

Mechanistic insights into mixed gravel-soil mulching effects on soil hydrology in arid ecosystems: A field micro-lysimeter study Postprint

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Abstract

Gravel mulching plays a vital role in modifying the hydrological cycle in arid and semi-arid areas. Yet, the mechanisms underlying long-term mulching effects on soil evaporation remain poorly understood. To investigate the hydrological effects of mixed gravel-soil mulching (MGSM), we conducted a controlled 39-d soil evaporation experiment (from 22 July to 30 August 2021) using micro-lysimeters at the field experimental site of Ningxia University, China. The soil evaporation rate (E), cumulative soil evaporation (E_c), soil water content (SWC), mulch resistance (r_m), and micro-meteorological variables were assessed for six mulch treatments, each containing a different proportion of gravel by volume: 100.00% (M1), 80.00% (M2), 60.00% (M3), 40.00% (M4), 20.00% (M5), and 0.00% (M6). The treatments (M2–M6) showed a prolonged soil moisture depletion phase and greater E_c (28.71%–83.31%) relative to the gravel-only treatment (M1) (Prm). As compared to E_c , the SWC showed an inverse response, decreasing as E_c increased. A robust exponential relationship was observed between E and r_m (Prm was particularly pronounced during the residual evaporation stage (>312 h post-wetting), with the strongest effect occurring in M3, where the mean r_m doubled. The SWC, mulch properties, and micro-meteorological parameters (i.e., air relative humidity and surface net radiation flux) were the most important predictors of r_m in the mulch treatments. Together, these results suggested that MGSM unexpectedly exacerbated surface soil moisture loss by reducing r_m . To mitigate this effect, an optimized mixed gravel-soil mulch, containing 60.00% gravel by volume, might be used; this mixture balances evaporation control with hydrological sustainability and represents a practical strategy for dryland management, offering a compromise between short-term water retention and sustained soil moisture regulation.

Full Text

Preamble

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Abstract

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To investigate the hydrological effects of mixed gravel-soil mulching (MGSM), we conducted a controlled 39-d soil evaporation experiment (from 22 July to 30 August 2021) using micro-lysimeters at the field experimental site of Ningxia University, China. The soil evaporation rate (E), cumulative soil evaporation (E_c), soil water content (SWC), mulch resistance (R_m), and micro-meteorological variables were assessed for six mulch treatments, each containing a different proportion of gravel by volume: 100.00% (M1), 80.00% (M2), 60.00% (M3), 40.00% (M4), 20.00% (M5), and 0.00% (M6). The treatments (M2–M6) showed a prolonged soil moisture depletion phase and greater (28.71%–83.31%) relative to the gravel-only treatment (M1) ($P < 0.050$); these effects were primarily attributed to reduced E . As compared to M1, the SWC showed an inverse response, decreasing as E decreased. A robust exponential relationship was observed between E and SWC ($P < 0.001$). Evaporation suppression mediated by R_m was particularly pronounced during the residual evaporation stage (>312 h post-wetting), with the strongest effect occurring in M3, where the mean doubled. The SWC, mulch properties, and micro-meteorological parameters (i.e., air relative humidity and surface net radiation flux) were the most important predictors of E in the mulch treatments. Together, these results suggested that MGSM unexpectedly exacerbated surface soil moisture loss by reducing E . To mitigate this effect, an optimized mixed gravel-soil mulch, containing 60.00% gravel by volume, might be used; this mixture balances evaporation control with hydrological sustainability and rep-

resents a practical strategy for dryland management, offering a compromise between short-term water retention and sustained soil moisture regulation.

Keywords

gravel mulching; gravel-soil matrix; hydrological regulation; soil evaporation; mulch resistance; micro-lysimeter Citation:

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1 Introduction

Globally, soil hydrology strongly shapes crop productivity, especially in arid and semi-arid areas (Konapala et al., 2020; Tugwell-Wootton et al., 2020). Soil evaporation represents a critical hydrological process that directly depletes plant-available water reserves. Excessive evaporation can significantly limit crop productivity, potentially exacerbating the degradation of agricultural ecosystems (An et al., 2018; Zhu et al., 2021). Both climate change and agricultural management practices inevitably affect soil evaporation, further amplifying variation in local hydrological cycles and crop growth (Marvel et al., 2019; Van Loon et al., 2019). Hence, it is essential to understand the drivers of soil evaporation to optimize agricultural production in arid and semi-arid areas (Konapala et al., 2020).

Mineral particles exceeding 2.000 mm in diameter are classified as rock fragments (Miller and Guthrie, 1984). Soils containing a large volume of rock fragments are widespread globally, primarily occurring in the Mediterranean region and on the Qinghai-Xizang Plateau and within the karst regions of the southwest in China (Poesen and Lavee, 1994; Zhang et al., 2016; Lai et al., 2022). These rocky soils have demonstrated agroecological value, enabling agricultural adaptation to extreme climatic conditions. Gravel mulching is an indigenous technique used to insulate agricultural soils in arid and semi-arid areas (Kaseke et al., 2012; Wu et al., 2024); the application of mulch to the soil surface promotes moisture retention by lowering soil evaporation (Halihan et al., 2019; Wang et al., 2023). Gravel mulch can also elevate soil temperatures by retarding the diffusion of water vapor and energy exchange (Xie et al., 2010; Lü et al., 2013; Zhang et al., 2024). However, over time, gravel mulch often becomes intermixed with soil due to the effects of irrigation, tillage, and wind erosion (Jia et al., 2024a). The addition of soil to the gravel mulch alters its texture, reducing its ability to retain soil moisture and nutrients (Qiu et al., 2015; Zou et al., 2018; Jia et al., 2024b). As such, the long-term sustainability of gravel-mulched fields

has been called into question, with concerns over negative economic returns and excessive energy use (Jia et al., 2024a).

Evaporation usually occurs from the soil surface and can be divided into three stages (Fisher, 1923; Lehmann et al., 2008; Lehmann and Or, 2009; Or et al., 2013). In the first stage, both the soil water content (SWC) and soil evaporation rate () remain high and relatively constant, with these dynamics mainly determined by local atmospheric conditions. As SWC is depleted, hydraulic continuity is interrupted and rapidly decreases, representing the second stage. In the final (or residual) stage, is minimal and controlled by water vapor diffusion. However, in the presence of gravel mulch, this process is greatly affected by the properties of the gravel layer, such as the gravel particle size distribution, mulch coverage and/or structure, and mulch thickness (Ma and Li, 2011; Wang et al., 2023; Kang et al., 2025). Generally, the inhibition of soil evaporation is negatively correlated with the gravel particle size, and mulch particle size is generally larger than the particle size of the subsoil (Diaz et al., 2005; Yuan et al., 2009; Xie et al., 2010). Small gravel particles increase mulch resistance () to water vapor transport (Qiu et al., 2014), thereby shortening the duration of the first evaporation stage (Yuan et al., 2009). However, the heterogeneity of gravel-soil matrices may complicate surface soil evaporation predictions due to variation in the hydraulic and thermal properties of the ground surface, including its capillarity and reflectivity (Bonachela et al., 2020; Lu et al., 2021). Field experiments with winter wheat crops have shown that mulching with less gravel lowers crop yields, energy inputs/outputs, and economic returns as compared to pure gravel mulching; these reductions are related to differences in soil insulation and water retention (Wang et al., 2019). In gravel-mulched fields, soil drying becomes more pronounced over time due to increasing variability in SWC (Zhao et al., 2020).

Although most studies have shown that mixed gravel-soil mulching (MGSM) strongly impacts soil moisture levels, the processes and potential mechanisms underlying soil evaporation in mulched fields remain poorly characterized.

As a key parameter characterizing the energy barrier to liquid-to-vapor phase transitions in soil pore water, has become a focal topic in agricultural hydrology research (Gardner, 1958).

Understanding the dynamics and the underlying mechanisms shaping these dynamics will support optimal mulching practices while advancing water-efficient agricultural practices through enhanced evaporation control (Yamanaka et al., 2004). Gravel and straw mulch effectively reduces soil evaporation; this effect does not rely on atmospheric stability and increases linearly or exponentially with mulch coverage, particle size, and thickness when the soil approaches saturation (Fuchs and Hadas, 2011; Qiu et al., 2014). To date, several evaporation models have been applied to assess mulch effects on soil moisture loss (e.g., Li et al., 2015; Sun et al., 2020).

However, the practical applicability of model results remains constrained by

parameter uncertainty and limited data availability (Kang et al., 2025). Particularly in areas affected by rocky desertification, MGSM may also restore physical processes that reduce soil evaporation via structural modification of the overlying strata. As such, characterizing the mechanisms by which gravel volume alters the represents an important research topic.

The primary objective of this study was to systematically investigate MGSM effects on soil evaporation dynamics and their underlying mechanisms across evaporation stages, using an integrated approach that combined macro-scale phenomenological observations with micro-scale mechanistic analyses. The , cumulative soil evaporation (), and SWC, were measured using micro-lysimeters in a field-based evaporation experiment. Several micro-meteorological variables were recorded simultaneously. Evaporation resistance was then calculated, and the relationships with gravel concentration (), SWC, and other environmental factors were assessed. We hypothesized that the presence of gravel-soil matrices in the mulch can significantly increase by reducing the , with this effect varying over time and across environments. However, there may be a threshold above which there is sufficient gravel in the mulch to offset soil moisture loss by promoting the formation of soil crusts. This study provides critical insights for optimizing mulching strategies in arid and semi-arid areas, with the goal of enhancing water conservation. It establishes a theoretical foundation for the development of sustainable agricultural practices aimed at improving surface soil moisture retention and increasing crop productivity under water-limited conditions. 2 Materials and methods

2.1 Study site

This study was conducted at the Xiangshan Research Station (36°56'N, 105°13'E) of Ningxia University in Ningxia Hui Autonomous Region, China. The study area possesses a typical semi-arid continental climate. The mean annual evapotranspiration is 2100-2400 mm; the mean annual precipitation is only 180-200 mm, with 60.00%-70.00% falling between July and September; and a total of 2600-2700 h of sunshine is received each year. The air temperature (), relative humidity (RH), and wind speed () at 2.000 m height, solar short-wave radiation (at ground surface, and precipitation were recorded at an automatic meteorological station (Vantage Pro2; DAVIS INSTRUMENTS, Hayward, USA) situated less than 20.000 m from the experimental field. During the experimental period (from 22 July to 30 August 2021), the daily averaged 22.05°C (with a maximum of 27.81°C and a minimum of 15.62°C); the daily RH averaged 49.16%; the daily averaged 2.20 m/s; and the mean daily was 19.02 MJ/(m (with maximum and minimum values reaching 28.63 and 3.91 MJ/(m d), respectively) (Fig. 1 [FIGURE:1]).

Precipitation events exceeding 1.000 mm occurred on experimental days 13, 28, 31, 32, and 40 post-initiation.

2.2 Experimental design

The soil used in the experiment was collected in April 2021 from a local gravel-mulched field that had been vegetated for the last 10 a and was representative of regional soil properties. The soil had a calcareous sandy loam texture according to the Chinese soil texture classification system, containing 11.82% sand (1.000–0.050 mm), 35.13% silt (0.050–0.010 mm), 31.93% clay

Meteorological conditions during the experimental period (from 22 July to 30 August 2021). , wind speed; , air temperature; RH, relative humidity; , solar short-wave radiation. (0.010–0.001 mm), and 21.12% colloidal particles (<0.001 mm). Soil samples were prepared by air-drying, crushing, and 1.000-mm sieving after removing the surface mulch. The gravel used in the experiment was obtained from the same area as the soil samples and was classified as metamorphic rock, containing 37.00% large-grain gravel (20.000–30.000 mm particle size) and 63.00% small-grain gravel (10.000–20.000 mm particle size) by volume, as determined using local gravel mulching methods. The gravel samples were washed at least three times using distilled water and then naturally air-dried for 72 h.

To simulate observed declines in the relative gravel content of the mixed gravel-soil mulch layer in agricultural fields, varied proportions of gravel (by volume) in the mulch layer were designed in the field experiment, with tested values of 100.00% (M1, pure gravel, as a control), 80.00% (M2), 60.00% (M3), 40.00% (M4), 20.00% (M5), and 0.00% (M6) (Fig. 2a [FIGURE:2]). Note that only the volume fraction of gravel in the gravel-soil mulch was varied, while the thickness of the mulch layer was constant across all experimental treatments. The details of the mulch treatments are presented in Schematic diagrams of the experimental set-up. (a), design of six mulch treatments containing different proportions of gravel by volume: 100.00% (M1), 80.00% (M2), 60.00% (M3), 40.00% (M4), 20.00% (M5), and 0.00% (M6); (b), field layout of the micro-lysimeter evaporation experiment.

Details of the mulch treatments and their properties Note: M1–M6 indicate six mulch treatments; is the volume fraction of gravel in the gravel-soil mixture; is the thickness of the mulch layer; , gravel amount in the gravel-soil mixture; is the soil amount in the gravel-soil mixture; is the total gravel and soil amount in the gravel-soil mixture; is the bulk density of the gravel-soil mixture. The bulk density of the gravel-soil mixture was determined via both theoretical calculations (based on the density and volume ratio of the soil and gravel components) and ring-knife measurements. using polyester foam barriers (2 cm thickness \times 40 cm height) to minimize thermal interference between experimental units, as shown in Figure 2b. The presence of the foam partitions did not otherwise affect the experiment.

Following previous studies (Xie et al., 2006; Yuan et al., 2009; Kaseke et al., 2012), the evaporation experiment was conducted in cylindrical PVC micro-lysimeters (20 cm inner diameter \times 25 cm height), including all six mulch treatments (M1–M6) with ten replicates (cm height) was installed 24 cm below the ground surface to prevent the backflow

of rainfall in each micro-lysimeter. All micro-lysimeters were installed within the larger PVC cylinders, with their upper surfaces precisely leveled to maintain continuity with the surrounding soil profile. This flush installation also prevented direct solar radiation of the micro-lysimeter sidewalls, minimizing edge effects on soil evaporation and temperature.

Prior to filling the micro-lysimeters with soil, Vaseline was uniformly applied to the inner walls of each micro-lysimeter to minimize boundary effects. The micro-lysimeters were filled in four layers, each 5 cm deep, to replicate the stratified structure of local soil horizons. The average soil bulk density was 1.37 g/cm³, consistent with in situ field conditions. To promote moisture retention, a 4-cm thick, uniform layer of dry gravel-soil mulch was applied to fully cover the surface soil (Diaz et al., 2005; Yuan et al., 2009; Xie et al., 2010). A total of 2.65 L of water was supplied to fully saturate the soil in each PVC pot, simulating a large rainfall or irrigation event; this volume of water was based on gravimetric analyses of moisture differentials between saturated and air-dried soils following established protocols (Jia et al., 2023). Finally, all pots were covered with plastic film and placed in a shaded area for 48 h to achieve complete water infiltration.

2.3 Soil evaporation measurements

The field experiment was conducted during the growing season, when the effects of gravel mulching on soil evaporation are most prominent (Yang et al., 2022). During the experiment, all soil samples were weighed daily at 08:00 am or 08:00 pm (LST) using an electronic balance (with an accuracy of ± 0.01 g) to obtain baseline evaporation data in the absence of rainfall. Based on the results of a preliminary experiment examining the (mm/h), measurements were collected every 12-24 h for the first 9 d and then every 48-72 h thereafter. The measurements were terminated when the variation in across all treatments remained below $\pm 10.00\%$ for three consecutive measurement cycles; in the end, the experimental period spanned 936 h (39 d) from 22 July to 30 August. The (mm) and , described in detail by Jia et al. (2023), were used to characterize soil evaporation across the mulch treatments. Besides, the critical time points distinguishing the two evaporation phases were identified using established methodology (Jia et al., 2023); this approach relies on the analysis of characteristic breakpoints in the evaporation process as defined for the three-stage theory.

2.4 SWC and micro-meteorological measurements Given that the SWC of surface soil is correlated with , SWC measurements may reflect soil evaporation in the presence of a mulch layer (Aydin et al., 2005). At 08: 00 am or 08: 00 pm daily, soil samples (about 15.0 g) were collected from all four sampling ports in each micro-lysimeter and then combined to form a single composite sample per micro-lysimeter. SWC (g/g) was measured at 0-1 cm depth for the composite samples from each treatment after drying at 105.00°C to a constant weight in the laboratory (Carter and Gregorich, 2008). After sampling, the micro-lysimeters were immediately topped up using the same field-collected soil as before and reweighed (Li et al., 2015).

Soil evaporation is mostly driven by the micro-meteorology of the top 15 cm of the surface soil (Weng et al., 1981). Therefore, the (°C), RH (%), and (m/s) were measured at 15 cm above the ground surface, while surface soil temperature (; °C) was measured at 0–1 cm depth for each mulch treatment. Here, all measurements were conducted every 2 h using psychrometers for and RH, micro-airflow meters for , and RTHOYE electronic thermometers for , with specific operational details provided in Jia et al. (2023).

In addition, the surface net radiation flux (; MJ/(m h)) for each treatment was calculated as: where is the surface albedo, measuring 0.25, 0.26, 0.27, 0.28, 0.29, and 0.30 for M1–M6, respectively; (MJ/(m h)) represents the solar short-wave radiation flux obtained from the automated meteorological station; and (MJ/(m h)) represents the surface net long-wave radiation flux, as computed by Allen et al. (1998). The surface albedo values were determined through interpolation using albedo values for bare soil and pure gravel mulch (Weng et al., 1981).

2.5 Soil evaporation resistance calculation When considering evaporation from a mulched surface, the total resistance (; s/m) represents a combination of the aerodynamic resistance (; s/m), surface soil resistance (; s/m), and (s/m).

In this study, was characterized by the following equation, which is analogous to Ohm’s law but for mulched conditions (Van Bavel and Hillel, 1976; Allen et al., 1998). The calculation frequencies of all evaporation resistance components (, and) were synchronized with the measurement frequency of soil evaporation.

$$\bullet \quad - = \times +$$

RH H T

$$\bullet \quad \times = \times \times + , (4)$$

33.5 if

$$= + > \quad = - + - \leq$$

4140() if where) and) represent the volumetric water content and saturated volumetric water content of the surface soil, respectively. value was calculated following Allen et al. (1998):

$$= , (7)$$

where (m/s) is the mean wind speed at a reference height (m), here taken as 0.150 m based on a similar study (Sun et al., 2020); is the von Karman constant (0.41); and (m) is the surface roughness. Surface roughness values for M1–M6 were 0.020, 0.022, 0.024, 0.022, 0.020, 0.010 m, respectively, corresponding to the gravel volume fraction in the mulch layer of the experimental treatments (Liu and Dong, 2003). , and were obtained, was calculated as:

$$3600 \cdot v_s v_a m a s H H r r r E - = - - (8)$$

2.6 Statistical analyses

All measured variables were checked for normality using Shapiro-Wilk tests, while Levene's tests were used to assess homogeneity of variance; variables were log transformed as needed to obtain normality and equal variances. One-way analysis of variance (ANOVA) and Duncan's multiple range tests were used to assess treatment effects for SWC, θ , and ψ at each evaporation stage.

Pearson correlation (using correlation coefficient r) and stepwise regression analyses were also employed to explore the relationships of θ , SWC, and other environmental factors (i.e., ψ , and ρ). Key determinants of θ were identified using stepwise regression and then incorporated into a path analysis to better understand the relationships between θ and its predictors (ψ , RH, ρ , SWC, and ρ). The results were presented as standardized direct (β) and indirect (β') path coefficients, which indicate the direct and indirect effects of one variable on another, respectively. The decision coefficient (D) was used to characterize the comprehensive determining effect of response variables on the dependent variable. The variable with the largest absolute value is the primary decision variable; if it is negative, it is the primary limiting variable.

The path analysis was also used to quantify the relative importance of each predictor. All statistical analyses were performed using IBM SPSS Statistics version 26.0 (IBM SPSS Inc., Chicago, USA).

Differences between treatments were considered statistically significant at <0.050 level.

3 Results

3.1 Soil evaporation process and soil water status rapidly declined from 12-108 h in M1 and from 12-264 h in M2, and then slowly and continuously decreased for the rest of the experiment (Fig. 3 [FIGURE:3]). However, a different pattern was observed for M3-M6, with the highest values of occurring between 12-72 h near the beginning of the experiment; then declined rapidly from 72-312 h, before stabilizing at a very low value thereafter. In addition, for all treatments, an exaggerated dip in θ was observed at 144 h, followed by a recovery at 168 h; this was caused by a small-scale rainfall event and associated delay to the evaporation measurements. Overall, θ exhibited three distinct stages (I-III), with the exact timing of each varying among treatments. For M1, stages I-II occurred from 12-108 h post-wetting, while stage III occurred >108 h post-wetting. Stages I-II were much longer for M2 (12-264 h post-wetting), with the onset of stage III therefore also occurring later (>264 h post-wetting). These

Dynamics of soil evaporation rate (E) for each mulch treatment. (a), M1; (b), M2; (c), M3; (d), M4; (e), M5; (f), M6. Critical time points (t_c) mark the transitions between stages I and II (t_{I-II}) and stages II and III (t_{II-III}) of soil evaporation. Delays were even more pronounced for M3-M6: stages I-II (12-312 h post-wetting) and stage III (>312 h post-wetting).

Both the mulch treatment and evaporation duration (i.e., time since wetting) significantly affected SWC and <0.001 ; Fig. 4 [FIGURE:4]). Over the 39-d evaporation period, both SWC and showed exponential relationships with time ($\$ \0.94 , <0.001 ; Table S2), but in opposite directions. Comparing treatments, SWC was highest in M1 and lowest in M6 (Fig. 4a), while was highest in M6 and lowest in M1 (Fig. 4b). Across treatments, there was a highly significant negative linear relationship between SWC $\$ \0.97 , <0.001 ; Fig. S1).

Variations in surface soil water content (SWC; a) and cumulative soil evaporation (; b) with evaporation time for six mulch treatments (M1-M6). Values are mean \pm SE ($n=10$). Shaded areas indicate 95.00% confidence intervals.

Compared to M1, SWC was significantly lower in M2-M6 at each evaporation stage; this difference was particularly marked for M5 and M6 (<0.050 ; Fig. 5a [FIGURE:5]). For stages I-II, compared to M1, the overall SWC was 20.23% lower in M2, 26.22% lower in M3, 31.04% lower in M4, 37.01% lower in M5, and 39.85% lower in M6. For stage III, the SWC in M1 averaged 1.76-2.34 times that of M2-M6, but differences among the M2-M6 treatments were more muted. For example, SWC did not differ between M2 (0.14 g/g) and M3 (0.14 g/g) nor between M5 (0.10 g/g) and M6 (0.11 g/g). Across all time points, SWC averaged 0.19 g/g in M2, 0.18 g/g in M3, 0.17 g/g in M4, 0.15 g/g in M5, and 0.15 g/g in M6 (Fig. 5b). These values represented significant reductions of 27.92%, 29.32%, 36.12%, 42.28%, and 43.83%, respectively, as compared to M1 (0.26 g/g).

For stages I-II, increased significantly (<0.050 ; Fig. 5c) as the declined. Although evaporation was minimal in stage III (for all treatments), remained higher in M1 than in M2-M6 by 26.96%-169.22% (<0.050 ; Fig. 5c). Notably, the most pronounced difference was observed between M1 and M3, with being 62.86% lower in M3 than in M1 (Fig. 5c).

Throughout the evaporation period, was significantly higher in M2-M6 than in M1 (<0.050 ; values descending in the following order: M6>M5>M4>M2>M3>M1).

Compared to M1, over the entire 39-d period, was 37.26% higher in M2, 28.71% higher in M3, 50.59% higher in M4, 63.52% higher in M5, and 83.31% higher in M6.

Dynamics of SWC and under six mulch treatments (M1-M6) at different evaporation stages (a and c) and across the entire experimental period (b and d). In panel (b), the lower and upper quartiles (Q1 and Q3) in the boxplots are demarcated by the respective lower and upper boundaries of the interquartile range box. The whiskers extend to 1.5 times the interquartile range (IQR) of each box, while group-specific means are indicated by blue circles, and the red circles are data points. Except for panel (b), all figures show the mean \pm SE ($n=10$) for each points. Different lowercase letters indicate significant differences (<0.050) among treatments.

3.2 Soil evaporation resistance

, and for each mulch treatment. Throughout the experimental period, remained low and nearly constant over time in all mulch treatments.

However, the mulch treatment and evaporation duration both influenced the relative contribution <0.001 ; Fig. 7a [FIGURE:7]). For example, compared to M1, the average relative contributions of in M2-M6 exhibited increases of 61.70%, 54.28%, 127.36%, 172.78%, and 515.46%, respectively.

Significant temporal variation was observed in the relative contribution of across mulch treatments ($=0.023$; Fig. 7b). In M1, did not vary significantly over time, increasing by only 37.58–45.20 s/m over the course of the experiment (Fig. 6a [FIGURE:6]). In M2-M6, showed progressive

Dynamics of aerodynamic resistance (ρ), surface soil resistance (r_s), mulch resistance (r_m), and total resistance (r_t) for each mulch treatment. (a), M1; (b), M2; (c), M3; (d), M4; (e), M5; (f), M6. The critical time point marks the transition between stages II and III of soil evaporation.

Relative contributions of (b), and (c) to across mulch treatments and evaporation time hourly increases, with inflection points occurring at 408 h in M2, 408 h in M3, 264 h in M4, 192 h in M5, and 192 h in M6 (Fig. 6b-f). Overall, the relative contributions of were much higher in M2-M6 versus M1 (<0.001 ; Fig. 7b), with mean relative increases of 333.86% in M2, 281.78% in M3, 517.79% in M4, 785.19% in M5, and 1032.82% in M6.

As shown in Figure 6, consistently exceeded both across all treatments. During stages I-II and the initial phase of stage III, showed marked increases across all treatments (M1-M6), followed by progressive declines later in stage III. For all treatments, the temporal dynamics of mirrored those of (Fig. 6). The relative contribution of exhibited similar temporal dynamics across all treatments ($=0.031$; Fig. 7c).

The mulch treatments significantly affected , with being higher in M1 than in all other treatments (Fig. 8 [FIGURE:8]). In M1, constituted 61.18%–97.87% of despite substantial temporal variation (Figs. 6a and 7c). However, this proportion decreased significantly in M2-M6 (<0.001 ; in M6 on average as compared to M1 (92.87% on average). Similarly, in M2-M6 averaged

21.21%–82.75% lower than that in M1 across the entire experimental period (<0.050 ; Fig. 8), with this decrease being more pronounced in stages I-II, where averaged 32.85%–89.83% lower in M2-M6 than in M1 (<0.050). For stage III, was higher in M3 than in M2 and M4-M6 (<0.050).

Dynamics of under six mulch treatments at different evaporation stages (a) and across the entire experimental period (b). In panel (a), the lower and upper quartiles (Q1 and Q3) in the boxplots are demarcated by the respective lower and upper boundaries of the interquartile range box. The whiskers extend to 1.5 times the interquartile range (IQR) of each box, while group-specific means

are indicated by blue circles, and the small black dots are outliers. In panel (b), the mean \pm SE ($n=10$) is provided for each mulch treatment. Different lowercase letters indicate significant differences among treatments ($p < 0.050$).

The relationship between for each treatment was well described by an exponential curve ($R^2 = 0.79$, $p < 0.001$; Fig. 9 [FIGURE:9]), with decreasing exponentially with for M1–M6. Notably, across mulch treatments, an inverse correlation was observed between and the decline rate of . In other words, a lower corresponded to steeper regression slope (characterized by smaller values of in the model), with the steepest decline observed for M6. In addition, under asymptotic conditions where approached infinity, the lowest value of occurred in M1 (0.039 mm/h, approximating model parameter), followed sequentially by M3 and M5 (0.043 and 0.041 mm/h, respectively), M4 (0.048 mm/h), M2 (0.050 mm/h), and M6 (0.063 mm/h).

Relationship between for each mulch treatment (M1–M6). , and are three fitting parameters for each regression equation. , coefficients of determination. Symbols represent all experimental observations ($n=23$ for each treatment).

3.3 Effects of

, SWC, and environmental variables on , SWC, and environmental variables on . In M1, only were strongly correlated with ($R = 0.47$, $p < 0.050$; Fig. 10a [FIGURE : 10]). For M2–M6, was negatively correlated with SWC ($R = -0.38$, $p < 0.001$; Fig. 10d); , RH, and also had significant ($p < 0.010$).

Stepwise regression revealed that , and were closely related to in M1 ($R = 0.72$, $p < 0.001$; Table 2). In the path analysis, both had direct negative effects on ($R = 0.32$, $p < 0.050$; Fig. 10b), with relative contributions of -46.33% and -18.45%, respectively (Fig. 10c).

Although were uncorrelated in M1 ($R = 0.16$, $p > 0.050$; Fig. 10a), the path directly connecting was significant ($R = 0.61$, $p < 0.010$; Fig. 10b), and accounted for 35.22% of the total variance in (Fig. 10c).

For M2–M6, was correlated with , RH, , and SWC ($R = 0.59$, $p < 0.001$; Table 2). Among these factors, RH, , and SWC had significant direct negative effects on ($R = 0.30$, $p < 0.001$; By contrast, was positively associated with $R = 0.46$, $p < 0.001$; Fig. 10e), and this effect was of greater magnitude ($R = 0.16$) than that of any other individual factors; also explained more of the variance in (26.95%) than other variables (Fig. 10e–f). Nevertheless, the residual error or unexplained variance () for was over 50.00% for all treatments (Fig. 10b and e).

Effects of , SWC, and environmental variables on for six mulch treatments (M1–M6). (a and d), Pearson correlations of with impact factors for M1 and M2–M6; (b and e), path diagram showing the effects of key environmental factors , and for M1 and key impact factors (, RH, , and SWC) on for M2–M6; (c and f), relative contributions of key environmental factors (, and) to variance in for M1 and key impact factors (, RH, , and SWC) to variance in for M2–M6. , gravel

concentration; surface soil temperature; , surface net radiation flux. The values beside purple solid and blue dashed arrows indicate standardized direct () and indirect () path coefficients, respectively; values in boxes are decision coefficient (represents the residual error. , significance at <0.001 level; , significance at <0.010 level; , significance at <0.050 level.

Stepwise regression equations for mulch resistance () and its drivers for M1 and M2-M6 Treatment Stepwise regression equation =302.18+120.33 <0.001 M2-M6 =2021.03+8.82 -14.62RH-395.39 -54.49SWC <0.001 Note: , gravel concentration; , surface soil temperature; , air temperature; RH, relative humidity; , wind speed; surface net radiation flux; SWC, soil water content; , coefficients of determination.

4.1 Effects of MGSM on soil evaporation

In this study, MGSM significantly influenced both soil evaporation and water dynamics (Figs. 3-5). Many studies have suggested that mulch texture and composition strongly affect surface soil moisture levels and soil evaporation, with gravel particle size being particularly important due to differences in capillarity (Meier and Hauer, 2010; Ma and Li, 2011). In this study, mulch texture significantly affected surface soil evaporation and its duration, with gravel-soil mixtures having different effects than pure gravel mulch. Compared to M1, MGSM treatments (M2-M6) lengthened evaporation stages I-II by 156-204 h and markedly increased the total evaporation loss (Figs. 3 and 4). The presence of soil particles in the mulch likely strengthened capillary action between the mulch matrix and the subsoil, promoting the upward movement of water vapor (Fig. 11 [FIGURE:11]). As decreases, surface mulch develops a mixed gravel-soil skeletal structure, rather than the gravel floating within the soil matrix itself (Lu et al., 2021); the evaporation front then shifts from deeper soil layers to the surface, weakening the insulating effects of the mulch.

Nevertheless, for M2-M6, decreased rapidly during stage III (Fig. 5a and c), likely due to heightened water losses in stages I-II (compared to M1) and the formation of a dry surface soil interface and gravel-soil layer, as shown in similar studies (Yamanaka et al., 2004; Katra et al., 2008; Jia et al., 2023). Conversely, in M1, more water was conserved in the surface soil and a dry surface soil layer was absent across all evaporation stages (Fig. 11), and increased only in stage III (Fig. 5c).

Mixtures of gravel and sand are more effective at reducing soil evaporation than gravel alone (Ma and Li, 2011; Lu et al., 2021), a difference that is driven by the pore characteristics of the mulch (Pérez, 2000). In this study, at stage III, SWC in M3 nearly equaled that in M2 (Fig. 5a), was lower in M3 than in M2 (Fig. 5c), suggesting that the gravel-soil matrix reduced Effects of the presence of a gravel-soil matrix within the mulch layer on both soil evaporation and evaporation resistance during evaporation stages - (a and c) and stage (b and d). Changes in , and panels b and c are relative to panel a, while those in

panel d are relative to panel c. Grayed-out text indicates no significant change in that parameter at that stage. , surface roughness.

soil evaporation. The incorporation of small amounts of soil particles into the gravel mulch layer, in combination with rapid water loss during stages I-II (Fig. 11), could result in the closure of gravel macropores while inducing the development of a dense and dry gravel-soil layer (Yamanaka et al., 2004; Katra et al., 2008; Jia et al., 2023). This would lead to a sharp decrease in water vapor transport, eventually decreasing soil evaporation during stage III. These findings are similar to those of Song et al. (2010), who found that surface mulch containing 75.00% sand achieved the lowest as it provided the thickest sand-soil interface layer. As discussed above, decreased during the final evaporation stage when the mulch contained 60.00%-80.00% gravel by volume. This suggested that the transition from pristine gravel mulch to fully degraded gravel mulch (containing a high volume of soil) represents a critical functional transition associated with altered soil water dynamics in arid and semi-arid areas and those affected by rocky desertification.

4.2 Effects of MGSM on soil evaporation resistance

The use of MGSM differentially regulated individual evaporation resistance components (Figs. 6-9). Evaporation resistance (, and) can be used to characterize water vapor transport from the soil evaporation front to the atmosphere through the mulch layer (Gardner, 1958). In this study, was relatively stable throughout the experiment, and the calculated values for all treatments were almost constant as a result (Fig. 6). Reducing the volume fraction of gravel in the mulch increased the relative contribution of (Fig. 7a), likely due to the suppression of turbulent vapor transport. This effect correlates with shifts in the mulch surface roughness, consistent with previous studies (Yamanaka et al., 2004; Qiu et al., 2014). Furthermore, primarily influenced by the thickness of the dry soil layer when the soil type is held constant (Ma and Li, 2011; Wang, 2015). During the experimental period, the relative contributions of were much higher in M2-M6 versus M1 (Fig. 7b), especially during stage III (Fig. 8a). This effect may be attributed to continuous water loss from the surface soil and the rapid development of a dry surface soil layer during stages I-II (Fig. 11) (Yamanaka et al., 2004; Li et al., 2015; Kang et al., 2025). It should be noted that the abrupt transition in occurred earlier as decreased (Fig. 6), further illustrating differences in the formation of the dry surface soil layer for M2-M6.

Interestingly, was more strongly affected by MGSM than (Fig. 9). is lower in the presence of pure gravel mulch as compared to bare soil due to the high of the gravel layer (Yamanaka et al., 2004; Kang et al., 2025). Nevertheless, the relative contribution of decreased by 17.80%-64.40% on average (Fig. 7c) in M2-M6 versus M1, particularly at stages I-II (Fig. 8a). By contrast, in M2-M6, the diminishing effect of were mostly overwhelmed during stage III (Fig. 8a), leading to declines in water loss from the surface soil (Figs. 3-5).

Notably, during stage III, the stronger adhesive forces induced by the gravel-soil matrix could likely explain the relatively high observed in M3 (Fig. 8a); as a result, was lower in M3 than in other treatments at this stage (Fig. 5c). Similar

results have also been reported by Yamanaka et al. (2004), Qiu et al. (2014), and Kang et al. (2025). In these studies, applying gravel mulch with a small grain size to the surface soil or mixing gravel into the soil itself effectively increased due to the presence of a dry insulating layer, which ultimately decreased soil evaporation.

Existing studies have predominantly investigated either pure gravel mulch or gravel embedded in the soil (e.g., Yamanaka et al., 2004; Qiu et al., 2014; Kang et al., 2025); as such, this study provides the experimental demonstration of how MGSM alters via the disruption of capillary action. This finding underscores the pivotal role of mixed-mulch-induced resistance in controlling soil evaporation.

4.3 Response of

, SWC, and environmental conditions In the gravel-soil mulch treatments, depended on , SWC, and environmental conditions (Fig. 10; Table 2). Across all treatments, decreased significantly late in evaporation stage III (Fig. 8a), as did (Fig. 5c). This pattern may be attributed to changes in SWC and other soil properties (Or et al., 2013; Li et al., 2015; Sun et al., 2020). Apart from mulch type,

environmental conditions were also important drivers of . The micro-meteorology of M2-M6 was altered to varying extents compared to M1 (Fig. 10d), probably due to changes in soil hydrological processes and near-surface energy exchanges; this variation in micro-meteorological conditions indirectly resulted in treatment differences in (Wang et al., 2019; Zhao et al., 2020; Lu et al., 2021). Solar radiation supplies energy for the movement of water vapor in the soil (Li et al., 2020). Surface mulching may alter soil thermal properties by modifying surface albedo and/or net solar radiation absorption (Bonachela et al., 2020). Here, were the strongest predictors of in M1 (Fig. 10b and c), likely due to the lower heat capacity of gravel and the higher heat energy conversion efficiency (Li, 2003). Nevertheless, gravel-soil mixtures tend to increase surface albedo and decrease net solar radiation absorption compared to pure gravel (Weng et al., 1981); this might explain the observed reduction in the negative effect of M2-M6 (Fig. 10e and f). Furthermore, RH is generally considered to be closely related to the diffusion of soil water vapor (Ritchie, 1973). The gravel-soil matrix in the mixed gravel-soil mulch was a key avenue for water vapor transport (Fig. 11). Here, in M2-M6, RH explained more than 20.00% of the variation in (Fig. 10e and f). Most importantly, as a source of water vapor, SWC was the strongest predictor of in M2-M6, explaining 33.06% of the variation (Fig. 10e and f). Nevertheless, neither RH nor SWC affected in M1, most likely due to reduced water vapor transport in this treatment (Fig. 10a). It should be noted that this analysis did not fully account for all factors affecting , such as gravel-soil matrix effects on the water retention capacity and mulch macro- and micro-pores (Li et al., 2000, 2005). Thus, factors included in this study explained only 59.00% of the variation in for M2-M6 (Table 2). Therefore, more research is needed to better characterize

how mulch properties are shaped by the gravel–soil matrix. Furthermore, the study findings primarily pertain to calcareous sandy loam. Future studies should therefore systematically evaluate how soil texture (particularly the sand content) moderates soil hydrological processes in gravel–soil mulching systems. Such research will be critical for the development of region-specific dryland management strategies.

5 Conclusions

This study investigated the regulatory effects of MGSM on evaporation dynamics in the surface soil belonging to arid ecosystems. A temporal analysis of revealed that decreasing accelerated cumulative water loss by 28.71%–83.31%; this effect was primarily mediated through alterations to that exacerbated surface soil desiccation. A robust exponential relationship was found between <0.001), with depending on ρ , RH, θ , and SWC. As the decreased, also decreased and increased, suggesting that the degradation of pure gravel mulch over time negatively impacts the surface soil water balance. Nevertheless, the use of 60.00% gravel mulch may partially counterbalance these negative effects. This study advances the current understanding of mixed mulch hydrology, providing critical insights for the design of sustainable soil moisture conservation strategies in water-limited agroecosystems.

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table S1 Applicability evaluation of different surface soil resistance () formulas under the mixed gravel-soil mulching (MGSM) treatments Formula Evaluation index

$$\begin{aligned} & \times - = \times \\ & 3.8113 \ 10 \ e \\ & - = \times \\ & 2.3 \ 3.5 \ 33.5 \ >0.45 \\ & = + \quad = - + - \leq \end{aligned}$$

4140(Note: is the saturated volumetric water content of surface soil (cm is the volumetric water content of surface soil is the aerodynamic resistance (s/m); is the surface soil temperature (°C); is the slope of linear fitting line. coefficients of determination; NSE, Nash-Sutcliffe Efficiency; MRE, mean relative error; MAE, mean absolute error; RMSE, root mean square error. The comparison of measured and predicted values was based on soil evaporation rate (Table S2 Fitting equations for surface SWC and as well as under different mulch treatments Treatment <0.001 <0.001 <0.001 <0.001 <0.001 <0.001 <0.001 <0.001 <0.001 <0.001 <0.001 Note: M1-M6 are six mulch treatments containing a different proportion of gravel by volume: 100.00% (M1), 80.00% (M2), 60.00% (M3), 40.00% (M4), 20.00% (M5), and 0.00% (M6). SWC, soil water content; , evaporation time; , cumulative soil evaporation. , and are the parameters of the regression equation, respectively. The sample size for each treatment is 23.

Fig. S1 Relationships between surface soil water content (SWC) and cumulative soil evaporation () for six mulch treatments containing a different proportion of gravel by volume: 100.00% (M1), 80.00% (M2), 60.00% (M3), 40.00% (M4), 20.00% (M5), and 0.00% (M6). Points represent all experimental observations (=23 for each treatment).

Figures

Source: ChinaXiv –Machine translation. Verify with original.

Figure 17

Figure 1: Figure 17

Figure 19

Figure 2: Figure 19