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Effect of the Release of Gravel Elements on Soil Nutrients and Jujube Fruit Yield under Wet-and-Dry Cycles

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Abstract: This study sought to evaluate the potential of mulched gravel to release nutrients in the field by conducting trials with three variations of wet-and-dry cycling of the soil beneath gravel mulch and bare soil. The results revealed that quartz, muscovite, clinochlore, and albite were the most abundant minerals in the gravels. Throughout the whole wet-and-dry cycle, the total content of 30 elements measured in the gravel-mulched soil was higher than in the bare soil treatment, and the content of the total element rose with increasing wet–dry cycle humidity. The enrichment ratio (B_r) of each element in soil under gravel mulch relative to bare soil was in the sequence Mg > Ca > K > Cr > Na > Mn > V > Zn > Fe > Ti > Si > C > N > B> Co > (B_r = 0) > Pb > Cu > Ga > P > Sn > Sr > Al > Be > Li > Mo > Ni > Se > As > S. Under gravel mulch, the elements impacted by the wet–dry cycle are primarily rock-forming, whereas the elements affected under bare soil are primarily trace elements. The wet-and-dry cycles of gravel affected soil nutrients mainly by increasing soil K, Ca, Na, and Mg contents. The differences in soil K and Ca contents significantly affected the growth of jujube trees and the jujube fruit yield. A dry/wet cycle level of 5 L/d per tree under gravel cover conditions can effectively improve soil nutrients and increase the jujube fruit yield without causing environmental problems.

Keywords: gravel mulch; dry and wet cycles; elemental release; jujube tree; sustainable agriculture

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1. Introduction

By 2050, the global need for crop output will increase by 100–110% due to the ongoing growth of the population and level of consumption [1]. Agricultural production at present is heavily dependent on chemical fertilizers; China is one of the main agricultural producers, and there has become a higher amount of fertilizer application globally [2]. The excessive application of fertilizers not only increases the cost of crop production but also causes serious soil and water pollution, which are important issues facing the sustainable development of agriculture in China [3].

One of the main factors justifying the use of rocks in agriculture is the possibility of reducing the use of chemical fertilizers [4]. The weathering of rocks is one of the primary geochemical processes that create the Earth's environment and is the source of mineral nutrients in soils. The P, K, Ca, and Mg levels have increased over time, and the productivity is comparable to or greater than soluble fertilization, according to research [5]. The substitution of nutrients in the soil is determined by the rate of mineral dissolution in rocks. When exposed to the Earth's surface, rocks become the primary source of elements in the soil [6,7].

For almost 300 years, metamorphic gravel has been utilized as a ground mulch to conserve moisture in agriculture in Arid Northwest China [8]. At the end of the 1990s, gravel-mulched fields mulched 118,000 hectares in Gansu Province and 66,000 hectares in the Ningxia Hui Autonomous Region [9]. Nevertheless, over time, man-made plowing and natural weathering have lowered the proportion of gravel on the surface and deteriorated moisture retention [10,11]. The abandonment of thousands of hectares of gravel–sand mulched land has caused rock desertification and limited agricultural and ecological development. The jujube tree (*Ziziphus jujuba Mill.*), a drought-resistant plant with outstanding vitality and adaptability, is commonly planted in China's semi-arid northwest and aids in soil and water conservation [12]. Therefore, the local government department decide to plant jujube trees to rehabilitate abandoned gravel–sand mulched land. Unfortunately, low precipitation and poor soil in the region make it difficult for jujube trees to grow [13,14]. Providing nutrients to the soil by rock weathering becomes a crucial option for the ecological and agricultural sustainability of comparable regions. This strategy helps in the resolution of environmental difficulties linked with stone desertification and the development of a more environmentally friendly alternative to soil fertilizing [15].

However, the weathering of rocks is always a very slow process under natural conditions [16,17]. Weathering converts primary minerals into secondary minerals and is partially responsible for the rate of leaching of nutrients from agricultural minerals into the soil solution [18]. The extensive literature on weathering reactions discusses factors such as the rock type, soil type, plant species, and the solid–liquid ratio [19,20]. Some researchers have suggested that periodic water–rock interactions accelerate the weathering of rock materials, thereby facilitating the release of chemical elements [21,22].

Limited research on multi-nutrient release under periodic wet-and-dry cycle action has been conducted to evaluate gravel mulch as an alternative fertilizer for desert zone soils. In particular, the impacts of nutrient release from rocks on field crops are understudied. To ensure that gravel is safe and efficient as a soil fertilizer, such a study is essential. As a consequence, the following are the key objectives of this research: (1) to characterize the petrographic and geochemical properties of gravels; (2) to evaluate the leaching under different degrees of wet-and-dry cycle tests of gravel, through field trials, and its potential to contribute to soil fertilization and the nutrition of jujube trees in arid zones; and (3) to support future studies of gravel used in the replacement of chemical fertilizers. This research proposes a sustainable option that might replace chemical fertilizers, thus lowering stone desertification pollution.

2. Materials and Methods

2.1. Soil, Gravel, Seedlings, and Water Samples

In the central desert zone of Ningxia, in the northwest of China, there exist vast quantities of Ordovician-aged metamorphic gravel. This study utilized gravel particles from Xiangshan Township, Zhongwei City, Ningxia Hui Autonomous Region, in the gravel–sand mulched land concentration area, for geochemical, mineralogical, and particle micro characterization investigations (37°0′6″ N, 105°13′41″ E) (Figure 1).

The particle size of the studied mulched gravels strongly influenced the release of nutrients [23]. It greatly influences the release of nutrients, because the smaller the particle size, the larger the surface area exposed to exogenous conditions, and the easier it is to weather [24]. In this study, polypropylene shovels were utilized to collect gravel from abandoned gravel–sand mulched land for test analysis and mulching. The samples were then split into different particle sizes using 5 mm and 10 mm sieves of mesh American Society for Testing and Materials (ASTM) and were subsequently transferred to clean polypropylene bags.

At the experimental site, degraded gravel-mulched soils from a jujube forest were gathered. To determine the chemical element content of the soil, 0–20 cm deep soil samples were collected. The soil was divided into two parts for investigation of its chemical composition and pH. The soil pH (H_2O) was determined in distilled water (1:2.5 w/v) using a glass membrane electrode (PHS-3C, Rex Electric Chemical, Shanghai, China) [25].

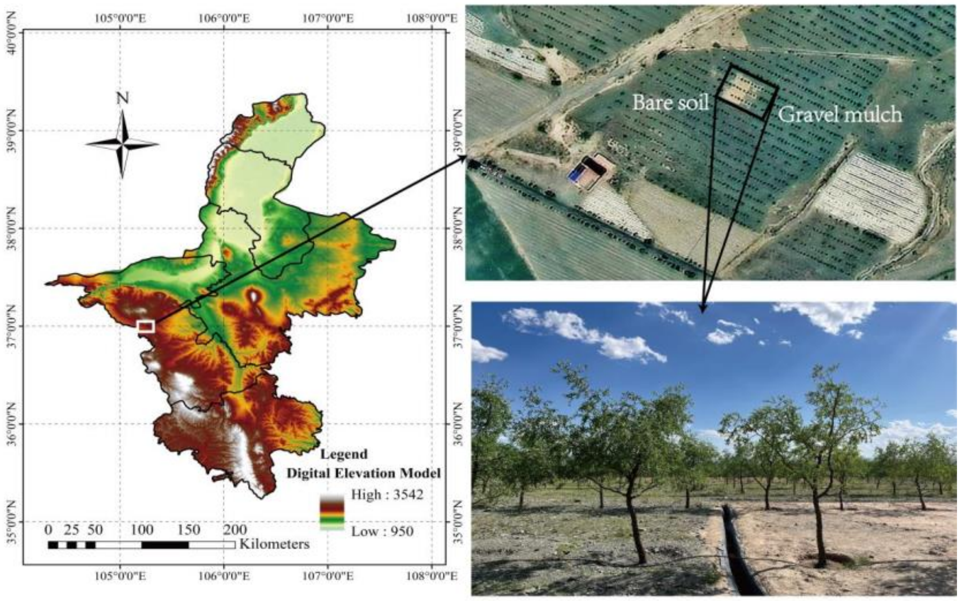

Figure 1. Location and layout of the experimental area, source: Tianditu.

The seedlings are 12-year-old jujube trees. There were 3 × 8 m between planting rows. The results are the average of three samples in triplicate, with three jujube trees per treatment. The variety was chosen for its drought resistance, high vigor, and homogeneity in the field. The jujube trees were supplied with local tap water for basic irrigation and daily drenching.

2.2. Mineralogy and Microscopy

The X-ray diffraction (XRD) (6100, SHIMADZU, Kyoto, Japan) technique was employed to characterize the mineralogical composition of the metamorphic rock samples using an X-ray diffractometer, equipped with a curved graphite monochromator, operating at 40 kV and 30 mA. The angle range analyzed was from 3 to 75. The XRD pattern has been collected by measuring the scintillation response to Cu K^{α} radiation, with a step size of 0.02° and a counting time of 3 s per step. The mineral identification from XRD data was performed using the High Score Software.

The microscopic characteristics and analysis of element types and contents of material microregions of the gravels were studied on polished flakes using a scanning electron microscope (SEM) (model EVO18, Zeiss, Oberkochen, Germany) equipped with an energy-dispersive X-ray spectrometer (EDS).

2.3. Chemical Composition

The gravel and soil samples were ground, passed through a 200-mesh sieve, and digested with three acids (HCl: HNO_3: HF) for 2 h in a microwave oven to determine major and selected trace elements. The analysis was performed at Ningxia University Testing Center (China) by inductively coupled plasma–mass spectroscopy (ICP-MS) (NexION 350X, Perkin Elmer, Waltham, MA, USA) and Elemental Analyzer (Vario EL cube, Elementar, Heraeus, Germany).

2.4. Experimental Setup

The studies were performed between May and September of 2021. The experimental location has a typical semiarid environment, with little precipitation, the average annual precipitation is 180–200 mm, with high evaporation, the average annual potential evaporation may reach 2100–2400 mm, and the average annual reference crop evapotranspiration of 1300–1400 mm [26]. During the test period, 91.6 mm of precipitation fell, and the average daily temperature was 25.9 °C (Figures 2b and 3). The degraded gravel–sand mulched land was left in its original state as a gravel mulch treatment (G) but the surface gravel was removed to create a bare soil treatment (B). A 1 m^2 pit was dug around each tree and filled with 10 cm of sieved 5–10 mm gravel in the gravel mulch treatment [27], while the bare soil treatment was left unfilled. Additionally, the isolation zone was excavated (Figure 1). An on-farm weather station (Vantage Pro2, DAVIS, San Francisco, USA) and sensors were used to measure the temperature of bare soil and gravel mulched 5 cm below the surface of the experimental location (ZL6, METER, Pullman, WA, USA). Variations in daily average temperatures of the gravel layer, bare soil, and air are presented in Figure 2a. At the hottest time of each no-effective-rainfall day (16:00), to accelerate the nutrient release from the weathered gravel, a wet–dry cycle was created by sprinkling water (water temperature approximately 25.0 °C) into the jujube tree's pit [28].

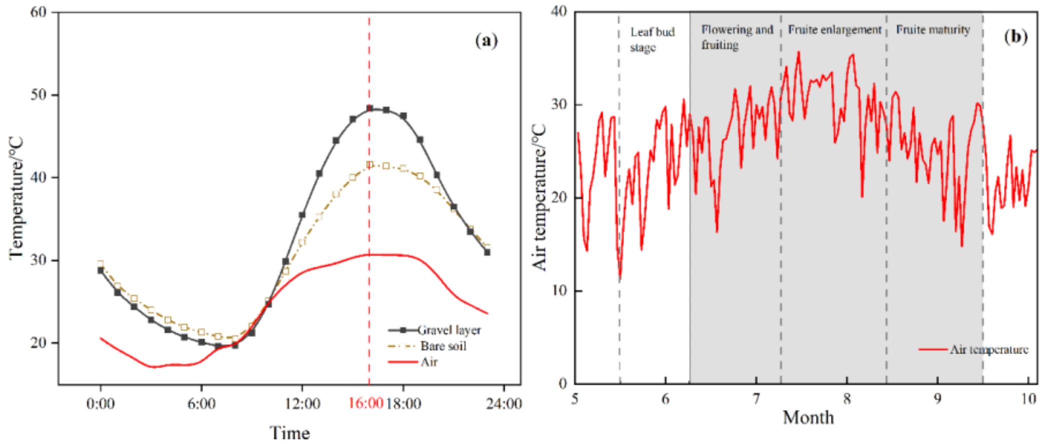

Figure 2. Variations in the daily average temperature of the gravel layer, bare soil, and air (**a**); air temperature during the jujube tree growing period (**b**).

2.5. Experimental Treatments

Using a random block design, the water requirement (W_c) was determined based on the water retention capacity of gravel layers (5.0%) [29] and mulching thickness (10 cm), and three dry and wet cycle degrees with the following amount of drench volume per tree were established: low moisture W1 (60% W_c): 3 L/d, moderate moisture W2 (100% W_c): 5 L/d, high moisture W3 (120% W_c): 6 L/d. Additionally, equivalent bare soil treatments were established for each dry and wet cycle degree, with a total of six treatments (BW1, BW2, BW3, GW1, GW2, GW3), three replications per treatment, and three jujube trees per experimental unit (Figure 3). During the reproductive time, the total irrigation water was the same for all the treatments, at 220 mm. Soil samples were collected at a depth of 0–20 cm at 40 cm from the trunk of jujube trees on days 0, 20, 40, 60, 80, and 100 d after the start of the wet–dry cycle treatment.

After 100 days of the wet–dry cycle test, the thickness and length of the new tips and hanging fruit were measured using vernier calipers and tape measures, and the fruit was collected by hand one by one to compute the yield of the various treatments.

2.6. Statistical Analysis

To clarify the principle of elemental precipitation through wet-and-dry cycles under gravel mulch conditions, the elemental difference between gravel and initial soil is quantified in terms of the elemental ratio R_I, which can be calculated using Equation (1).

$$R_I = \frac{G_I}{S_I} \tag{1}$$

where G_I is the amount of element I in the gravel and S_I is the amount of element I in the soil.

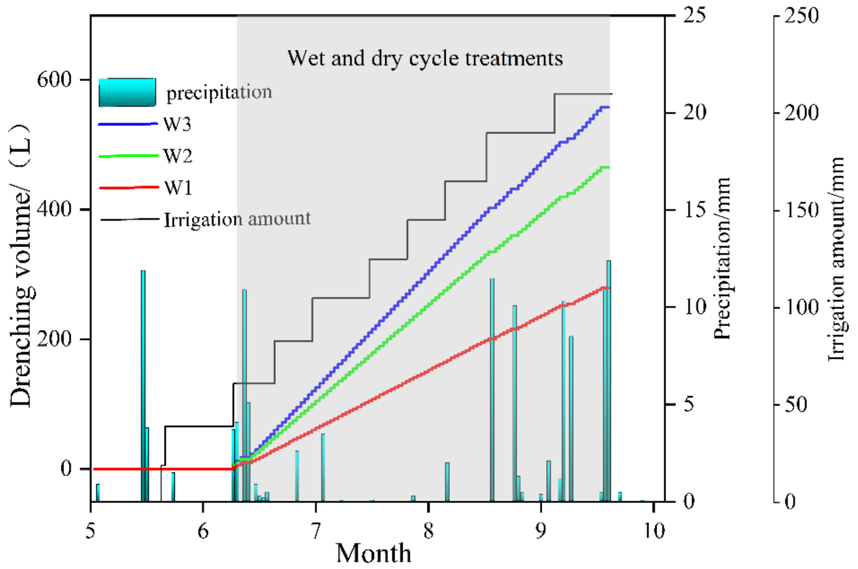

Figure 3. Precipitation during the growing period of the jujube tree, basic irrigation, and drenching treatments (the drenching volume per tree was W3: 6 L/d, W2: 5 L/d, and W1: 3 L/d, respectively).

The element enrichment ratio was used to quantitatively describe the differences in elements between gravel-mulched and bare land soils. The element enrichment ratio refers to the accumulation of elements within gravel-mulched soils relative to bare land soils, which can be calculated using Equation (2).

$$B_r = \frac{C_g - C_b}{C_b} \tag{2}$$

where B_r is the element enrichment ratio, C_g is the content of chemical elements in gravel-mulched soil, and C_b is the content of chemical elements in bare land soil.

All data are provided as the mean of three replicates, and differences in jujube tree growth and yield were examined using SPSS 25.0 using one-way ANOVA. Pearson correlation analysis was used to explore the relationship between the degree of dry and wet cycles and soil element content. Principal component analysis (PCA) with Origin2021 was used to eliminate the collinearity of numerous variables and to reveal the difference in soil elemental system composition between bare soil and gravel mulch utilizing a correlation matrix. The Mantel test was used to examine the influence of chemical components on soil nutrients and jujube tree growth and yield, and the Pearson correlation analysis highlighted the connection between elements in the soil, which was accomplished using the (linkET) package in the R software.

3. Results

3.1. Gravel Mineralogy and Microscopy

The principal four peaks in Figure 4a are made up of well-known metamorphic minerals, including quartz (SiO_2), muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$), clinochlore ($(Mg,Fe)_{4.75}Al_{1.25}[Al_{1.25}Si_{2.75}O_{10}](OH)_8$), and albite ($Na(AlSi_3O_8)$). According to semi-quantitative estimates, the mineral composition of the gravel is as follows: quartz (45.5%), albite (24.8%), muscovite (15.8%), and clinochlore (13.9%).

Figure 4b depicts the natural surface morphology of a piece of mulched gravel. The surface morphology of the sample is quite rough, exhibiting a concave river-like pattern. The surface is uneven and has a slate structure resembling a slab. The surface of the slab is formed of minerals, structured in a directed pattern, with well-developed microcracks and microfractures. The fine structure of the rock is seen in terms of the grain morphology, which is mostly scale-like and elongated, with a few blocky and granular grains, and the grains have a rather distinct shape. The grain size and shape vary significantly, and the grain size is rather tiny. The particles' pores are interconnected, and they overlap and collect to produce a porous, sparse structure. The results of EDS showed that the weight percentages (weight%) of elements scanned on the gravel surface are, in descending order, Si, O, Al, C, Fe, Na, K, Mg, and Ca (Figure 4c).

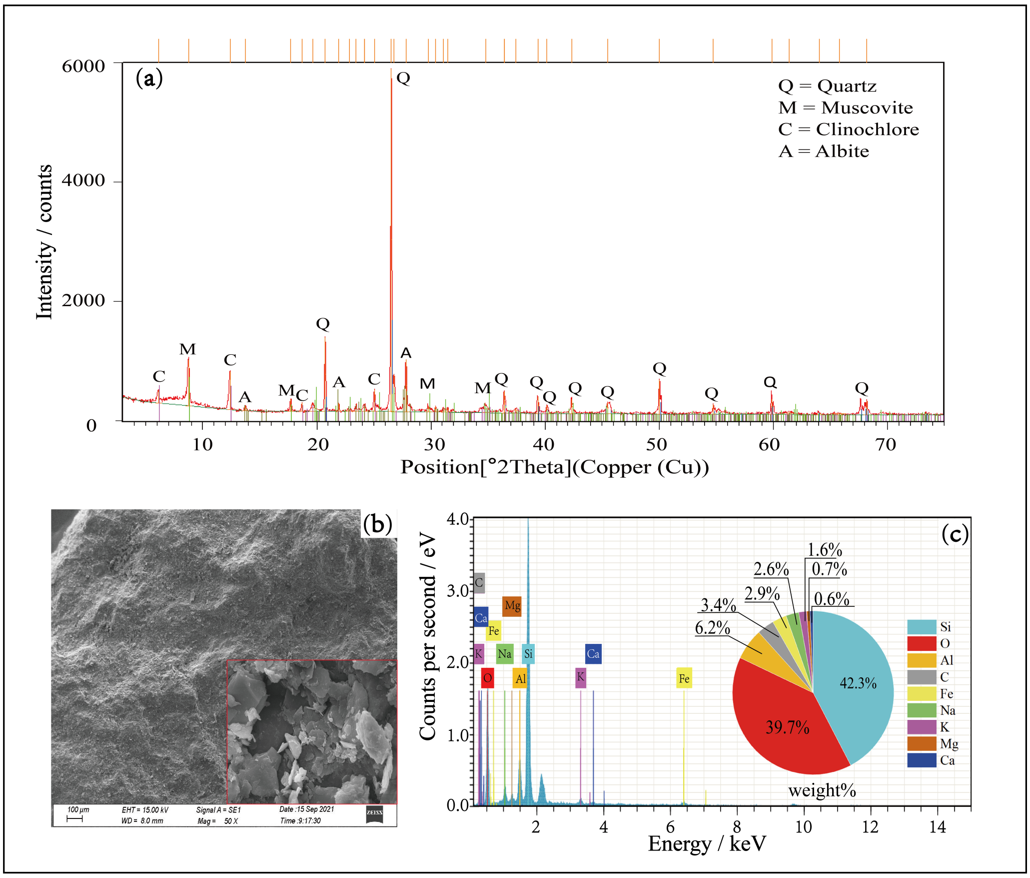

Figure 4. Gravel sample X-ray diffractogram (**a**); scanning electron micrograph (**b**); type and weight% of elements detected in gravels by energy dispersive spectroscopy (**c**).

3.2. Chemical Characterization of Elements in Water, Gravel, and Soil

In this investigation, the pH of gravel, soil, and water was 9.2, 8.0, and 7.8, respectively. Gravels, irrigation water, and initial soil contents of major, trace, and potentially toxic elements are shown in Table 1. The total content of these 30 elements in gravel, soil, and water was 562.5 g/kg, 135.9 g/kg, and 115.3 mg/L, respectively, of which the total elemental content of water was only 0.02% of the gravel.

Not all of the 30 elements in the gravels were higher than in the soil, with P, Mn, Cu, As, Be, Mg, S, and Ca being lower than in the soil. Except for W, which was not detected in soil, the ratio of gravel to soil (R_I) for the remaining 21 elements was, from largest to smallest, Si > Pb > Sn > Cr > Na> Ti > Sr > Li >Al > Ni > Ga > K > C > N > B > Zn > Se > V > Fe > Co > Mo. Approximately 99.86% of the total elemental content of the conglomerate is composed of major elements and rock-forming elements. Essential trace elements and potentially toxic elements each account for 0.12% and 0.02% of the total elemental content of the gravel. The average contents of the initial major, trace, and potentially toxic elements in the soil were 135.5 g/kg, 332.6 mg/kg, and 42.1 mg/kg, respectively.

Table 1. Content of chemical elements in irrigation water, gravel, and soil.

Element	Content			R_I	Element	Content			R_I
	Water (mg/L)	Gravel (mg/kg)	Soil (mg/kg)			Water (mg/L)	Gravel (mg/kg)	Soil (mg/kg)	
Si	4.4	348,614.8	894.6	389.7	Zn	—	122.9	48.0	2.6
Al	—	105,915.6	31,750.0	3.3	V	0.0	108.5	52.4	2.1
Fe	—	42,136.9	21,234.5	2.0	Cr	—	86.9	7.8	11.1
K	4.0	29,531.5	10,591.5	2.8	Sr	0.6	84.3	17.9	4.7
Na	31.9	8463.2	1060.4	8.0	B	0.1	94.6	36.5	2.6
Ti	—	4208.4	803.9	5.2	Cu	—	94.3	125.6	0.8
Ca	37.0	3549.1	46,567.1	0.1	Ni	—	76.5	24.5	3.1
Mg	24.4	1373.1	12,822.6	0.1	Se	—	21.6	9.9	2.2
Mn	—	472.7	510.9	0.9	Co	—	15.3	8.6	1.8
Li	0.0	89.4	23.9	3.7	Sn	—	14.3	0.4	40.1
W	0.0	4.6	0.0	—	Mo	0.0	1.7	1.1	1.5
C	1.2	14,800.4	5620.2	2.6	Ga	—	40.8	13.5	3.0
N	1.0	1600.6	611.5	2.6	Pb	—	35.8	0.9	41.6
P	—	686.9	697.8	1.0	Be	—	5.4	16.5	0.3
S	10.7	213.6	2356.5	0.1	As	—	4.7	11.2	0.4

Notes: the elemental difference between gravel and initial soil is quantified in terms of the elemental ratio R_I.

3.3. Accumulation and Transport of Chemical Elements in Soils

The total content of 30 elements in the soil was calculated under each treatment to assess the enrichment capacity of the chemical elements in the gravel to soil and during the wet-and-dry cycle of the soil (Figure 5). The results showed that the average total elemental content was higher than the initial value for all treatments except BW1. The total elemental content of all gravel mulch treatments was higher than that of bare soil with the same amount of drench (Figure 5a). There was a significant positive correlation (r = 0.81, $p < 0.05$) between the total amount of elements in the soil increasing with the amount of watering in the wet-and-dry cycles. The total soil elemental content of gravel mulch increased by 1.9%, 2.5%, and 7.0% compared to bare soil under dry and wet cycling conditions for W3, W2, and W1, respectively.

In addition, the nutrients in the soil were depleted due to the growth of the jujube trees, and during the test period, there was a trend of increasing and then fluctuating decreases in the major and trace elements and potentially toxic elements with the number of cycles (Figure 5b). The proportions of major elements, essential trace elements, and potentially toxic elements in the soil under bare soil and gravel mulch conditions averaged 99.74%, 0.23%, and 0.03% and 99.75%, 0.22%, and 0.03% of the total 30 elements measured during the test period, respectively.

The total elemental content of both bare and gravel mulch soils followed the same trend as that of the major elements (Figure 5b,c), with the total elemental content of both peaking at the flowering and fruiting stage at an average of 148.5 g/kg and 152.3 g/kg, and the fruit maturity stage at an average of 126.6 g/kg and 130.7 g/kg. In addition, the difference in total elemental content between the two soils was the lowest at 40 days of cycling (2.5 g/kg) and the highest at 80 days of cycling (8.3 g/kg).

The soil pH gradually increased with the duration of the cycle (Figure 5c) and reached a maximum at 100 days of the cycle. The average pH values for bare soil and gravel mulch were 8.5 and 8.8, respectively, a rise of 0.5 and 0.8 units from the initial pH of the soil. Furthermore, the soil pH increased with drenching, with W1, W2, and W3 having pH values of 8.3, 8.4, and 8.5, respectively (Figure 5d). For the same soil pattern, the average total element content of the soil at different watering levels ranged from high to low: 142.4 g/kg, 139.5 g/kg, and 131.4 g/kg for W3, W2, and W1, respectively. When compared to W1, the total elemental content of W3 increased the most at 80 days of cycling with 12.6%, and the least at 60 days of cycling with 4.0%.

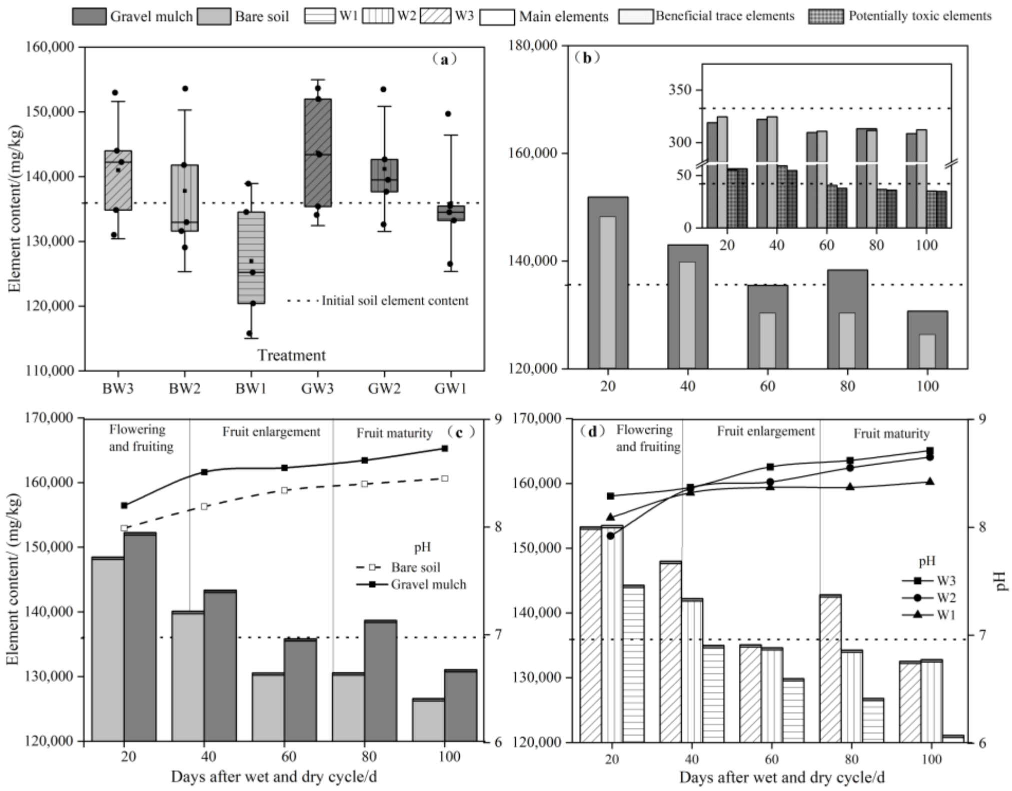

Figure 5. Variation in soil elemental content across treatments (**a**). Elemental amounts vary with cycle time for the major elements, trace elements, and potentially toxic elements (**b**), gravel-mulched and bare soil (**c**), and different dry and wet levels (**d**). W1, W2, and W3 denote treatments of 3 L/d, 5 L/d, and 6 L/d drenching volume per jujube tree, respectively.

3.4. Enrichment and Depletion of Soil Elements

Figure 6 shows the contents of the 30 elements in bare and gravel-mulched soils and the enrichment rate of gravel-mulched soils relative to bare soils. Figure 6a shows the average content and enrichment rate of trace elements. Except for W, which was not detected in the soil, relative to bare soil, the 11 trace elements of the soil under gravel mulch were depleted, in descending order of depletion, as follows: Ni > Li > Sr > As > Se > Ga > Cu > Pb > Be > Sn > Mo. The other six trace elements increased relative to bare soil, in descending order of increase: Mn > Cr > V > Zn > B > Co.

Figure 6b indicates the average content and enrichment rate of massive elements. Compared to bare soil, three major elements were depleted in the soil under gravel mulch, in descending order of depletion: Al > S >P. The other nine massive elements were enriched relative to bare soil, in descending order of increase: Ca > K > Mg > Na > Fe > C > Ti > Si > N.

Compared to bare soil, fifteen elements were enriched in gravel mulch conditions ($B_r > 0$). The total amount of enriched elements was 5730.2 mg/kg, of which 99.9% were major elements and 0.1% were trace elements. The other 14 elements were depleted ($B_r < 0$). The total amount of depleted elements was 738.2 mg/kg, of which 99.4% were major elements and 0.6% were trace elements. The elemental enrichment rate under gravel mulch in descending order is: Mg > Ca > K > Cr > Na > Mn > V > Zn > Fe > Ti > Si > C > N > B > Co > ($B_r = 0$) > Pb > Cu > Ga > P > Sn > Sr > Al > Be > Li > Mo > Ni > Se > As > S.

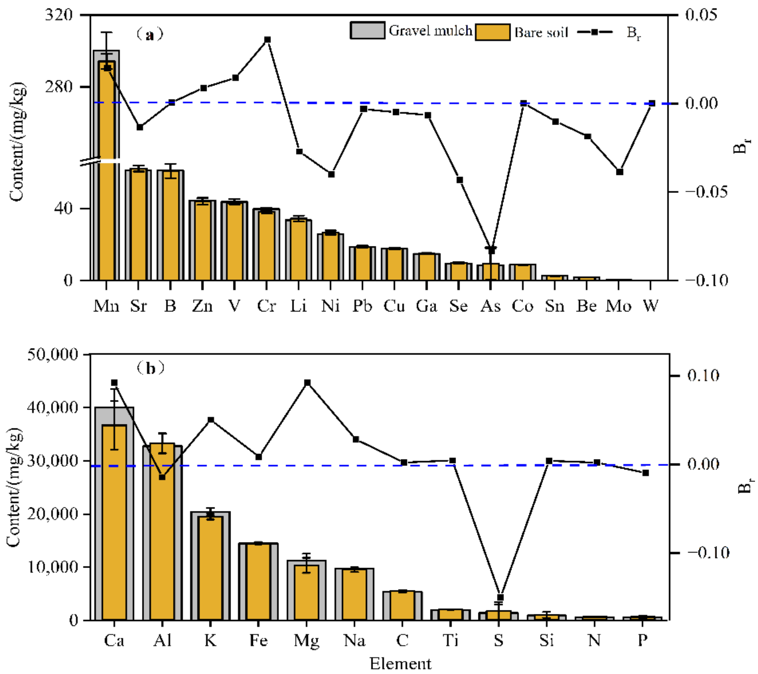

Figure 6. Average trace elements (**a**) and major elements (**b**) content and enrichment B_r in soil under bare soil and gravel mulch circumstances.

3.5. Growth and Yield Indicators of Jujube Tree

As shown in Table 2, gravel mulch significantly ($p < 0.05$) increased the fruit mass and yield of jujube fruit as well as the length of new shoots, thickness of new shoots, and thickness of jujube hangers compared to bare soil. The yield and single fruit mass of GW2 were the highest, while the yield and fruit mass of BW1 was the lowest. The best length and thickness of the new tip and hanging fruit of the jujube tree occur at GW3. The yields of W3, W2, and W1 were 17.0%, 24.8%, and 32.0% higher, respectively, than those of the bare soil treatment under gravel mulch. All the growth indicators of the jujube tree increased with increasing water drenching, with the highest in the GW3 treatment and the lowest in the BW1 treatment. The increase in all indicators of gravel mulch over bare soil was, in descending order: new tip length (45.9%) > new tip thickness (42.3%) > hanging fruit length (26.6%) > yield (24.1%) > hanging fruit thickness (17.3%) > single fruit mass (13.2%). The interaction between the gravel mulch and drench volume only reached a significant level ($p < 0.05$) for the hanging fruit length.

Table 2. Growth and yield indicators of jujube tree under different treatments.

Treatments	Single Fruit Mass/g	Y/(kg·hm^{-2})	New Tip Length/cm	New Tip Thick/mm	Hanging Fruit Length/cm	Hanging Fruit Thickness/mm
BW1	11.8 ± 0.8 d	2113.6 ± 31.6 c	44.2 ± 6.0 d	5.5 ± 0.4 c	20.1 ± 0.7 d	1.4 ± 0.1 e
BW2	14.0 ± 0.3 c	2600.2 ± 156.7 b	55.2 ± 3.9 cd	5.9 ± 0.4 c	21.6 ± 0.9 cd	1.4 ± 0.1 de
BW3	15.1 ± 0.4 b	2595.9 ± 99.5 b	56.3 ± 6.9 c	7.0 ± 0.2 b	23.7 ± 1.3 c	1.6 ± 0.1 cd
GW1	14.1 ± 0.2 c	2790.0 ± 33.2 b	67.0 ± 10.0 cd	7.3 ± 0.5 b	21.1 ± 2.1 cd	1.6 ± 0.1 bc
GW2	16.2 ± 0.4 a	3244.7 ± 53.6 a	75.6 ± 4.5 b	9.4 ± 0.4 a	28.9 ± 1.2 b	1.7 ± 0.1 ab
GW3	16.0 ± 0.3 ab	3037.7 ± 110.2 a	84.5 ± 7.2 a	9.4 ± 0.9 a	32.8 ± 1.1 a	1.8 ± 0.1 a

Notes: Different means with small letters show a significant variation between different treatments. BW1, BW2, BW3, GW1, GW2, and GW3 denote the treatments for per jujube tree: 3 L/d under bare soil, 5 L/d under bare soil, 6 L/d under bare soil, and 3 L/d under gravel mulch, 5 L/d under gravel mulch, and 6 L/d under gravel mulch, respectively. Values are means ± standard deviation of the means (SD; n = 3).

4. Discussion

4.1. Petrographic and Geochemical Characteristics of the Gravels

This study demonstrates that it has a significant proportion of weatherable glassy amorphous matrix in its composition as well as many silicate minerals such as quartz, muscovite, clinochlore, and albite, which are easily decomposed minerals [30]. Albite is a feldspar-like mineral with a peculiar structure that is less resistant to weathering and has a strong capacity to release its own Na into the medium [31]. Muscovite is a potassium-bearing silicate mineral with a potential potassium supply. It has a layered structure, which means there is less interlayer potassium binding force, and it is more likely to release insoluble K, Si, and other elements during weathering [32]. Clinochlore is rich in Fe and Mg elements. When exposed to external conditions, it has low mineralogical stability, making it appropriate for use in soil re-mineralization [33]. It may facilitate the discharge of nutrients into the environment. EDS analysis proved to be a surprisingly satisfactory technique for the chemical characterization of the waste rock samples. In addition, certain percentages of Fe, Na, K, Mg, and Ca elements were detected, reflecting the possibility of nutrient release from the gravels [5].

Water is one of nature's most abundant solvents. The gravels mulch the soil's surface in the presence of natural precipitation or artificial irrigation, and the gravel's constituents move by leaching [34,35]. Some major elements and essential trace elements were detected in the water, and no toxic elements were detected. Although toxic elements were detected in the gravels, low concentrations of toxic elements in an alkaline environment do not represent an environmental risk [36].

4.2. Differences in Soil Nutrients and Jujube Yield among Treatments

The difference between the soil element content under gravel mulch and bare soil increased 40–80 days after the application of the treatment, i.e., during the fruit expansion period, probably because gravel weathering replenished the elements needed in large quantities during the jujube fruit expansion period [37]. The total elemental content of the gravel-mulched soil was higher than the initial total elemental content of the soil up to the first stage of fruit maturity, while the elemental content of the soil under bare soil was higher than the initial total elemental content of the soil only at the first stage of fruit expansion. The results indicate that the nutrients from the weathering of the gravels were able to delay the depletion of soil nutrients caused by the growth of the jujube tree [4]. With the continued depletion of nutrients by jujube tree growth, the total elements in the soil under the gravel mulch and bare soil decreased at 100 days of cycling compared to the initial soil, indicating that if the soil nutrients are replenished by the gravel dry and wet cycle alone in the long term, this may result in an imbalance in the soil of jujube forest elemental system and soil impoverishment [10]. The calculation of enrichment rates (B_r) revealed that the potentially toxic elements (As, Ga, Pb, Be) of the soil under gravel mulch were reduced relative to bare soil, while major elements (Ca, K, Mg, Na, Fe, C, Ti, Si, N) were enriched. This indicates that gravel has good potential to act as a supplementary nutrient for the soil under dry and wet cycles without posing an environmental risk [38].

As the degree of wet-and-dry cycles increased, the highest nutrient content was found in GW3 with high humidity, probably because W3 had a more sufficient leaching time than W2 and W1 [39]. GW2 had the highest yield and single fruit quality, but the difference with GW3 did not reach a significant level ($p < 0.05$). The lower yield was likely due to the lower increase in total soil composition in GW3 compared to GW2, along with the increase in invalid water consumption [40]. Compared to GW3, the total elemental content in GW2 soil increased by 6.4% in jujube fruit yield, although it decreased by 1.8%. Therefore, a drenching volume of 5 L/d per tree under gravel mulch (GW2) was considered an effective treatment considering soil nutrients and the growth and yield of jujube trees.

4.3. Difference between Soil Elements under Bare Soil and Gravel Mulch

Rock weathering can increase the amount of major and trace elements in soils, affecting agricultural production, biogeochemical processes, and water quality in arid zones [41]. In this study, principal component analysis (PCA) of the entire dataset of soil elements was able to distinguish between the two soil patterns (bare soil and gravel mulched) (Figure 7a), i.e., the elements that are affected differently by the wet-and-dry cycle for the two soil patterns [42]. The first two principal components account for 70.1% of the total variation. The rotated loading matrix of the first principal component shows that the largest loadings are for trace elements, which are depleted under gravel mulch relative to bare soil, especially Li, Sn, Be, As, etc. These results indicate those trace elements are the primary constituents that change in bare soil during the wet-and-dry cycles. Soil aggregates fragment and increase the element enrichment under wet-and-dry cycling conditions, enhancing phosphorus activity, carbon sequestration, and trace element precipitation [43,44]. The rotated loading matrix of the second principal component reveals that rock-forming elements such as Ca, Ti, Mn, and Fe have the highest loadings. The high Pb content of gravels compared to soils may explain the large contribution of Pb to the second principal component [45]. These results indicate that rock-forming components are the most variable in gravel mulch soils during dry and wet cycles [46].

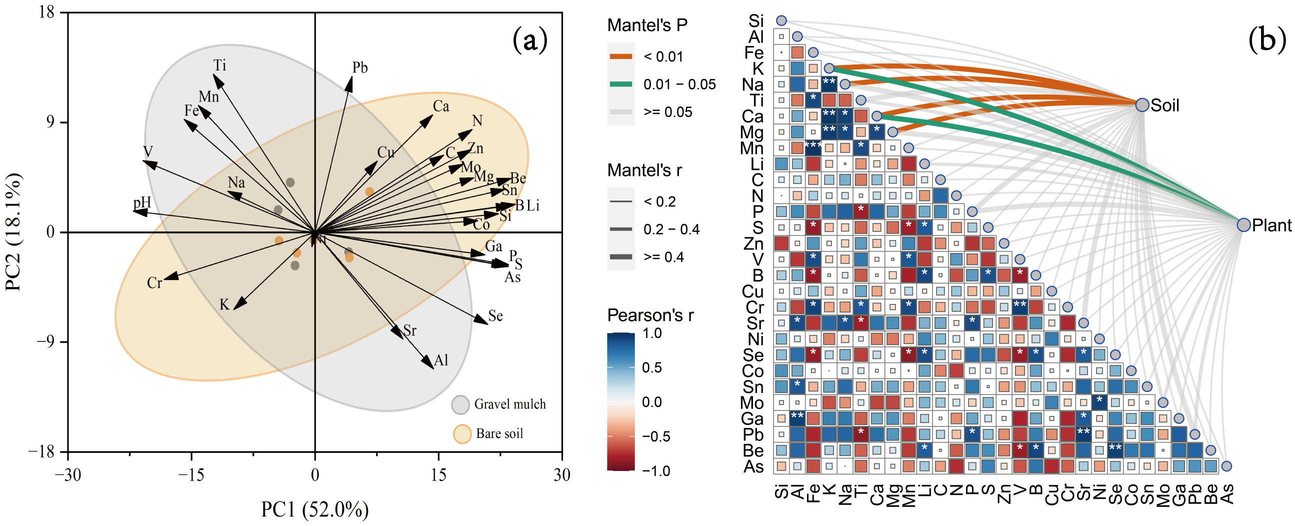

Figure 7. (**a**) Displays the principal component analysis (PCA) of soil pH, soil nutrients (major elements, beneficial trace elements), and potentially harmful elements for bare and gravel-mulched soils. Correlation between elements in soil, and Mantel test analysis of each element about jujube tree growth and production (single fruit mass, yield, new tip length, new tip thick, hanging fruit length, hanging fruit thick) and soil nutrients (total elements, major elements, beneficial trace elements) (**b**). In the figure, * and ** indicate inter-element correlations that are significant at the 0.05 level ($p < 0.05$) and at the 0.01 level ($p < 0.01$), respectively.

Rock-forming elements were identified to be strongly related to soil pH, with the soil pH under gravel mulch increasing with increasing days of wet-and-dry cycles, implying that by-products may come into contact with the soil and thus neutralize the soil H^+ [36]. The gravel mulch released more nutrients into the soil than the bare soil under wet-and-dry cycling conditions, neutralizing more of the acid fraction in the soil, and the gravel itself had a high pH, which may have contributed to the higher pH in the gravel mulch than in the bare soil. Furthermore, with increasing degrees of dry/wet cycling, so did soil nutrient elements and pH. This variation is primarily caused by the soil water content, the number of neutral salts, and the type of cations in the soil solution and exchange complexes [47].

In this study, the soil pH and rock-forming elements were positively correlated but negatively correlated with trace elements. This indicates that the entry of rock-weathering elements into the soil will increase the pH and that increasing the soil pH is a promising strategy for reducing the risk of heavy metal elements in the soil [48].

4.4. Chemical Elements Affecting Soil Nutrients and Jujube Growth and Yield

To identify the key driving elements among the 30 elements and the correlations among them [49], distance-corrected differences in soil and plant composition were correlated with differences in soil elements (Figure 7b). In general, K, Na, Ti, Ca, Mg, P, Sr, and Pb are closely related to the total soil nutrients, total beneficial trace elements, and total major elements. Among them, the effects of K, Na, Ca, and Mg on soil nutrient contents reached significant levels ($p < 0.05$). In addition, gravel weathering under dry and wet cycles mainly affected the growth and yield of jujube fruits through the contents of K, Na, Mg, and P in the soil, among which the effects of K and Ca reached significant levels ($p < 0.05$) [7]. Among them, K, Na, Ti, Ca, and Mg were enriched in the soil under gravel mulch ($B_r > 0$), while P, Sr, and Pb were depleted ($B_r < 0$). P levels in gravel-mulched soil are lower than in bare soil because the pH of the soil is higher, and plants can more easily take P from the soil [50]; additionally, Sr and Pb showed a significant positive correlation with P, decreasing with P. K and Ca showed the strongest correlation with soil nutrients and jujube tree growth production. The significant increase in K and Ca from gravel weathering was crucial during fruit expansion, compensating for jujube nutritional requirements and, as a result, boosting the fruit mass and yield relative to bare soil [37]. Furthermore, significantly increased K, Ca, Mg, and Na content in the soil promotes the growth of branches and leaves [51], and the jujube trees grown in gravel mulch have bigger new tips and hanging fruit. Finally, the components precipitated by the wet and dry cycle of gravel can boost soil nutrients and increase jujube fruit yield, fostering healthy jujube tree growth.

5. Conclusions

The gravel shows many easily weathered silicate minerals in its composition, such as clinochlore, muscovite, and albite, which are rich in nutritional elements and easily released into the soil. The principal soil components that were altered under gravel mulch and bare soils were rock-forming elements and trace elements, respectively. Compared to bare soil, the soil under gravel mulch is enriched in large amounts of elements and depleted in trace elements. The analysis showed that the total nutrient content of the soil under gravel mulch was higher than that of the bare soil. K, Na, Ca, and Mg contributed significantly to the difference in nutrients between the two soils. Among them, the contents of K and Ca significantly affected the growth and yield of jujube trees. The total amount of elements in the soil was significantly and positively correlated with the drenching volume of the wet-and-dry cycles. For the same amount of water, a drenching volume of 5 L/d per tree under gravel mulch (GW2) was considered an effective treatment considering soil nutrients as well as the growth and yield of jujube trees. Therefore, the application of a wet-and-dry cycle to mulched gravels in agriculture can replenish soil nutrients and improve crop yields and may be an effective means to address the problem of rock desertification in arid areas and reduce soil and water pollution by chemical fertilizers, thus maintaining sustainable agriculture.

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