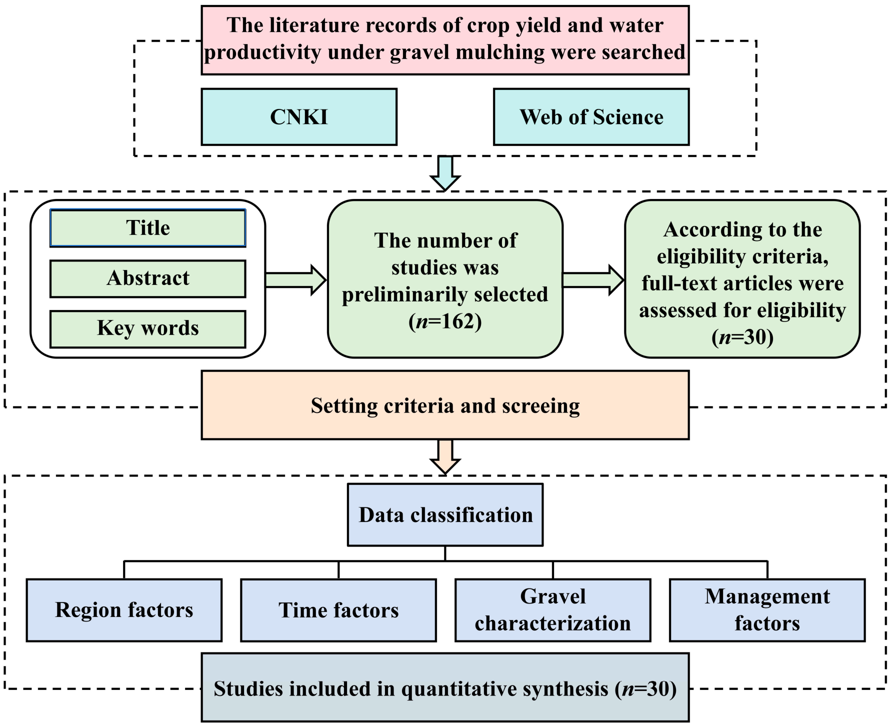

Figure 1. Flow diagram of the literature search and screening.

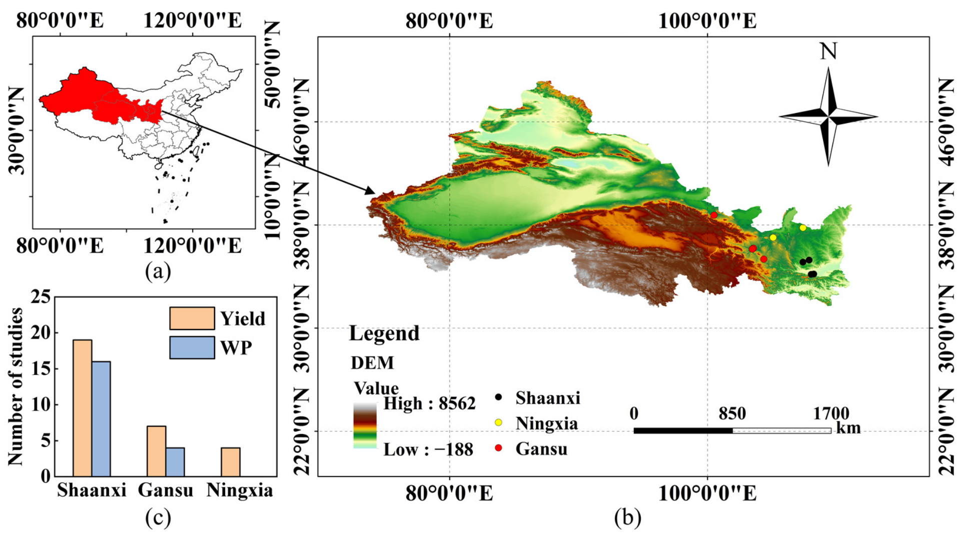

Figure 2. Map of China (**a**); geographical distribution of studies collected from the literature (**b**); number of studies included (**c**). A single point may represent more than one case study published

in the same region. China's map data were sourced from the Standard Map Service System of the Ministry of Natural Resources, China (http://bzdt.ch.mnr.gov.cn, accessed on 5 November 2023), under the approval number GS(2019)1822. Elevation data (DEM) for the five northwestern provinces were obtained from the Geographic Data Cloud (https://www.gscloud.cn/search, accessed on 5 November 2023), specifically the SRTMDEMUTM 90 M resolution digital elevation data product.

2.2. Data Classification

To further elucidate the impacts of GM on crop yield and WP, this study aimed to systematically and quantitatively analyze previously published data to explore which parameters have critical effects on crop yield and WP. The following information was compared among these studies, including the region, average annual precipitation (AAP), average annual temperature (AAT), altitude (A), experimental year, gravel size (GS), amount of gravel mulching (AGM), degree of gravel mulching (DGM), gravel mulching thickness (GMT), crop type, fertilization, and moisture management (Table 1). The selected indicators were grouped into statistics by considering their types or based on evaluating the number and distribution of the samples and excluding the groups with a number of research pairs ≤ 3.

Table 1. Data classification and samples distribution.

Factors		Subgroups	Sample Size
Regional factors	Region	Shaanxi, Gansu, Ningxia	185 (130)
	AAP	<200, 200–400, 400–800 mm	185 (129)
	AAT	0–9, >9 °C	185 (130)
	A	500–1000, >1000 m	185 (130)
Time factors	Experimental year	≤2010, 2011–2015, ≥2016	184 (130)
Management factors	Fertilization measures	Fertilization, no fertilization	178 (127)
	Moisture management	Rainfed, irrigated	185 (130)
	Crop type	Food crops, cash crops	185 (130)
Gravel characterization factors	GS	<1, 1–3, >3 cm	167 (121)
	DGM	Partial mulching, full mulching	185 (130)
	GMT	<3, 3–6, >6 cm	95 (83)
	AGM	<23, 23–46, >46 kg/m^2	95 (59)

Note: Number of water productivity samples in brackets.

2.3. Meta-Analysis

The data extracted from the literature primarily consisted of the mean value (X), sample size (n), and standard deviation (SD) of crop yield and WP. A conversion calculation was carried out using the following formula in cases where only the standard error (SE) was provided in the literature. If no SD or SE value was provided, 1/10 of the average value was chosen as the default [44].

$$SD = SE\sqrt{n} \tag{1}$$

Effect size (ln$R$, the natural logarithm of the response ratio R), a metric commonly used in meta-analyses, was used to assess the effect of GM on crop yield and WP. Effect size was calculated as follows [45]:

$$\ln R = \ln(X_t/X_c) = \ln X_t - \ln X_c \tag{2}$$

where ln$R$ is a dimensionless parameter. If ln$R$ > 0, it would indicate that GM positively affects crop yield and WP. Conversely, it would indicate that GM has a negative impact. R represents the ratio of the mean value for crop yield or WP in the treatment group (GM; X_t) to that in the control group (non-mulching; X_c).

The variance (V) corresponding to a single effect size was calculated as follows:

$$V = \frac{SD_t^2}{N_t SD_t^2} + \frac{SD_c^2}{N_c SD_c^2} \quad (3)$$

where SD_t and SD_c are the standard deviations (yield or WP) for the treatment (GM) and control (non-mulching) groups, respectively. N_t and N_c are the sample sizes (yield or WP) of the treatment (GM) and control (non-mulching) groups, respectively.

The weights (ω) of the comparisons in this meta-analysis were calculated as follows [46]:

$$\omega = \frac{1}{V} \quad (4)$$

The weighted response ratio ($\ln R_{++}$) was used to further derive the overall responses observed in treatment (GM) and control (non-mulching) groups:

$$\ln R_{++} = \frac{\sum_{i=1}^{N} \omega_i \ln R_i}{\sum_{i=1}^{N} \omega_i} \quad (5)$$

To directly describe the responses of crop yield and WP to GM, a response percentage (I) value was used to represent the percentage change rate of relevant indicators in the treatment group (GM) compared with the control group (non-mulching) [45]:

$$I = \left(e^{\ln R_{++}} - 1\right) \times 100\% \quad (6)$$

The 95% confidence interval (95%CI) was calculated as follows:

$$95\%\text{CI} = \ln R_{++} \pm 1.96 \sqrt{\frac{1}{\sum_{i=1}^{N} \omega_i}} \quad (7)$$

If the 95% confidence interval of I contained 0, the difference between the treatment and control groups was considered to be insignificant ($p > 0.05$); conversely, it indicated that there was a significant difference between the treatment and control groups ($p < 0.05$).

In the current study, a heterogeneity analysis was conducted to assess statistically significant differences among the results of different studies using the Q statistic. P_Q is the significance value of Q. When $P_Q < 0.1$, it indicates heterogeneity among the studies. A random-effects model was selected, and subgroups were considered in order to explore the source of heterogeneity further. Otherwise, the fixed-effects model was specified.

In addition, the Rosenthal fail-safe method [47] was used further to demonstrate the credibility of the meta-analysis results. The meta-analysis results were deemed reliable only when the values from the fail-safe number N was higher than $5n + 10$ (n = the number of effect sizes); conversely, publication bias was considered to exist.

2.4. Statistical Analyses

This study used Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA) software to record the data from the literature. The meta-analysis was performed using Metawin2.1 (Sinauer Associates Inc., Sunderland, MA, USA). All statistical tests and analyses were performed using IBM SPSS Statistics ver. 26.0 (SPSS Inc, New York, NY, USA) and OriginPro 2018 (Origin Lab, Northampton, ME, USA). All differences between treatments were considered significant when $p < 0.05$. OriginPro 2018 (Origin Lab, Northampton, ME, USA), ArcGIS 10.2 (Esri Inc., Redlands, WA, USA), and Microsoft PowerPoint 2016 (Microsoft Corporation, Redmond, WA, USA) were each used for plotting.

3. Results

3.1. Effects of GM on Crop Yield and WP

3.1.1. Overall Effects

This study employed a random-effects model due to the highly significant heterogeneity test results ($P_Q < 0.01$) for crop yield and WP under GM. The Q values for crop yield and WP were 1193.31 and 181.56, respectively (Table 2). A subgroup analysis was needed to explore the source of heterogeneity. Publication bias was assessed using the fail-safe method, with the fail-safe number N calculation results for yield and WP being 40,425.80 and 13,696.90, respectively (Table 2). These values were higher than $5n + 10$, indicating the absence of publication bias. Overall, the crop yield and WP significantly increased with GM, resulting in mean I values of 29.47% (95%CI = 26.78–32.22%) and 28.03% (95%CI = 24.37–31.80%), respectively, compared to non-mulching (Table 2).

Table 2. Overall effects of gravel mulching on crop yield and water productivity and tests for data heterogeneity and publication bias.

Item	Model	Increase Rate (%)	95% Confidence Interval		Total Heterogeneity		Fail-Safe Number	n
			Lower Limit (%)	Upper Limit (%)	Q	P_Q		
Yield	Random-effects model	29.47	26.78	32.22	1193.31	0.000 **	40,425.80	185
WP	Random-effects model	28.03	24.37	31.80	181.56	0.002 **	13,696.90	130

Note: Q is the statistic of heterogeneity; P_Q is the significance value of Q; **—P_Q < 1%.

3.1.2. Regional Factors

The responses of crop yield (Figure 3a) and WP (Figure 3b) to GM varied among regional factors. Compared with non-mulching, with different regional factors, the 95% confidence interval of the I values of crop yield (Figure 3a) and WP (Figure 3b) under GM did not contain 0, showing significant positive benefits ($p < 0.05$). In terms of crop yield, GM in Ningxia had the highest positive benefit, with a mean of 114.58% (95%CI = 95.64–135.37%), and GM in Shaanxi had the lowest positive benefit, with a mean of 23.05% (95%CI = 20.29–25.87%). The effect of GM on yield initially increased, and then we observed a decreasing trend with increasing AAP, an increasing trend with increasing AAT, and an increasing trend with increasing A. Regions with an AAP of 200–400 mm, an AAT of 0–9 °C, and an A > 1000 m had the highest I values, with means of 102.59% (95%CI = 89.42–116.67%), 66.25% (95%CI = 57.82–75.14%), and 52.62% (95%CI = 46.79–58.71%), respectively.

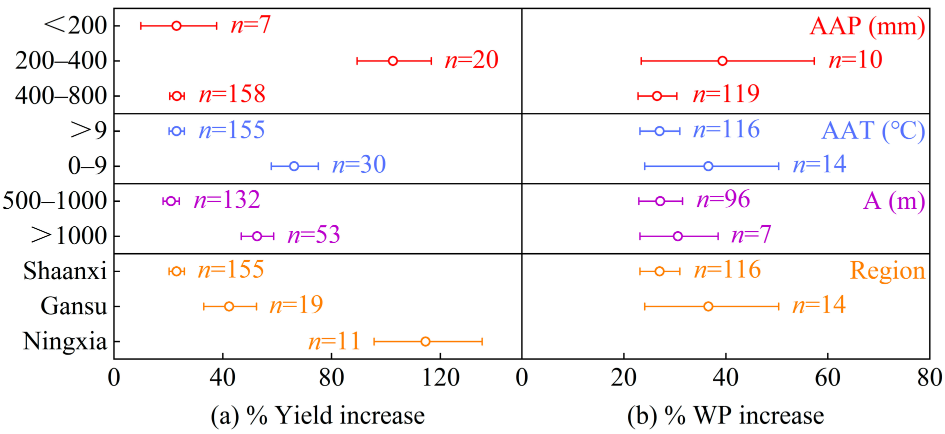

Figure 3. Effects of gravel mulching on crop yield (**a**) and water productivity (**b**) under different regional factors. AAP, AAT, and A represent the average annual precipitation, average annual temperature, and altitude, respectively. Error lines indicate 95% confidence intervals, and n is the number of observations—the same applies to Figures 4–6 below.

For WP, the positive benefit of GM in Gansu was higher than that in Shaanxi, with means of 36.59% (95%CI = 24.10–50.35%) and 27.02% (95%CI = 23.17–30.98%), respectively. Differing from yield, the WP of crops with GM showed a decreasing trend with increasing AAP, a decreasing trend with increasing AAT, and an increasing trend with increasing A. Regions with an AAP of 200–400 mm, an AAT of 0–9 °C, and an A > 1000 m had the highest *I* values, with means of 39.35% (95%CI = 23.40–57.35%), 36.59% (95%CI = 24.10–50.35%), and 30.60% (95%CI = 23.60–38.50%), respectively.

3.1.3. Time Factors

Under different experimental years, the 95% confidence interval of the *I* values of crop yield (Figure 4a) and WP (Figure 4b) did not contain 0, showing significant positive benefits ($p < 0.05$). The positive benefit of GM for crop yield and WP in different experimental years showed a gradually decreasing trend, and the highest *I* values were 48.42% (95%CI = 40.69–56.58%) and 42.90% (95%CI = 30.97–55.94%) before 2010, respectively. The lowest *I* values occurred after 2016, at 20.51% (95%CI = 13.17–28.35%) and 21.96% (95%CI = 12.55–32.15%), respectively.

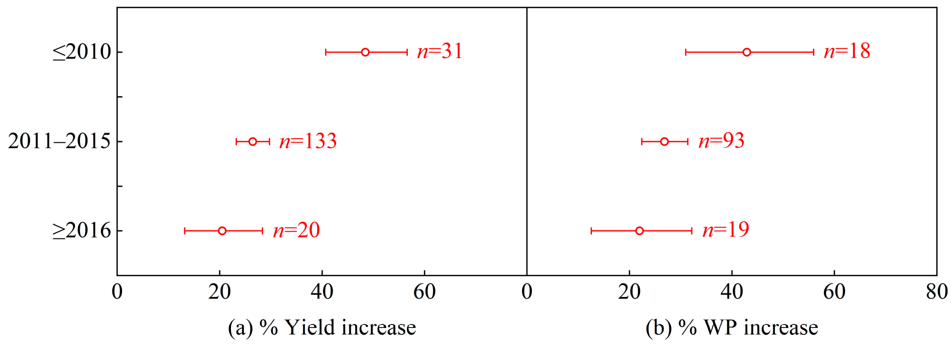

Figure 4. Effects of gravel mulching on crop yield (**a**) and water productivity (**b**) under different time factors.

3.1.4. Gravel Characterization Factors

The responses of crop yield (Figure 5a) and WP (Figure 5b) to GM varied with different gravel characterization factors, such as GS, AGM, DGM, and GMT. For yield, this study found that different GS values significantly impacted crop yield. As the GS increased, there was an overall increasing trend in yield. However, it is worth noting that when the GS > 3 cm, the confidence interval of the *I* values of crop yield exhibited significant fluctuations. With an increase in the AGM, the crop yield showed an increasing trend, and when the AGM > 46 kg/m^2, the *I* values for yield reached their maximum, which was 39.71% (95%CI = 28.54–51.83%). When comparing between full mulching (FM) and partial mulching (PM), the crop yield was notably higher under FM, with *I* values of 32.34% (95%CI = 29.37–35.39%) and 13.60% (95%CI = 7.24–20.33%), respectively. Furthermore, the influence of GMT on crop yield was also highly significant. Specifically, when the GMT was between 3 and 6 cm, the highest *I* values were observed, with a mean of 34.69% (95%CI = 28.79–40.86%).

For WP, as the GS increases, the effect of GM on crop WP follows the same trend as that observed for its effect on crop yield. When the GS was > 3 cm, the highest *I* values were found, with a mean of 41.20% (95%CI = 29.38–54.10%). With an increase in the AGM, the *I* values showed an increasing trend, and when the AGM > 46 kg/m^2, the *I* values reached their maximum, at 46.68% (95%CI = 36.27–57.87%). Differing from yield, the WP of crops with PM was insignificant. The WP of crops with GM showed an increasing trend with increasing GMT values.

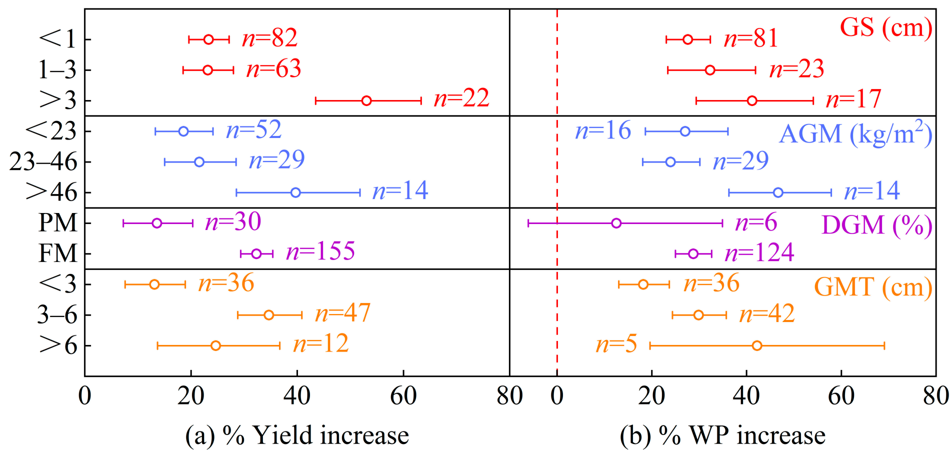

Figure 5. Effects of gravel mulching on crop yield (**a**) and water productivity (**b**) under different gravel characteristics. GS, AGM, DGM, GMT, PM, and FM represent the gravel size, the amount of gravel mulching, the degree of gravel mulching, the gravel mulching thickness, the use of partial mulching on the surface of the soil, and the use of full mulching on the surface of the soil, respectively.

3.1.5. Management Factors

The responses of crop yield (Figure 6a) and WP (Figure 6b) to GM were affected by crop type, fertilization, and irrigation. Regarding the crop type, cash crops (e.g., watermelons, apples, and round dates) showed more excellent positive benefits of GM in terms of crop yield and WP compared to food crops (e.g., maize and wheat), with *I* values of 71.24% (95%CI = 62.95–79.95%) and 43.30% (95%CI = 32.26–55.26%), respectively. Fertilization had the highest positive effect on crop yield compared to no fertilization, with an *I* value of 25.41% (95%CI = 23.13–27.71%). Additionally, the *I* value of WP with fertilization was 28.15% (95%CI = 24.43–31.97%). Furthermore, GM had a more significant positive benefit on crop yield and WP under irrigation when compared to rainfed crops, with *I* values of 39.47% (95%CI = 35.12–43.98%) and 29.76% (95%CI = 23.85–35.93%), respectively.

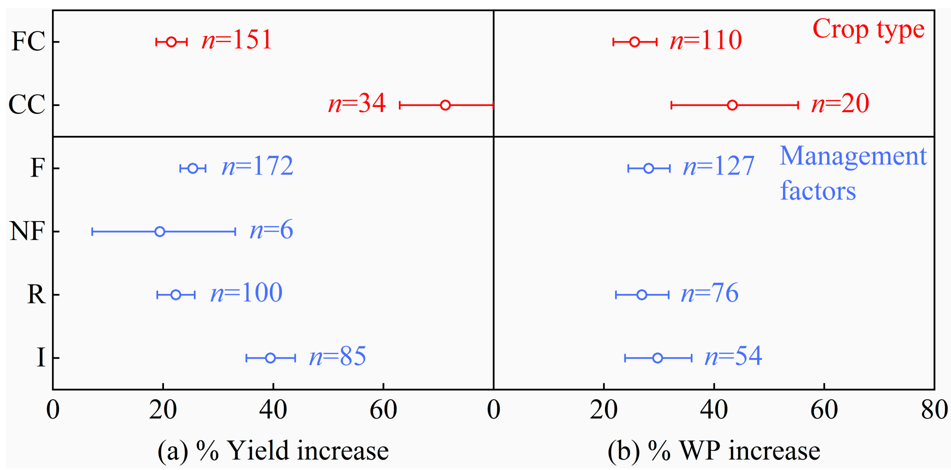

Figure 6. Effects of gravel mulching on crop yield (**a**) and water productivity (**b**) under different crop types and management factors. FC, CC, F, NF, R, and I represent food crops, cash crops, fertilization, no fertilization, rainfed, and irrigated, respectively.

3.2. Regression Analysis of Effects of GM on Crop Yield and WP

Through single-factor regression analysis, stepwise multiple linear regression analysis, and path analysis, the influence degree and path of each factor were revealed, providing a better explanation for the heterogeneity of GM on *I* values of crop yield and WP.

3.2.1. Single-Factor Regression Analysis

In the present study, consideration of AAP, AAT, A, GS, AGM, DGM, and GMT based on data obtained from literature, the single-factor regression analysis revealed the effects of GM on crop yield (Figures 7 and 8) and WP (Figures 7 and 8) determining factors. The AAP, AAT, A, GS, AGM, DGM, and GMT significantly affected the effect size of crop yield ($p < 0.05$). Differing from yield, only AAP, GS, AGM, DGM, and GMT have a significant impact ($p < 0.001$) on the effect size of crop WP. The AAT and A had an insignificant impact ($p > 0.05$) on the effect size of crop WP.

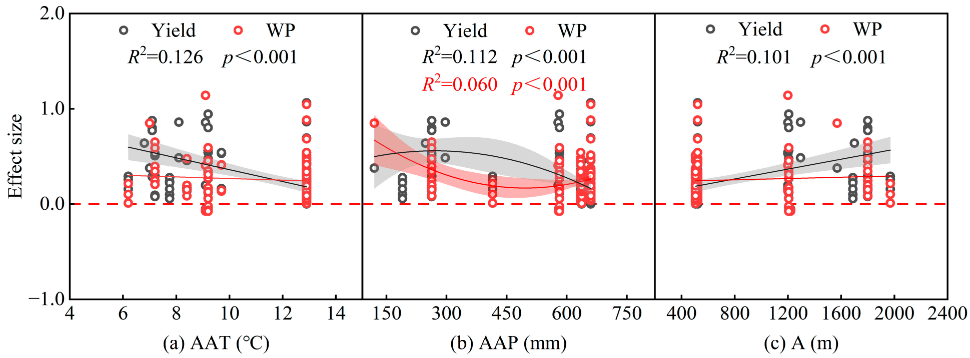

Figure 7. Relationship between the effect sizes of crop yield or water productivity and regional factors.

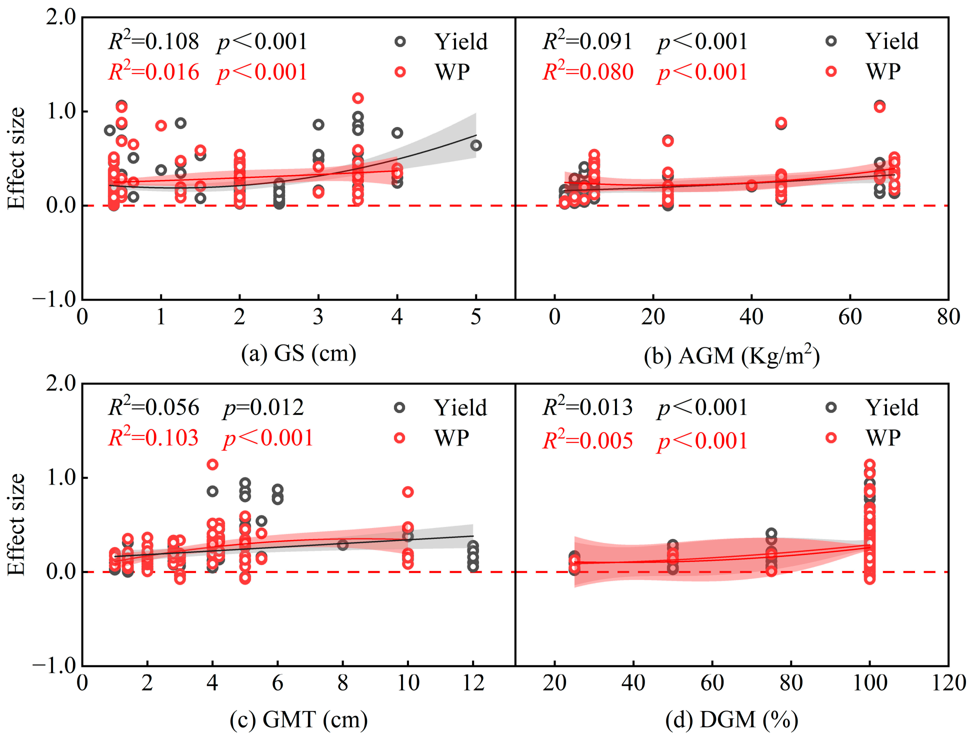

Figure 8. Relationship between the effect sizes of crop yield or water productivity and gravel characterization factors.

3.2.2. Stepwise Multiple Linear Regression Analysis and Path Analysis

Stepwise regression was performed using SPSS to identify the most significant and relevant predictors. Stepwise regression is an approach used to select a subset of effects for a regression model. This method is commonly used in research [48–50]. Researchers often prefer stepwise regression when focusing on predictors that interact effectively to improve model fit and reduce variance by excluding unnecessary terms due to multicollinearity concerns. This study adopted stepwise regression to select predictors efficiently.

Stepwise multiple linear regression was utilized to analyze the variables impacting crop yield and WP with GM. In the present study, six numerical variables (AAP, AAT, A, GMT, GS, and DGM) were chosen from a total of twelve variables in the data classification. These specific variables were then employed in conducting a stepwise multiple linear regression analysis on the yield and WP of crops under GM, resulting in a more comprehensive evaluation of the data. The results (Table 3) indicate that the primary regional factors influencing yield were AAT and A, contributing 43.14% and 53.09%, respectively. GMT and GS were identified as the significant gravel characterization factors impacting yield, contributing 82.63% and 17.37%, respectively. AAP and GMT were the main regional and gravel characterization factors affecting WP.

Table 3. Stepwise multiple linear regression analysis of crop yield and water productivity under gravel mulching.

Item	Factors	Relative Contribution of Each Factor (%)	Regression Relation	R^2	*F*
Yield	AAP, AAT, A	−3.77, 43.14, 53.09	Yield = 75.54A + 1.31 × 10^4AAT − 19.30AAP − 1.90 × 10^5	0.738 **	164.60
	GMT, GS	82.63, 17.37	Yield = 4.33 × 10^3GMT + 1.78 × 10^3GS − 5.72 × 10^3	0.647 **	70.64
WP	AAP	100.00	WP = 283.30 − 0.41AAP	0.701 **	300.23
	GMT	100.00	WP = 14.32GMT − 18.63	0.613 **	120.20

Note: **—$p < 1\%$.

To further clarify the action path and the degree of multiple influencing factors on the yield, a path analysis of the main factors was conducted (Figure 9). GMT had a direct positive effect on the yield (0.728, $p < 0.01$), while GS had a mainly indirect impact on the yield (0.308). AAT and A had a direct positive effect on yield (2.379, $p < 0.01$; 2.928, $p < 0.01$), and AAP had a mainly indirect impact on yield (2.086). Therefore, GMT, A, and AAT are the three main factors affecting the yield of crops under GM.

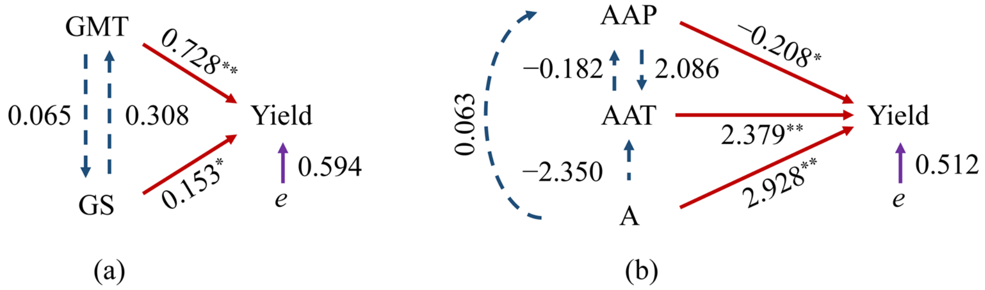

Figure 9. Path analysis of yield and influencing factors under gravel mulching considering gravel characterization factors (**a**) and regional factors (**b**). The solid line is the direct path, the dashed line is the indirect path, the arrow shows the direction from the cause to the result, the number is the path coefficient, and *e* is the residual factor. *—$p < 5\%$; **—$p < 1\%$.

4. Discussion

This study offers a comprehensive and quantitative examination of the impact of GM on crop yield and WP in the arid and semi-arid regions of Northwest China. This analysis is grounded in experimental studies disseminated in peer-reviewed scientific reports. Research indicates GM as a viable and promising agricultural practice, showcasing a mean improvement of 29.47% in crop yield and 28.03% in WP (Table 2). Notably, the efficacy of GM is contingent upon various factors, including the region, the time of the experiment, gravel characteristics, the crop type, and management practices. As elucidated by this systematic study, these nuanced considerations underscore the need for a context-specific approach when implementing GM strategies.

4.1. Effects of GM on Crop Yield and WP

Soil moisture evaporation and plant transpiration are critical processes in exchanging matter and energy within the soil–plant–atmosphere system [51]. Crop growth is negatively impacted in regions with low precipitation and high evapotranspiration, such as arid and semi-arid areas. GM has a history of more than 300 years of being used as a traditional agricultural tillage management practice in the arid and semi-arid regions of Northwest China [52]. This practice plays a vital role in enhancing crop yields and WP.

GM significantly impacts soil physical properties, particularly in regulating critical hydrological processes such as soil moisture evaporation, infiltration, and run-off. Soil moisture evaporation is a crucial pathway for exporting soil moisture. In GM, the soil surface is covered with a layer of gravel to reduce evaporation, which creates a physical barrier that restricts the evaporation path of water [29,53]. This restriction slows down the rate of soil moisture evaporation and improves the soil's ability to retain water, creating optimal conditions for robust crop growth. This phenomenon is essential for ensuring an adequate water supply to sustain crop growth and development during dry conditions. Soil moisture infiltration is a crucial pathway for soil moisture input. GM can alter the surface roughness, reducing surface run-off and increasing water infiltration [23,28]. It also helps prevent the occurrence of soil surface crusting and pore closure, which can decrease surface run-off during precipitation events. This prolonged contact time between water flow and the soil surface enhances the infiltration rate. Furthermore, the soil temperature in farmland agriculture directly or indirectly affects various processes such as crop seed germination, root growth, nutrient absorption, and physiological metabolism. Soil temperature is a critical factor that limits crop yields, especially in arid regions with a significant temperature difference between day and night. Therefore, implementing appropriate farmland temperature control measures is crucial to maintain stable agricultural development in arid regions. Research has shown [30] that GM has a heat-preserving effect on soil due to its low heat capacity and poor thermal conductivity. GM acts as a barrier, preventing the exchange of hot and cold air between the atmosphere and the soil, effectively preserving the heat in farmland soil. It is worth noting that GM can also effectively slow down the scouring and erosion of the soil by rainwater, prevent the loss of nutrients and organic matter from the soil [31,32], and stabilize the soil structure to help provide a more suitable environment for the growth of the crop root system, thus promoting the growth and development of the crop and increasing the crop yield and WP.

Applying GM alters the chemical properties of soil and modifies the soil environment. In the arid and semi-arid regions of Northwest China, intense surface evaporation and imbalances in irrigation drainage lead to soil salinization, in which salts in the deeper layers of the soil follow the soil capillary water transport and accumulate on the soil surface. Research has shown [33] that the use of GM measures can effectively reduce the rate of accumulation of salts in the surface layer of soil and alleviate the phenomenon of secondary salinization in soil, which has a potentially positive effect on the sustainable development of agriculture in arid regions and the protection of the soil ecological environment. GM's positive impact stems from the ability of surface gravel to curtail soil moisture evaporation while concurrently promoting enhanced soil moisture infiltration. This dual mechanism reduces salt accumulation within the soil surface, creating a conducive environment for crop growth. It is worth noting that the effectiveness of GM's soil salinity regulation decreases as the number of continuous cropping years increases. In addition, the gravel exposed on the soil surface is subjected to freeze–thaw and dry–wet cycles (irrigation, rainfall, etc.), and the mineral elements inside them are leached and released, thus affecting the fertility of the soil. Studies have shown [34] that gravel increases the potassium, calcium, sodium, and magnesium contents of soil through these dry and wet cycles of freezing and thawing and that differences in the potassium and calcium contents of the soil significantly affect the growth, development, and yield of jujube trees.

GM significantly impacts enzyme activity and soil microbial characteristics, crucial for promoting plant growth, maintaining soil ecosystem stability, and enhancing soil fertility.

Soil enzyme activity is an essential indicator of soil fertility and microbial metabolism, and GM positively affects this by increasing the soil enzyme activity and changing the soil microbial communities. However, after 16 years of GM, the positive impact of GM on crops diminishes [35], correlating with a gradual decline in soil enzyme activity and microbial communities with continuous cropping. Therefore, it is essential to consider the long-term effects of GM on soil health and productivity and take appropriate measures to maintain the soil ecosystem's health and sustainable productivity.

Plants typically employ three strategies to cope with water scarcity. The first strategy, escape, involves adjusting growth patterns, such as accelerating or delaying the transition from vegetative to reproductive stages, to prevent reproductive failure under severely water-scarce conditions. The second strategy, avoidance, entails modifying the root system architecture, adjusting leaf traits, and optimizing photosynthesis to minimize water loss and enhance water use efficiency. The third strategy is tolerance, and its mechanisms include osmotic adjustment, the activation of antioxidant defenses, responses to phytohormones, and maintenance of the chlorophyll content. These adaptive strategies enable plants to survive and recover from water scarcity [54]. It is clear from the above analysis that moisture, temperature, and nutrients are the critical factors for crop growth. GM can enhance soil moisture, regulate soil temperature, reduce soil salinity, boost soil mineral contents, and modify soil microbial communities and enzyme activities. It resists water scarcity, promotes crop growth, and increases crop yields. These positive and active dynamic protective effects are essential in promoting crop resistance to water scarcity (Figure 10).

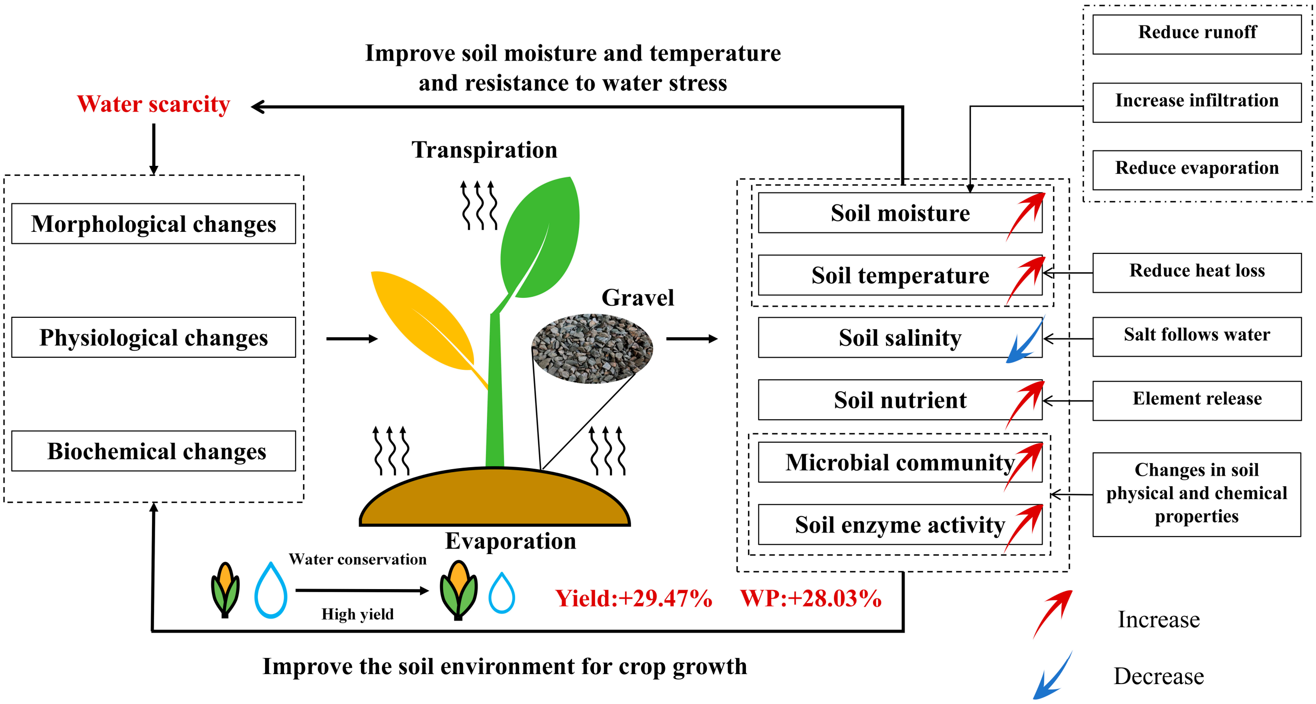

Figure 10. Mechanisms of dynamic crop protection through gravel mulching. The black arrows in the figure indicate the direction from the cause to the result; the red and blue arrows indicate the increase and decrease effects on the result, respectively.

In summary, the complexities of factors affecting crop yield and WP with GM are well documented in the literature. Numerous scholars have shown [36–38] that GM can enhance crop yield and WP, which is consistent with the findings obtained in this study (Table 2).

4.2. Impact Factors for Crop Yield and WP

4.2.1. Effects of Regional Factors on Crop Yield and WP

Based on the meta-analysis, the 30 scientific reports collected in this study were distributed across Gansu, Shaanxi, and Ningxia (Figure 2) and showed that GM had significant positive effects on crop yield and WP in those regions (Figure 3), with *I* values ranging from 23.05 to 114.58%. In these regions of severe water scarcity, GM is commonly used in agriculture to fully utilize rainfall and obtain higher crop yields and WP with less irrigation water. Compared with Gansu and Ningxia, the positive benefits of GM on crop yield and WP were the lowest in Shaanxi, with *I* values of 23.05% and 27.02%, respectively. The main reason for the above results is that the adoption of GM in agriculture should be accompanied by full consideration of the local cropping structure, with food crops such as wheat and maize being the primary research targets in Shaanxi [37,55,56], and high-economy crops such as melons and fruit trees being the primary research targets in Gansu and Ningxia [34,52,57]. This study found that under GM, the *I* values for the yield and WP of cash crops were higher than those for the yield and WP of food crops (Figure 6).

In addition, the crop yield and WP in different regions were closely related to environmental conditions such as precipitation, temperature, and A [58,59]. Studies on the effects of temperature, precipitation, and A showed that GM had the most significant impact on crop yield and WP in the lower-AAP (200–400 mm, Figure 3), lower-AAT (0–9 °C, Figure 3), and higher-A (>1000 m, Figure 3) regions. Crop yield first increased and then decreased with increasing AAP (Figure 3), decreased with increasing AAT (Figure 3), and increased with increasing elevation (Figure 3). Crop WP decreased with increasing AAP (Figure 3), decreased with increasing AAT (Figure 3), and increased with increasing A (Figure 3). Some scholars [48] conducted a meta-analysis on the response of alfalfa yield and WP to farmland mulching. Their results regarding the AAT and A were the same as those found in the present study. The reason for the inconsistency between their AAP results and those of the present study is that alfalfa is a deep-rooted, water-consuming crop with an annual water requirement of 500–900 mm, i.e., it needs a higher water supply than other crops. At the same time, when the precipitation is too high, soil water cannot be fully absorbed and utilized by this crop: most of it will be lost through evaporation and seepage. Additionally, high precipitation levels may contribute to fertilizer leaching, ultimately diminishing soil fertility.

Similarly, the results of the single-factor regression analysis were consistent with the meta-analysis results in showing that the AAP, AAT and A significantly affected crop yield ($p < 0.001$), where the AAT and AAP had a negative effect and A had a positive impact (Figure 7). For WP, only AAP had a significant negative effect ($p < 0.001$, Figure 7). The stepwise multiple linear regression analysis showed that the main regional factors affecting crop yield were AAT and A, and the primary regional factor affecting WP was the AAP (Table 3). In addition, it was further shown by the pathway analysis (Figure 9) that AAT and A had a direct positive effect on yield (2.379, $p < 0.01$; 2.928, $p < 0.01$), while AAP had a predominantly indirect impact on yield (2.086). In this study, it is concerning that in Table 3, the coefficients for AAP are negative. In comparison with non-mulching, with different AAP values, the 95% confidence interval of the *I* values for crop yield (Figure 3a) and WP (Figure 3b) under GM did not contain 0, showing significant positive benefits ($p < 0.05$). Meanwhile, the effect of GM on yield initially increased, and then we observed a decreasing trend with increasing AAP values. This shows that the yield generally increases with increasing AAP values, reaching a maximum of 200–400 mm. The pathway analysis indicated that AAP mainly indirectly impacted yield (2.086). From the point of view of their mathematical expressions, the contributions of AAT and A are more significant, while the contribution of AAP is indirect. Therefore, the coefficient for AAP is negative. The above findings indicate that the regional factors affecting crop yield and WP are complex, and the results of this study will provide a basis for the application of GM in different regions.

4.2.2. Effects of Time Factors on Crop Yield and WP

Besides the fact that GM can improve crop yield and WP, it offers a valuable avenue for farmers to boost their income. However, the productivity of gravel–sand mulched fields tends to decrease significantly with the extension of planting time, resulting in reduced crop yields and lower WP. The diminishing yield and WP in gravel–sand mulched fields caused by continuous cropping can be ascribed to various intricate factors. Initially, there may be a tendency for the soil quality to be progressively depleted throughout the season, particularly in terms of organic matter and nutrients. This gradual decline in soil quality directly constrains crop growth and yield. Studies have shown that soils' fundamental physicochemical properties and ecological functions show a declining trend from year to year as the number of years of continuous cropping increases. Specifically, the content of critical nutrients, such as soil organic matter, total nitrogen, total phosphorus, and total potassium, shows a declining trend, which may lead to a yearly weakening of the soil fertility, thus affecting the growth and yield of the crops [20]. Secondly, the characteristics of sandy field soils, such as their low water-holding capacity, significantly increased bulk weight and decreased water-holding capacity with increasing years of continuous cropping, and tendency to gradually lose their insulating function, indicate a deterioration of their soil structure, which in turn restricts the exchange of water and gasses and affects the growth of crop roots and nutrient uptake. In addition, soil enzyme activities are also affected, with a gradual decline in the activities of key enzymes such as urease, sucrase, phosphatase, and catalase [60], which may lead to the restriction of decomposition and nutrient release of organic matter in the soil, and consequently affect the efficiency of nutrient uptake and utilization by the crop. Similarly, the results of a functional diversity analysis of microbial communities showed that the activity of soil microbial communities gradually decreases after a certain number of years of continuous cropping in sand-suppressed land [35], which may lead to the destruction of the stability of soil ecosystems, thus affecting the sustainable use of the soil and the maintenance of its productivity in the long term. In addition to the decline in land quality caused by continuous cropping, in the actual agricultural production process, farmers—in pursuit of higher economic benefits—employ long-term irrational irrigation schemes, plant single structures, and mechanical crushing of the land, among other factors, lead to compact sand and gravel to increase the dispersion of the surface cover, i.e., the surface cover is often in the form of a mixture of sand and soil, which also destroys the soil ecological environment [19]. In summary, the continuous cultivation of pressurized gravel–sand mulched fields leads to a decline in soil quality and productivity year on year, and this study also confirmed this conclusion: across the overall time scale, GM's positive effects on crop yield and WP over time showed a decreasing trend (Figure 4). Nevertheless, the role of GM in improving crop yield and WP cannot be ignored. To maintain the quality of gravel–sand mulched fields, after many years of continuous cropping, it is necessary to fertilize these fields by applying fertilizers, re-sanding, and employing other measures in order to improve their productivity levels.

4.2.3. Effects of Gravel Characterization Factors on Crop Yield and WP

Factors such as the GS, AGM, DGM, and GMT significantly affect the regulation of surface moisture and crop-growing environments in farmland agriculture. As a surface mulch, gravel aids soil moisture distribution and evaporation and regulates soil temperature. The use of GM helps to maintain soil stability and healthy crop root growth. However, excessive or uneven mulching may produce localized overheated or overcooled microenvironments, altering the evaporation and infiltration of soil moisture and affecting crop development and yield. Therefore, when selecting the GS, AGM, DGM, and GMT, factors such as soil moisture, temperature, microenvironment, and crop requirements must be considered comprehensively to achieve the best GM effects and promote the healthy development of agroecosystems. Related studies have shown that water evapotranspiration positively correlates with the gravel particle size [29], i.e., gravel with a small particle size is more conducive to retaining water in the soil. However, this differs from the results of this study: our meta-analysis and single-factor regression analysis showed that gravel size was positively correlated with crop yield and WP (Figures 5 and 8). According to the results of previous studies, gravel size has a weaker effect on soil hydrological processes compared to gravel location and coverage, resulting in the impact of gravel size on soil hydrological processes being masked by the effects of other factors [28].

The AGM, DGM, and GMT were positively correlated with crop yield and WP (Figures 5 and 8), which is consistent with the findings of Wang et al. and Liu et al. [61,62]. With increases in the AGM, DGM, and GMT, GM was more likely to keep the soil in a suitable hydrothermal environment for crop growth. It was shown by the stepwise multiple linear regression analysis (Table 3) that the main gravel characteristics affecting crop yield were the GS and GMT, and the main gravel characteristic affecting crop WP was the GMT. As the GMT increases, it can effectively reduce soil moisture evaporation [63], increase soil water infiltration [64], and keep more water in the soil for crop growth. In addition, the path analysis (Figure 9) further showed that GS had a predominantly indirect effect on yield (0.308). Notably, the residual path coefficients of the crop yield and WP related to the influencing factors exceeded 0.50 (0.594, 0.512), indicating the need to thoroughly consider unknown variables, especially the absence of soil chemical and biological processes. Therefore, this comprehensive analysis of GM needs to be continued and deepened.

4.2.4. Effects of Management Factors on Crop Yield and WP

Studies have shown that with GM, the yield and WP of cash crops are higher than those of food crops (Figure 6), which may be closely related to market demand, economic efficiency, and agricultural inputs and technologies. In Gansu and Ningxia, where GM is more widely used, farmers prefer to grow cash crops in order to cater to market demand and gain higher profits. Yu et al. studied two typical cash crops in arid regions of Northwest China and found that these two cash crops had higher water-saving potentials than the major food crops [65]. Therefore, the economic value generated by growing cash crops is higher in particular regions.

Moderate fertilization can significantly increase crop yield and WP. This study found that fertilization led to higher crop yields compared to no fertilization (Figure 6). The main reason for the existence of cases where not applying fertilizer led to increased crop yields could be that (1) gravel in these included samples was subjected to wet–dry and freeze–thaw cycles [34], which led to increased potassium, calcium, sodium, and magnesium contents in the soil and improved the nutrient conditions of the soil to an extent that provided suitable conditions for crop growth; or (2) the results may have been obscured due to insufficient samples, and the research in this area needs strengthening.

Irrigation significantly increased the yield and WP of cash crops compared to rainfed crops (Figure 6). In water-deficient areas, supplemental irrigation can make up for the rainfall deficit and improve the WP of the farmland. Wang et al. also showed that supplemental irrigation could significantly increase the yield and WP of watermelon crops [52].

Therefore, the crop type, fertilization, irrigation, and other field management practices affect crop yield and WP. Exploring the mechanisms behind GM's effects on crop yield and WP under different crop types and management modes provides a scientific basis for precision agriculture and farmland water management.

5. Conclusions

In the present study, a meta-analysis, a regression analysis, and a path analysis were performed to assess the impact of GM on crop yield and WP in the arid and semi-arid regions of Northwest China using 185 yield comparisons and 130 WP comparisons from 30 scientific reports. The meta-analysis showed that GM significantly increased crop yield by 29.47% and WP by 28.03% compared to non-mulching. This study considered factors such as the region, experimental years, gravel characteristics, and management factors, all of which had significant positive effects on crop yield and WP, except for partial mulching. Consequently, this study offers new insights into agricultural practices that can be applied to similar crop-growing environments in other countries worldwide. The interactions between gravel, soil, microbes, and plants constitute an organic whole that is interdependent, inseparable, and synergistically evolving. However, due to the absence of relevant sample data and the limitations of existing research, this study did not consider the impacts of the soil's physical properties, enzyme activities, and microbial community structures or the effects of continuous cropping over multiple years on the crop yield and WP. Therefore, further studies are essential to explore the factors influencing GM's effects and to clarify the long-term mechanisms underlying the application of GM, which would thereby validate the accuracy of the meta-analysis results presented here.

Author Contributions: Conceptualization, Y.W.; methodology, S.G.; software, Y.W.; validation, Z.J.; formal analysis, Y.W.; investigation, Y.W.; resources, X.N.; data curation, Y.W.; writing—original draft preparation, Y.W.; writing—review and editing, Y.H., Z.J. and W.L.; visualization, Y.W., Z.J. and X.Z.; supervision, W.L.; project administration, W.L.; funding acquisition, W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 52169010), the National Key Research and Development Program of China (No. 2021YFD1900600), the Tsinghua University Ningxia Yinchuan Water Network Digital Water Control Joint Research Institute Project (No. sklhse-2023-Iow013), and the first-class Discipline Construction Program of Ningxia Higher Education Institutions (No. NXYLXK2021A03).

Data Availability Statement: The data presented in this study are available on request from the corresponding author (The data are not publicly available due to privacy or ethical restrictions).

Conflicts of Interest: The authors declare no conflicts of interest.

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