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Effects of Microbial Organic Fertilizer (MOF) Application on Desert Soil Enzyme Activity and Jujube Yield and Quality

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Abstract: Developing effective regulatory strategies to enhance irrigation water and fertilizer efficiency in the southern Xinjiang region of China, while simultaneously combatting desertification, is of paramount significance. This study focuses on Chinese jujube in Xinjiang and presents findings from a two-year field experiment aimed at investigating the optimal application strategy of microbial organic fertilizer (MOF). The research aims to provide a scientific foundation for achieving high-quality jujube production. The experiment involved a control group (utilizing only freshwater, referred to as CK) and various combinations of MOF treatments. In 2021, these treatments included M1 (0.6 t/ha), M2 (1.2 t/ha), M3 (1.8 t/ha), and M4 (2.4 t/ha), while in 2022, they encompassed M1 (0.6 t/ha), M2 (1.2 t/ha), M4 (2.4 t/ha), and M5 (4.8 t/ha). Over the two-year trial period, we assessed various indices, including the soil's physical properties, hydraulic characteristics, soil enzyme activities, and relative chlorophyll content. Additionally, we evaluated jujube yield, quality, and economic benefits. The results indicate that MOF application led to significant improvements in soil conditions. Specifically, the average moisture content and profile water storage of the 0–50 cm soil layer increased by 10.98% to 36.42% and 1.8% to 26.8%, respectively. Moreover, in both the 2021 and 2022 experiments, soil saturated water content (SSWC) and water-holding capacity (WHC) increased by 6.25% to 15.98%, while soil hydraulic conductivity (Ks) and bulk density (BD) decreased by 2.91% to 9.88% and 0.63% to 8.08%, respectively. In 2021, MOF application resulted in significant enhancements in soil enzyme activities, with urease activity increasing by approximately 22.5% to 100.5%, peroxidase activity rising by around 24.2% to 148.5%, and invertase activity augmenting by about 5.4% to 32.9%. Notably, the M4 treatment in 2021 demonstrated a substantial jujube yield increase of approximately 19.22%, elevating from 7.65 t/ha to 9.12 t/ha. Based on comprehensive analysis, this study recommends an optimal MOF application rate of approximately 2.4 t/ha. This approach not only provides robust support for the sustainable development of the jujube industry but also serves as a valuable reference for enhancing local soil resilience against desertification.

Keywords: jujube; microbial organic fertilizer; enzyme activities; growth and yield; economic benefit

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1. Introduction

Jujube, one of China's distinctive traditional fruits, is renowned for its abundant nutritional value [1]. China stands as the world's largest producer of jujube, with a production volume of 7.46 million tons in 2019, representing a substantial 76% of the global output [2]. Xinjiang, in particular, serves as the primary hub for high-quality jujube production in China, contributing over half of the nation's total yield [3]. Leveraging the region's abundant sunlight and significant day–night temperature fluctuations, Xinjiang has emerged as an ideal habitat for the jujube tree [4]. According to incomplete data, the jujube tree planting area in Xinjiang has expanded to an impressive 3.2×10^5 hectares, with approximately 80% concentrated in the vicinity of the Taklimakan Desert in southern Xinjiang [5].

The jujube cultivation industry in Xinjiang generates approximately 20 billion Chinese Yuan (CNY) in revenue for local farmers each year and provides employment opportunities for around one million individuals [3]. Simultaneously, the extensive cultivation of jujube trees has proven effective in curbing desertification and improving the local ecological environment [6]. However, this region is susceptible to extreme aridity due to its continental desert climate, which leads to land aridification and desertification issues [7]. The annual average rainfall in this area is a mere 35 mm, while evaporation exceeds 2480 mm (http://data.cma.cn/, accessed on 20 May 2021). Factors such as minimal precipitation, scorching temperatures, intense evaporation, infertile land, and the scarcity of water resources pose significant challenges to sustainable agricultural development in this region [8].

The widespread cultivation of jujube trees has had a noteworthy impact on curtailing desert expansion and fostering positive ecological changes [9]. To maximize economic returns, farmers often resort to increased irrigation and fertilization to ensure optimal jujube yields [3,8]. However, a significant portion of the arable land in southern Xinjiang comprises desert soil, which is characterized by exceptionally low organic matter content and inadequate water and nutrient retention capabilities [10]. Consequently, inefficient utilization of irrigation water and fertilizers hampers overall net returns [10]. Therefore, it becomes imperative to implement effective measures that enhance water and nutrient utilization efficiency while concurrently bolstering the moisture and nutrient retention capacity of desert soils. This is especially crucial given the region's limited water and soil resources [11].

Driven by this pressing need, our study aims to make a modest contribution to addressing this challenge. In recent years, microbial organic fertilizer (MOF) has emerged as a promising approach to enhance plant growth. MOFs, specifically those containing Bacillus strains with spore-forming and metabolite-producing capabilities, have demonstrated significant potential [12–14]. Numerous studies have shown that the application of MOF can optimize nutrient absorption and utilization, leading to substantial improvements in crop growth and development while reducing dependence on chemical fertilizers [13,14]. MOF not only stimulates crop root growth and volume but also confers notable agronomic advantages. For instance, cotton crop yields and growth increased by as much as 30% following MOF application [12]. Moreover, MOF has been shown to delay the coloration of blood orange peel and flesh, increase leaf nitrogen and potassium concentrations, and reduce titratable acidity (TA) [15]. These findings underscore the significance of beneficial soil microbes in suppressing pathogen growth effectively while facilitating plant nutrient uptake and utilization [16]. Beneficial microorganisms such as *Bacillus* and *Trichoderma* have found widespread use as biocontrol agents, effectively managing pathogens [17]. Particularly, *Bacillus* preparations have been shown to promote the growth of beneficial microbes in soil, creating favorable microenvironments for plants [18]. This discovery further emphasizes the pivotal role of beneficial microorganisms in soil ecosystems, providing robust support for healthy crop growth and production. Furthermore, MOF's substantial organic content elevates soil carbon reserves, improves soil microenvironments, and enhances root development. MOF actively increases the population of beneficial microbes in the soil, promoting nutrient transformations and effectively ameliorating soil physicochemical properties [19].

Additionally, MOF enhances the organic matter content in the soil, promoting the formation of water-stable aggregates in the soil [7,20,21]. The substantial presence of mycelium and organic binding substances within MOF enhances the adhesion of soil particles, thereby increasing the curvature of soil pores and the number of capillary pores [7]. Consequently, this improves the soil water retention and nutrient-holding capacity, reducing surface runoff and deep percolation losses, and consequently enhancing the effectiveness of irrigation water [22–24]. Meanwhile, as a sustainable agricultural practice, MOF has demonstrated exceptional effects on various crops such as wheat, rice, and cucumber, not only laying a solid foundation for further development and use of organic fertilizers but also infusing new vitality into agricultural sustainability [25,26].

Soil, as a reservoir and supplier of essential water and nutrients required for plant growth, plays a pivotal role in fostering healthy plant development due to its excellent hydraulic and physical characteristics [7,20,25,26]. Especially in desert soils, the presence of an abundance of sand particles and a scarcity of clay particles results in soil porosity predominantly consisting of numerous interconnected macro-pores, rendering desert soils with extremely poor water-holding capacity [7]. Consequently, soil improvement strategies for desert soils primarily focus on reducing bulk density (BD), enhancing soil pore volume (SPV), increasing soil saturation water content (SSWC), and improving soil-saturated hydraulic conductivity (Ks) [20]. Previous research has indicated that reducing BD and increasing SPV significantly enhance gas exchange capacity within the soil and augment the number of micro-pores, leading to improved effectiveness of water and nutrient retention in the soil [7]. Similarly, reducing Ks in desert soils is crucial for curtailing the vertical movement of irrigation water [25]. Therefore, reducing Ks prolongs the residence time of moisture in the upper soil layers, consequently increasing the water and nutrient content in the plant root zone [26]. This is vital for conserving water and fertilizer usage while enhancing their effectiveness [27]. Furthermore, another critical factor influencing soil quality and functionality is enzyme activity, which can rapidly adapt to changes in the soil environment and impact numerous vital ecological processes, including organic matter decomposition, nutrient cycling, and plant growth [27,28]. Consequently, in many previous studies, soil enzyme activity has been utilized as a significant indicator for assessing soil quality, fertility, crop yield, and the efficacy of land management practices aimed at soil improvement [29,30]. In general, soil enzyme activity is employed to evaluate the impact of land conversion and agricultural practices on the soil environment, and it also contributes to obtaining critical ecological information pertaining to soil [31–33].

Nonetheless, it is imperative to recognize that comprehensive studies examining the effects of MOF application on soil water distribution, hydraulic properties, water–fertilizer productivity, jujube yield, and quality are still relatively scarce [7]. This research gap is particularly conspicuous in the context of southern Xinjiang, where the advancement of the jujube industry hinges on the comprehensive enhancement of the physical and hydraulic properties of desert soil to create an optimal root environment for jujube trees. Reviewing the existing literature, it becomes evident that MOF application indeed influences the soil's physical and chemical properties, exerting a positive impact on crop growth and development. Given this backdrop, it is reasonable to hypothesize that MOF application could yield favorable outcomes on multiple fronts. Firstly, it may augment the efficiency of irrigation water, facilitating a more effective water supply to plants. Secondly, MOF could enhance the water and nutrient retention capacity of desert soil, thereby establishing a more conducive growth environment for jujube trees. Ultimately, these beneficial effects might extend to improvements in jujube yield and quality, consequently enhancing the income of local farmers in the region. However, empirical research is imperative to validate this hypothesis. Such validation would not only offer scientific support for the sustainable progression of the jujube industry in southern Xinjiang but also provide valuable insights into desert soil improvement and innovative agricultural practices. Therefore, conducting comprehensive experiments and investigations is crucial to gaining a thorough understanding of the actual effects of MOF application in agricultural production in the region, ultimately providing practical guidance for future agricultural development.

Based on these considerations, this study aims to achieve three primary objectives: (1) evaluate the impact of MOF on soil water distribution, water retention capacity, and soil enzyme activity; (2) assess the contribution of MOF to jujube yield, quality, water-fertilizer productivity, and economic benefits; and (3) comprehensively evaluate the efficacy of MOF application in soil enhancement and jujube tree growth. By accomplishing these research objectives, we aim to obtain a comprehensive understanding of the influence of MOF on both soil and crops, thereby establishing a scientific foundation for the sustainable development of jujube cultivation in southern Xinjiang. This endeavor will not only contribute to soil optimization through MOF application, leading to improved jujube yield and quality but also provide valuable insights into innovation and sustainable agricultural practices. Through a comprehensive exploration of MOF's potential in soil–water management, we aspire to address the challenges posed by aridity and desertification in southern Xinjiang, ultimately promoting greater economic benefits for local farmers and fostering a mutually beneficial scenario for both the ecological environment and agricultural development.

2. Materials and Methods

2.1. Experimental Site

A two-year jujube cultivation experiment was conducted in the jujube planting area situated at the 8th company of the 224th regiment in Kunyu City, southern Xinjiang, China (37°21′45″ N, 79°19′60″ E). This region is characterized by a typical continental desert climate with the following climatic features: an average annual temperature of 12.2 °C, abundant sunlight duration of 2705.6 h, minimal annual precipitation of just 35 mm, and a relatively high evaporation rate of 3008.9 mm. The frost-free period spans 225 days, accumulating a temperature exceeding 10 °C and totaling 4208.1 °C [7].

Average temperatures for the jujube growing seasons in 2021 and 2022, recorded using a portable weather station, were 20.1 °C and 22.4 °C, respectively (Figure 1). Precipitation levels for these years were 24.5 mm and 28.9 mm, respectively. Additionally, it is essential to note that the groundwater depth in this area exceeds 3.0 m.

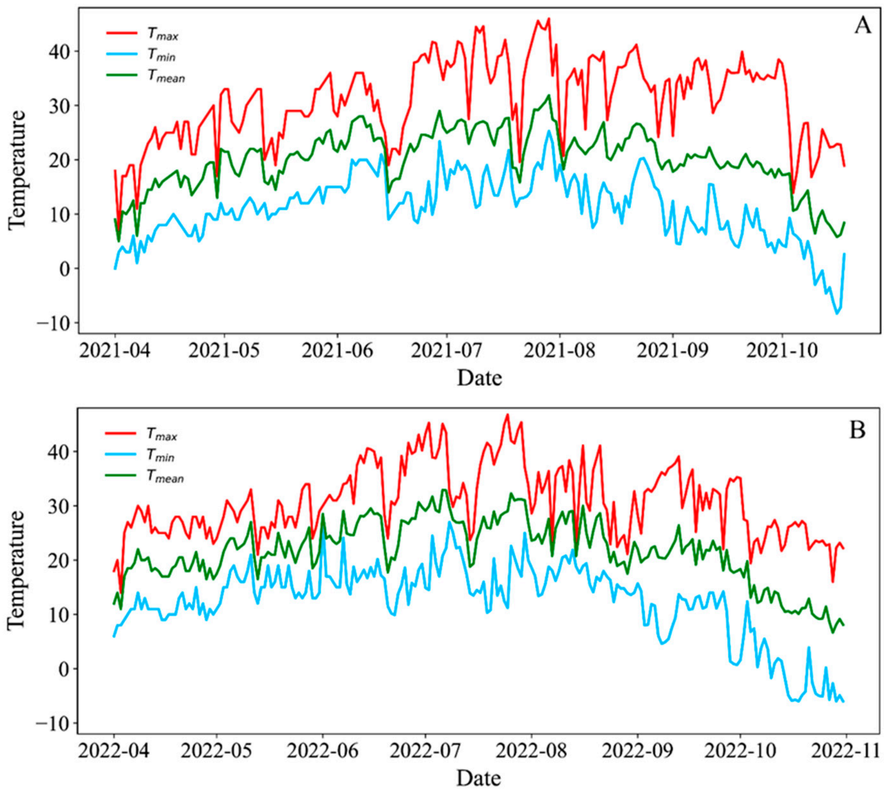

Figure 1. Temperature changes during the growing season of the jujube tree in 2021 (**A**) and 2022 (**B**).

Surface (0–80 cm) soil samples were collected prior to the commencement of the jujube experiment in 2021, and their specific physical and chemical characteristics are detailed in Table 1.

Table 1. Basic parameters of soil physicochemistry.

Soil Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Soil Bulk Density (g cm^{-3})	pH	Available Potassium Content (mg kg^{-1})	Available Phosphorus Content (mg kg^{-1})
0–20	86.77	13.20	0.03	Sandy soil	1.62	8.3	25.31	12.31
20–40	86.68	13.14	0.18	Sandy soil	1.61	8.2	22.14	8.29
40–60	85.49	12.33	2.18	Sandy soil	1.59	8.3	20.11	6.52
60–80	85.29	12.47	2.24	Sandy soil	1.60	8.4	15.18	4.87

2.2. Experimental Design

2.2.1. Jujube Tree Agronomic Practices

Jujube trees of approximately 12 years old were used in the study. A dwarf high-density planting pattern was adopted, with an average tree height of 2.2 m, a spacing of 1.0 m between trees, and a row spacing of 4.0 m. A drip irrigation system with one line of two pipes was employed (Figure 2). Each experimental plot covered an area of 4.0 m in width and 20.0 m in length, accommodating 20 jujube trees. A buffer zone measuring 4.0 m in width and 20.0 m in length was established between every two experimental plots to prevent mutual interference between treatments.

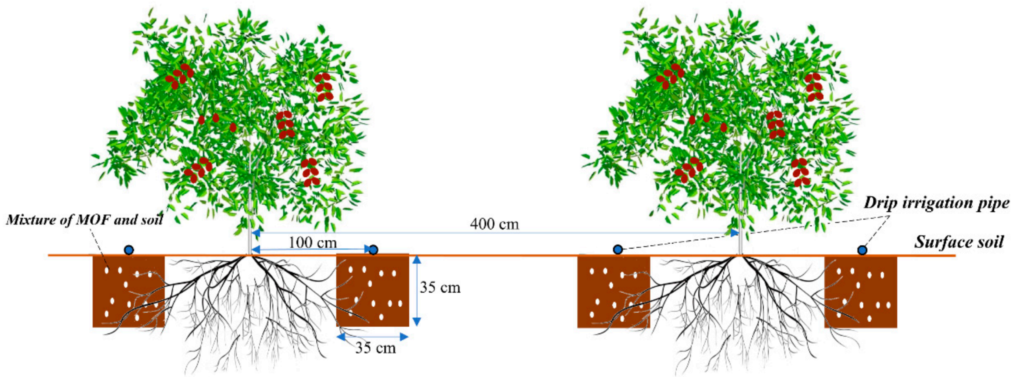

Figure 2. Jujube planting, irrigation mode and MOF application.

Irrigation and fertilization regimes for the years 2021 and 2022 are outlined in Table 2. Irrigation water was sourced from the Kunlun Mountains' ice and snow meltwater, with an electrical conductivity of 3.0×10^{-2} dS m^{-1}, qualifying as freshwater. The fertilizers used in this study consisted of N (urea, N 46%), P (phosphoric acid, P_2O_5 12%), and K (potassium sulfate, K_2O 50%). Fertilizers (N, P, K) were applied concurrently with irrigation, following a drip irrigation approach. A total of 10 irrigation intervals were conducted throughout the jujube growth period.

Table 2. Irrigation and fertilization program in 2021 and 2022.

Year	Irrigation Date	Irrigation Amount (mm)	Urea (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)
2021	20 April	32.0	37.95	18.90	6.48
	5 May	32.0	37.95	18.90	6.48
	20 May	32.0	37.95	18.90	6.48
	3 June	32.0	37.95	18.90	6.48
	17 June	32.0	37.95	18.90	6.48
	2 July	32.0	43.20	14.40	38.40
	15 July	32.0	43.20	14.40	38.40
	1 August	32.0	43.20	14.40	38.40
	16 August	32.0	43.20	14.40	38.40
	2 September	32.0	43.20	14.40	38.40

Table 2. *Cont.*

Year	Irrigation Date	Irrigation Amount (mm)	Urea (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)
2022	28 April	32.0	37.95	18.90	6.48
	13 May	32.0	37.95	18.90	6.48
	28 May	32.0	37.95	18.90	6.48
	10 June	32.0	37.95	18.90	6.48
	25 June	32.0	37.95	18.90	6.48
	8 July	32.0	43.20	14.40	38.40
	21 July	32.0	43.20	14.40	38.40
	2 August	32.0	43.20	14.40	38.40
	18 August	32.0	43.20	14.40	38.40
	3 September	32.0	43.20	14.40	38.40

2.2.2. Microbial Organic Fertilizer (MOF) Treatment

The MOF used in this study was supplied by Hubei Yangfeng Group and is an organic microbial pellet fertilizer derived from organic solid waste, including organic waste, straw, livestock and poultry manure, cake meal, agricultural by-products, and solid waste from food processing. It undergoes microbial fermentation, deodorization, and complete maturation. The beneficial microbial population primarily consists of *Bacillus subtilis* ($\geq$2.5 $\times$ 10^8 CFU/g), *Bacillus licheniformis* ($\geq$1 $\times$ 10^8 CFU/g), *Bacillus amyloliquefaciens* ($\geq$1 $\times$ 10^8 CFU/g), *Actinomycetes* (*Strephomyces*), and *yeast* (*Saccharomyces cerevisiae*), with a total effective viable count of approximately 5 $\times$ 10^8 CFU/g. MOF's properties were determined according to standard methods. MOF exhibited an organic matter content of 530 g/kg, a pH of 8.5, and a total N content of 18.31 g/kg, as well as percentages of Ca (7.12%), Si (6.69%), K (6.27%), Cl (3.58%), Fe (2.42%), P (1.37%), S (1.31%), and Mg (1.08%).

Considering the root distribution characteristics of jujube trees in the region and the local farmers' basal fertilizer application practices, MOF was incorporated into the soil through trench application to avoid disturbing root growth. In April of both 2021 and 2022, MOF was applied in trenches measuring 35.0 cm in width and 35.0 cm in depth directly beneath the drip irrigation line, 1.0 m away from the jujube trees on both sides. The MOF–soil mixture was backfilled to a depth of 5.0 cm to 35.0 cm, followed by a 5.0 cm soil cover on the top.

The application rate of MOF was determined based on local farmers' fertilization practices, cost-effectiveness, and a comprehensive review of existing research. Blank control groups (CK), where no MOF was added, were established for both 2021 and 2022. In 2021, a total of four MOF application treatments were set up, including M1 (0.6 t/ha), M2 (1.2 t/ha), M3 (1.8 t/ha), and M4 (2.4 t/ha). In 2022, the treatments included M1 (0.6 t/ha), M2 (1.2 t/ha), M4 (2.4 t/ha), and M5 (4.8 t/ha).

2.3. Parameter Determination and Quantitative Assessment

2.3.1. Soil Water Content and Water Storage

Soil samples were collected at various depths (5, 15, 30, 50, and 80 cm) within the jujube planting area, encompassing jujube tree planting zones, drip irrigation areas, and inter-rows. Soil sampling was conducted using a handheld soil auger. Subsequently, the collected soil samples were dried in a preheated oven at 105 °C for 8 h, and the soil water content (SWC) was determined using a weighing method [11]. The soil water storage (SWS) in the jujube root growth layer (0–50 cm) was calculated using the following formula:

$$SWS = 500 \times \overline{\theta}_{0\text{–}50\ \mathrm{cm}} \quad (1)$$

where $\overline{\theta}_{0\text{–}50\ \mathrm{cm}}$ is the mean soil water content in the soil layer of 0–50 cm.

2.3.2. The Soil's Physical and Hydraulic Indicators

During the jujube harvest seasons of 2021 and 2022, soil samples were collected from a depth of 10 cm to 30 cm in the MOF application areas to determine soil bulk density

(BD) [11]. A cutting ring containing undisturbed soil was immersed in deionized water for 48 h to determine the saturated soil water content (SSWC) [7]. The cutting ring, covered with filter paper to prevent evaporation, was left in a cool place for 24 h to measure soil water-holding capacity (WHC) [11]. A new cutting ring was placed on top of the soil in the first cutting ring, and the two cutting rings were connected using waterproof tape. Deionized water was poured into the new cutting ring, and the outflow was collected in a measuring cylinder placed below the first ring to calculate the saturated hydraulic conductivity (Ks) within a fixed time [7]. Each soil sample was measured three times, and the average value was used.

Soil porosity (SPV) was calculated using the following formula [7]:

$$SPV = 1 - \frac{BD}{PD} \tag{2}$$

where PD is soil particle density (=2.65 g cm^{-3}).

2.3.3. Soil Enzyme Activity

Catalase activity (CE) in the soils was determined using the $KMnO_4$ titrimetric method [34,35]. In a 100 mL conical flask, 5 g of soil was placed, and 40 mL of distilled water along with 5 mL of a 0.3% H_2O_2 solution were added. The mixture was vigorously shaken for a duration of 20 min. Subsequently, 5 mL of 3 mol L^{-1} H_2SO_4 was introduced, and the resulting mixture was subjected to filtration. A 25 mL portion of the filtrate was ultimately titrated with 0.1 mol L^{-1} $KMnO_4$.

For the determination of urease activity (UE), a colorimetric method based on ammonium detection was employed [34,35]. Initially, 3 g of soil sample was treated with 1 mL of toluene for 15 min and mixed with 5 mL of an urea solution (10%) and 10 mL of a citrate buffer solution (pH 6.7). This mixture was then incubated at 37 °C for 24 h. Following incubation, the mixture was promptly filtered. The absorbance of the filtrate was measured at 578 nm using a spectrophotometer. A control without the substrate was measured for each sample. Urease activity was quantified as the amount of NH_3-N produced per 1.0 g of air-dried soil.

To determine sucrose activity (SE), the following steps were carried out: 2.0 g of the soil sample was treated with 1 mL of toluene and then mixed with 15 mL of an 8% sucrose solution and 5 mL of a phosphoric acid buffer preparation (pH 5.5). This mixture was incubated for 24 h at 37 °C and subsequently filtered. A total of 1 mL of filtrate was transferred to a 50 mL volumetric flask and mixed with 3 mL of a solution of 3,5-Dinitrosalicylic acid. The mixture was heated in a water bath for 5 min and then cooled for 10 min. The absorbance of the filtrate was measured at 508 nm using a spectrophotometer. A control without the substrate was measured for each sample [21].

2.3.4. Jujube Chlorophyll Content, Yield, and Quality

A handheld chlorophyll meter (Japan) was used to measure the relative chlorophyll content (RCC) [11]. During the harvest periods of 2021 and 2022, all the jujubes from the ten trees in each plot were collected and weighed to calculate the jujube yield. Four jujube samples were collected from each plot's southeast, northwest, northeast, and southwest corners. The determination of flavone (FL) content used the aluminum nitrate–sodium nitrite colorimetric method, the determination of titrable acid (TA) employed the acid-base neutralization transfer method, and the determination of soluble sugar (SS) utilized the phenol method [1,36].

2.4. Productivity and Economic Assessment

2.4.1. Productivity of Irrigation Water and Fertilizer (N, P, K)

The productivity of irrigation water (*IWP*) represents the ratio of jujube yield (t/ha) to total irrigation water (m^3/ha), with all treatments receiving 320 m^3/ha of irrigation water.

Similarly, the fertilizer (N, P, K) productivity (*FP*) is defined as the ratio of jujube yield to the total amount of each fertilizer input (kg/ha) [11,22]:

$$IWP = \frac{Jujube\ yield}{Irrgation\ water} \quad (3)$$

$$FP = \frac{Jujube\ yield}{Fertilization} \quad (4)$$

2.4.2. Net Income

The total investment during the jujube growth period included drip irrigation consumables (1000 CNY/ha), fertilizers (N, P, K) and pesticides (1600 CNY/ha), labor costs (15,000 CNY/ha), water costs (300 CNY), and the MOF unit price (2.0 CNY/kg). Jujube income was calculated based on an average market price of 8.0 CNY/kg. Net income was calculated using the following formula [11]:

$$Net\ income = Income - Outcome \quad (5)$$

2.5. Comprehensive Evaluation Methods

2.5.1. Cluster Analysis

The agglomerative hierarchical clustering (AHC) algorithm was employed to cluster the soil's physical and hydraulic properties, soil enzyme activity, jujube yield and quality, and other indicators, revealing the contributions of different treatments [7].

2.5.2. TOPSIS Method

A TOPSIS method, combining the entropy weight method with TOPSIS, was utilized to eliminate subjective weighting and human errors in test indicators. Initially, the entropy weight method was used to determine the weights of various aspects such as the soil's hydraulic and physical properties, enzyme activity, physiological growth, yield, quality, and economic benefits in the jujube root zone. Subsequently, the improved TOPSIS method was employed to rank the indicators related to the soil's hydraulic and physical properties, enzyme activity, physiological growth, yield, quality, and economic benefits regulated by MOF. This approach avoids the influence of subjective weighting and human errors, ensuring the objective reliability of research results. In terms of weight determination, we referred to the concept of the entropy weight method and considered the information entropy of each indicator to allocate weights. With the help of the TOPSIS method, the comprehensive performance of different indicators was effectively evaluated and ranked, revealing the regulatory effects of MOF on the soil's hydraulic and physical properties, enzyme activity, physiological growth, yield, quality, and economic benefits in the jujube root zone [37].

2.6. Statistical Analysis

The variance analysis was performed using SPSS software, version 25.0 (SPSS Institute, Inc., Cary, NC, USA). Fisher's LSD (least significant difference) was used to detect differences between treatments, and the significant differences were determined by LSD at $p < 0.05$. All data represent an average of three replicates. Data processing was performed using EXCEL 2019, and data visualization and model calculations were carried out using Python 3.8.

3. Results

3.1. Soil Water Distribution and Water Storage

To quantitatively evaluate the influence of MOF (Microbial Organic Fertilizer) on the distribution of soil moisture profiles, we collected samples from three distinct locations: beneath jujube trees during the fruit expansion phase, beneath the drip line, and in the inter-row spaces. These samples were utilized to determine water content. The resultant soil moisture distribution patterns under various treatments are visually represented in Figure 3.

Overall, our analysis revealed that different treatments had a significant impact on soil moisture content within the horizontal range of 25–175 cm from the jujube tree and within the vertical span of 0–45 cm ($p < 0.05$). Notably, in the year 2021, as the application rate of MOF increased from 0.6 t/ha (M1) to 2.4 t/ha (M4), the lower boundary of the 0.20 cm^3/cm^3 water content curve within the jujube root growth zone (0–50 cm) shifted from 30 cm (M1) to 40 cm (M4), surpassing the control group (CK), which exhibited a lower boundary at 20 cm (Figure 3A–E). This underscores the significant influence of MOF application in augmenting soil moisture content in the jujube tree's root growth zone, particularly when MOF application rates reached 2.4 t/ha.

In the subsequent year, 2022, we observed a similar trend. With increasing MOF application rates from 0.6 t/ha (M1) to 4.8 t/ha (M5), the lower boundary of the 0.20 cm^3/cm^3 water content curve in the jujube root growth zone (0–50 cm) shifted from 32 cm (M1) to 43 cm (M4), before subsequently declining to 38 cm (M5). Once again, this shift in the lower boundary significantly exceeded the control group (CK), which maintained a boundary of 22 cm (Figure 3G–K). It is noteworthy that while MOF application had a clear positive impact on soil moisture content in the jujube root growth zone, this effect did not consistently intensify with higher MOF application rates. Indeed, when MOF application exceeded 2.4 t/ha, we observed a decrease in soil moisture content.

For a comprehensive view of the average soil moisture content of the soil at depths of 0–50 cm directly below the drip line, please refer to Figure 3F,L. In 2021, the mean soil water content (SWC) under MOF application was 0.192 (M1), 0.216 (M2), 0.229 (M3), and 0.236 cm^3/cm^3 (M4). These values represented respective increases of 10.98%, 24.86%, 32.37%, and 36.42% compared to the control group's SWC of 0.173 cm^3/cm^3. In 2022, the mean SWC under MOF application was 0.201 (M1), 0.215 (M2), 0.239 (M4), and 0.215 cm^3/cm^3 (M5), marking increases of 12.92%, 20.79%, 34.27%, and 20.79% compared to the control group's SWC of 0.178 cm^3/cm^3. These findings provide further evidence of MOF's positive influence on average soil moisture in desert soil, enhancing its hydraulic characteristics and augmenting water content within the jujube root growth zone, particularly when MOF application was maintained at a rate of 2.4 t/ha.

To comprehensively evaluate the impact of MOF on soil water distribution in the root zone of jujube trees, Soil Water Storage (SWS) data for four key growth stages of jujube trees were compiled in Table 3. Overall, there were significant differences in SWS among treatments as the jujube trees progressed through different growth stages ($p < 0.05$), showing a trend of decreasing SWS followed by an increase, with the lowest SWS occurring during the fruit enlargement stage. Simultaneously, the application of MOF significantly increased SWS compared to CK at different growth stages ($p < 0.05$). Taking the fruit enlargement stage as an example, in 2021, the application of MOF increased SWS compared to CK by 1.8% to 26.8%, reaching 65.2 mm in M4. In 2022, the application of MOF increased SWS compared to CK by 3.4% to 21.5%, reaching 68.4 mm in M4. However, the SWS in M5 was only 63.2 mm, representing a 7.6% reduction compared to M4. In both 2021 and 2022, the mean SWS in M4 treatment increased by 21.3% and 19.4%, respectively, compared to CK ($p < 0.05$). This indicates that the application of 2.4 t/ha of MOF can effectively enhance the water and nutrient retention capacity of desert soils, reducing deep water infiltration and mitigating water loss due to evaporation.

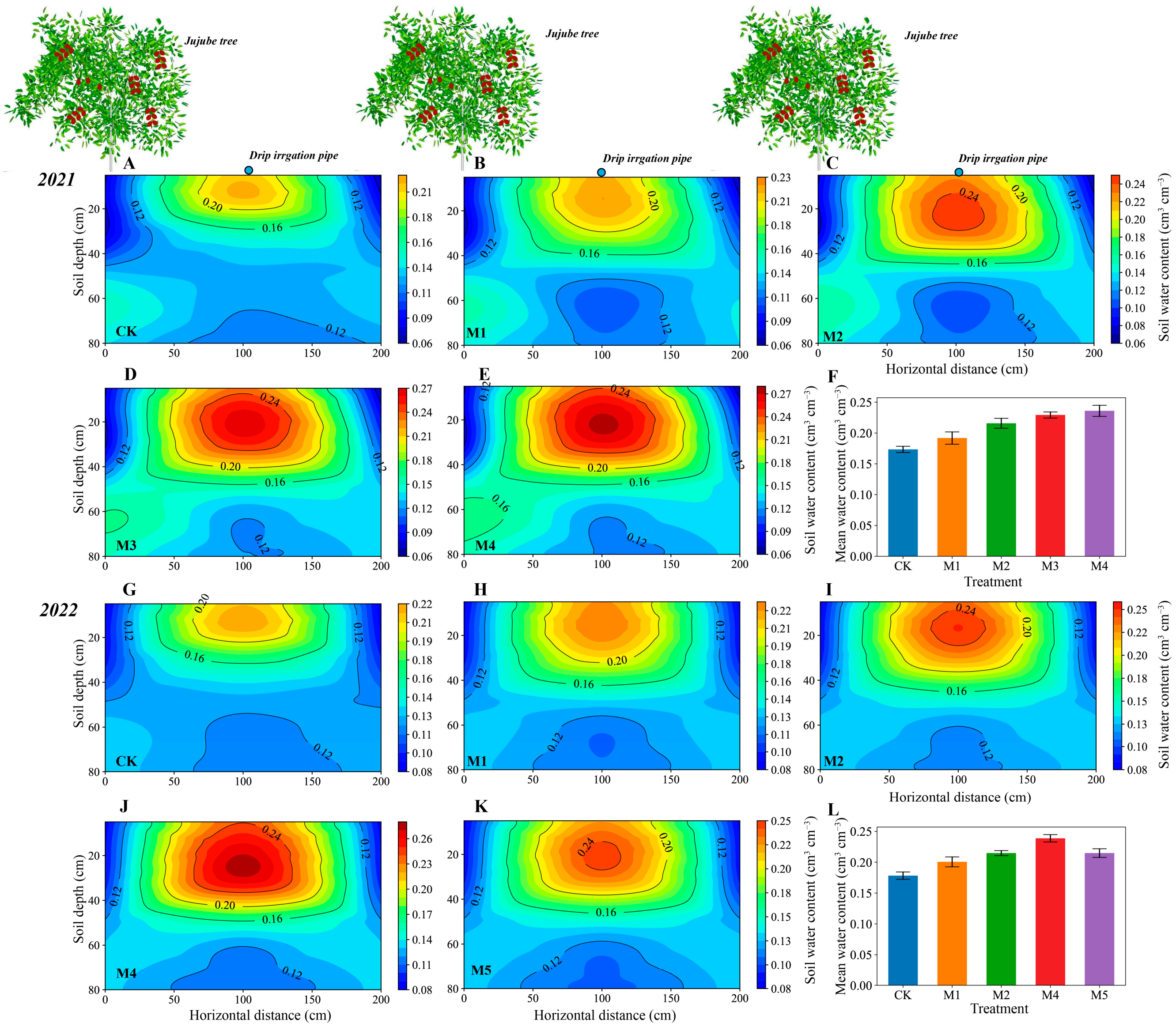

Figure 3. Soil water distribution in the profile of jujube trees during the fruit expansion stage.

Table 3. Soil water storage (SWS) during the germination and leaf spreading stage, flowering and young fruit stage, fruit expansion stage, and maturity stage in 2021 and 2022.

Year	Treatment	SWS (mm)				Mean SWS (mm)
		Germination and Leaf Spreading Stage	Flowering and Young Fruit Stage	Fruit Expansion Stage	Maturity Stage	
2021	CK	63.20 ± 0.25 d	60.10 ± 1.21 de	51.40 ± 0.32 d	61.20 ± 0.54 c	58.98
	M1	64.30 ± 0.31 cd	62.30 ± 0.87 d	52.30 ± 0.19 d	63.80 ± 0.380 c	60.68
	M2	67.20 ± 0.28 c	65.80 ± 0.96 c	56.30 ± 0.38 c	67.30 ± 0.63 b	64.1
	M3	71.20 ± 0.64 b	67.20 ± 1.18 b	60.50 ± 1.11 b	72.30 ± 1.32 ab	67.80
	M4	75.60 ± 0.38 a	71.20 ± 0.49 a	65.20 ± 0.78 a	74.10 ± 0.97 a	71.53

Table 3. *Cont.*

Year	Treatment	SWS (mm)				Mean SWS (mm)
		Germination and Leaf Spreading Stage	Flowering and Young Fruit Stage	Fruit Expansion Stage	Maturity Stage	
2022	CK	65.30 ± 0.49 cd	61.20 ± 0.84 d	56.30 ± 0.59 cd	59.30 ± 0.68 d	60.53
	M1	67.20 ± 0.27 c	63.50 ± 1.31 cd	58.20 ± 0.48 c	63.40 ± 0.49 c	63.08
	M2	69.80 ± 0.53 b	65.20 ± 0.79 c	62.30 ± 0.32 b	65.70 ± 0.37 b	65.75
	M4	77.27 ± 0.29 a	71.60 ± 0.43 a	68.40 ± 0.68 a	71.20 ± 0.82 a	72.12
	M5	70.31 ± 0.18 b	67.60 ± 0.87 b	63.20 ± 0.46 b	64.90 ± 0.66 bc	66.50

Note: values with different lowercase letters in the same column were significantly different at the 0.05 level. Each data point is the mean ± SD.

3.2. Soil Hydraulic and Physical Characteristics

Figure 4 illustrates the efficacy of MOF on SSWC, WHC, Ks, BD, and SPV within the soil. Overall, MOF significantly increased SSWC, WHC, and SPV, while decreasing Ks and BD ($p < 0.05$). In 2021, compared to CK, SSWC and WHC under M1, M2, M3, and M4 increased by 6.25~13.31%, and SPV increased by 2.75~11.93%. Moreover, Ks and BD decreased by 2.91~9.88% and 1.86~8.08%, respectively. In 2022, SSWC and WHC under M1, M2, M4, and M5 increased by 7.16~15.98%, and SPV increased by 0.91~10.01%, while Ks and BD decreased by 3.59~8.38% and 0.63~6.88%, respectively.

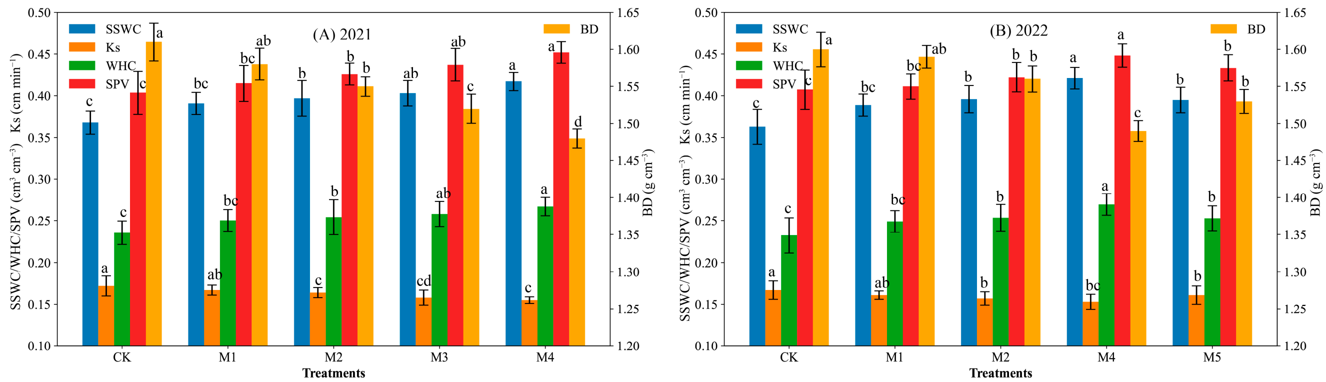

Figure 4. Soil saturated water content, water holding capacity, saturated hydraulic conductivity, soil bulk density, and soil porosity volume in (**A**) 2021 and (**B**) 2022. Among the different treatments, the same lowercase letters did not differ from each other, $p \geq 0.05$. The bars stand for mean ± SD.

However, it is essential to note a crucial finding that the transition from MOF application rates of M4 to M5 did not yield further improvements in SSWC, WHC, and SPV. This intriguing observation highlights that excessive MOF application may incur additional costs without commensurate benefits in terms of soil structure enhancement [21,22]. In light of these results, we recommend a MOF application rate of 2.4 t/ha as the optimal choice for enhancing the hydraulic characteristics of desert soil while concurrently mitigating water transport capacity within soil pores.

3.3. Soil Enzyme Activity

Table 4 presents enzyme activity in jujube root zone soil during fruit expansion. Urease, peroxidase, and sucrase activities gradually increased under MOF treatment. In 2021, compared to CK, different MOF concentrations (M1 to M4) increased urease activity by approximately 22.5% to 100.5%, peroxidase by 24.2% to 148.5%, and sucrase by 5.4% to 32.9%. This enhancing trend was confirmed in 2022, particularly in M5, with urease, peroxidase, and sucrase activities increasing by about 116.8%, 135.9%, and 37.7%, respectively, compared to CK.

Table 4. Soil enzyme activity during the fruit expansion stage in 2021 and 2022.

Year	Treatment	Urease (mg g^{-1} d^{-1})	Catalase (mg g^{-1} h^{-1})	Sucrase (mg g^{-1} d^{-1})
2021	CK	1.82 ± 0.06 e	0.33 ± 0.02 e	13.83 ± 0.11 d
	M1	2.23 ± 0.07 d	0.41 ± 0.03 d	14.51 ± 0.13 c
	M2	2.68 ± 0.11 c	0.54 ± 0.01 c	15.21 ± 0.15 bc
	M3	2.97 ± 0.12 b	0.67 ± 0.01 b	16.87 ± 0.09 b
	M4	3.64 ± 0.10 a	0.82 ± 0.03 a	18.41 ± 0.12 a
2022	CK	2.03 ± 0.05 e	0.39 ± 0.02 d	14.21 ± 0.11 d
	M1	2.37 ± 0.08 d	0.43 ± 0.05 c	15.11 ± 0.10 c
	M2	2.73 ± 0.11 c	0.61 ± 0.02 b	15.73 ± 0.09 c
	M4	3.76 ± 0.12 b	0.93 ± 0.03 a	18.99 ± 0.08 b
	M5	4.39 ± 0.13 a	0.91 ± 0.03 a	19.31 ± 0.13 a

Note: values with different lowercase letters in the same column were significantly different at the 0.05 level. Each data point is the mean ± SD (n = 3).

Comparing data from 2021 and 2022 revealed interannual variations. Enzyme activity slightly fluctuated in CK between the two years, which was possibly due to natural environmental changes like soil temperature and nutrient content. However, MOF treatment consistently demonstrated enhancement. For instance, urease activity in CK was 1.82 and 2.03 mg/g/d in 2021 and 2022, respectively, while corresponding values in M4 were 3.64 and 3.72 mg/g/d. Remarkably, increasing MOF concentration in M5 further enhanced soil enzyme activity in 2022. This signifies that MOF significantly enhances urease, peroxidase, and sucrase activities, displaying both temporal consistency and dose dependence. These results are consistent with previous studies on MOF application in soils, supporting the premise that MOF enhances soil microbial activity, nutrient cycling, and enzyme secretion, ultimately improving soil fertility and plant nutrient availability [28,30].

3.4. Leaf Chlorophyll Content

Figure 5 provides a visual representation of the temporal fluctuations in relative chlorophyll content (RCC) in response to MOF application. In summary, RCC exhibited a noteworthy pattern of initial increase followed by subsequent decline over the observation period. Importantly, MOF treatment consistently led to elevated RCC compared to CK, demonstrating statistical significance ($p < 0.05$).

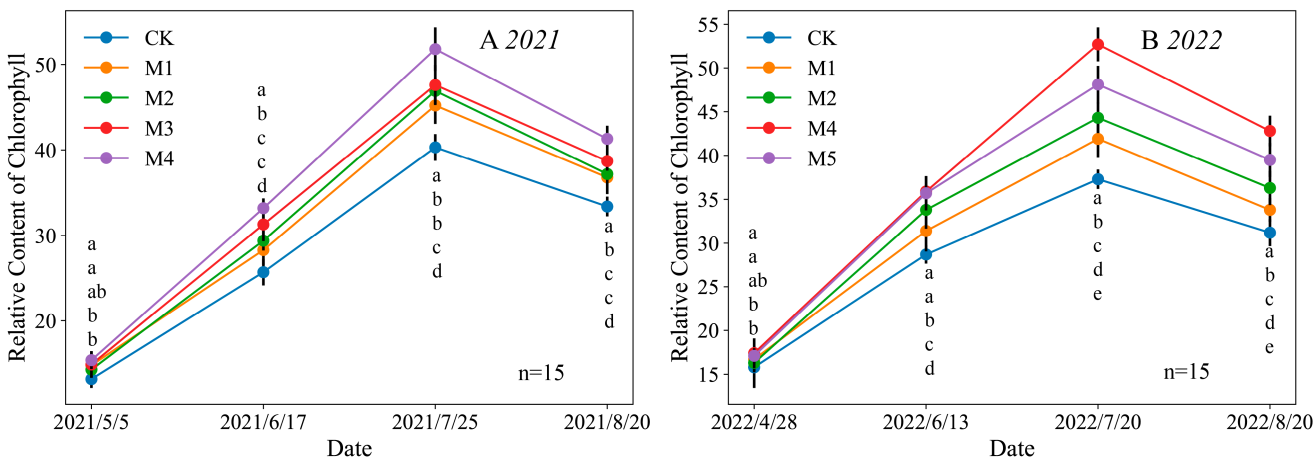

Figure 5. Relative chlorophyll content of jujube leaf in (**A**) 2021 and (**B**) 2022. Among the different treatments, the same lowercase letters did not differ from each other, $p \geq 0.05$. The bars stand for mean ± SD.

On 25 July 2021, as the quantity of MOF applied increased, RCC in the treatment groups (M1, M2, M3, and M4) displayed significant increments of 12.33%, 18.77%, 28.95%, and 41.29%, respectively, relative to the control group (CK). However, since the optimal MOF application rate had not been determined in 2021, MOF application was further intensified to 4.8 t/ha (M5) in 2022. On 20 July 2022, RCC in the treatment groups (M1, M2, M4, and M5) exhibited notable increases of 12.16%, 18.11%, 28.53%, and 16.38%, respectively, in comparison to CK.

It is particularly intriguing to note that under the M5 treatment, RCC did not achieve higher values despite the larger MOF application rate. This observation suggests that excessive MOF utilization may lead to a counterproductive scenario in which the relative chlorophyll growth process becomes inhibited. Therefore, it underscores the critical importance of determining the appropriate MOF application rate to maximize the positive impact on chlorophyll content in jujube leaves. These findings shed light on the intricate relationship between MOF application and chlorophyll content, emphasizing the necessity of precise dosage management for optimizing the desired effects.

3.5. Yield and Quality

3.5.1. Yield

As presented in Table 5, it is evident that MOF application exerted a significant and positive influence on jujube fruit yield in both 2021 and 2022 ($p < 0.05$). However, it is noteworthy that the overall jujube yield was lower in 2021 compared to 2022, with the yields from various treatments in 2021 generally falling on the lower side of the spectrum.

Table 5. Yield and quality index of the jujubes in 2021 and 2022.

Year	Treatment	Yield (t/ha)	Yield Growth Rate (%)	Titrable Acid (g/kg)	Soluble Sugar (g/kg)	Flavone (g/kg)	Sugar-Acid Ratio (g/g)
2021	CK	7.65 ± 0.04 d	/	19.12 ± 1.11 a	652.30 ± 8.23 c	1.13 ± 0.05 d	34.12
	M1	7.93 ± 0.05 c	3.66	17.61 ± 1.21 b	676.19 ± 6.17 bc	1.33 ± 0.08 c	38.40
	M2	8.36 ± 0.08 bc	9.28	18.21 ± 0.89 b	689.32 ± 8.34 b	1.48 ± 0.04 b	37.85
	M3	8.76 ± 0.12 b	14.51	15.22 ± 0.92 c	708.39 ± 6.28 ab	1.50 ± 0.09 b	46.54
	M4	9.12 ± 0.09 a	19.22	12.19 ± 1.10 d	731.27 ± 9.16 a	1.86 ± 0.11 a	59.99
2022	CK	8.70 ± 0.06 d	/	12.71 ± 0.87 a	718.29 ± 11.13 cd	1.31 ± 0.02 d	56.51
	M1	9.35 ± 0.13 c	7.47	12.17 ± 0.26 a	733.83 ± 6.28 c	1.53 ± 0.09 c	60.30
	M2	9.76 ± 0.12 b	12.18	10.18 ± 0.97 b	749.17 ± 8.54 b	1.71 ± 0.05 b	73.59
	M4	10.56 ± 0.08 a	21.38	9.33 ± 0.79 c	776.32 ± 8.23 a	2.31 ± 0.06 a	83.21
	M5	9.68 ± 0.11 b	11.26	9.82 ± 1.13 c	737.29 ± 10.12 bc	1.82 ± 0.04 b	75.08

Note: values with different lowercase letters in the same column were significantly different at the 0.05 level. Each data point is the mean ± SD (n = 3).

A notable observation emerges when comparing the yield of M3 in 2021 (8.76 t/ha) to the yield of the control group (CK) in 2022 (8.70 t/ha), where M3 exhibited a slightly higher yield. This discrepancy can be attributed to a series of severe sandstorms that swept through the study region during May and June of 2021. These sandstorms resulted in a reduction in fruit set due to the loss of jujube flowers, consequently impacting the jujube yield adversely.

In 2021, the jujube yield progressively increased across different treatments. Relative to the control group (CK), the yield of M4 recorded an impressive increment of approximately 19.22%, rising from 7.65 t/ha to 9.12 t/ha. Similarly, in 2022, the yields of M4 and M5 demonstrated substantial increases of about 21.38% and 11.26%, respectively, in comparison to CK.

However, it is essential to highlight a noteworthy finding. Despite the fourfold increase in MOF application rate in M5, its yield (9.68 t/ha) was slightly lower than M2 (11.2 t/ha). This intriguing observation suggests that excessive MOF application may induce physiological drought conditions within the jujube root systems, potentially leading to inhibition of soil respiration and nutrient transformation. Consequently, it is prudent to refrain from excessive utilization of M5, as it does not appear to enhance jujube yield significantly.

Nevertheless, it is important to underscore that MOF treatments consistently showcased substantial growth advantages over the two years, strongly indicating the promoting effect of MOF on jujube yield. These findings underscore the need for careful consideration of MOF dosage to maximize its benefits while avoiding potential drawbacks.

3.5.2. Quality

As depicted in Table 5, the application of MOF demonstrated a significant impact by reducing titratable acid (TA) content while concurrently elevating soluble sugar (SS), flavone (FL), and the sugar–acid ratio (S/A) in both 2021 and 2022 ($p < 0.05$).

In 2021, the average TA content in the control group (CK) was 19.12 g/kg. However, the highest MOF concentration treatment, M4, significantly reduced TA content to 12.19 g/kg. Similarly, in 2022, CK had an average TA content of 12.71 g/kg, while M4 recorded a content of 9.33 g/kg. This unequivocally indicates that MOF application led to a reduction in the acidity of jujube fruits, suggesting its potential influence on acid-base metabolism pathways within the fruit.

Furthermore, MOF application had a beneficial impact on the SS content of jujube fruits. The SS content consistently increased across different treatments, with M4 exhibiting a significant enhancement ($p < 0.05$). In 2021, CK had an average SS content of 652.30 g/kg, while M4 recorded a notable increase to 731.27 g/kg. This trend persisted into 2022, with CK registering 718.29 g/kg, while M4 reached 776.32 g/kg. This phenomenon underscores the capacity of MOF application to augment the sweetness of jujube fruits, thereby enhancing their overall flavor quality.

Flavone, recognized as a vital secondary metabolite, exerts a substantial influence on plant quality. Analysis revealed that MOF application significantly increased FL content in jujube fruits ($p < 0.05$). Notably, in the M4 treatment, FL content in 2021 and 2022 reached 1.86 g/kg and 2.31 g/kg, respectively. These values represented remarkable increases of 64.60% and 76.34% over the respective CK values for each year. This underscores the positive effect of MOF in stimulating the synthesis of secondary metabolites in jujube fruits, which is potentially related to its influence on crucial biochemical pathways involving hormones and enzymes.

Likewise, in 2021 and 2022, the S/A ratio within the M4 treatment reached 59.99 and 83.21, respectively, marking significant increases of 75.82% and 47.24% over the respective CK values for each year. This highlights the enhancement of jujube fruit quality attributed to MOF application.

In summary, the quantitative analyses presented here collectively demonstrate that MOF enhances jujube fruit sweetness, balance, and overall edibility by reducing acidity, increasing soluble sugar content, elevating flavone content, and improving the sugar–acid ratio. These findings underscore the potential of MOF to positively influence fruit quality in jujube cultivation.

3.6. Water and Fertilizer Productivity and Economic Benefits

3.6.1. Irrigation Water Productivity and Partial Productivity of N, P, and K

As presented in Table 6, the application of MOF had a significant and positive impact on the productivity of irrigation water (IWP) as well as the productivity of partial fertilizers N, P, and K in both 2021 and 2022 ($p < 0.05$).

Table 6. *IWP*, *FP*, and economic benefits in 2021 and 2022.

Year	Treatment	Irrigation Water Productivity (kg/m^3)	Fertilizer Productivity (kg/kg) N	P	K	Income (CNY)	Outcome (CNY)	Net Income (CNY)
2021	CK	2.39 b	18.85 b	45.95 c	34.15 c	61,200 c	17,900 c	43,300 c
	M1	2.48 b	19.03 b	47.63 c	35.40 c	63,440 c	19,100 b	44,340 c
	M2	2.61 ab	19.54 ab	50.21 b	37.32 b	66,880 b	20,300 ab	46,580 b
	M3	2.74 a	19.97 a	52.61 a	39.11 a	70,080 ab	21,500 a	48,580 ab
	M4	2.85 a	20.28 a	54.77 a	40.71 a	72,960 a	22,700 a	50,260 a
2022	CK	2.72 c	21.44 ab	52.25 d	38.84 d	69,600 d	17,900 d	51,700 c
	M1	2.92 bc	22.44 a	56.16 c	41.74 c	74,800 c	19,100 cd	55,700 b
	M2	3.05 b	22.82 a	58.62 b	43.57 b	78,080 b	20,300 c	57,780 b
	M4	3.30 a	23.48 a	63.42 a	47.14 a	84,480 a	22,700 b	61,780 a
	M5	3.03 b	19.61 b	58.14 b	43.21 b	77,440 b	27,500 a	49,940 d

Note: values with different lowercase letters in the same column were significantly different at the 0.05 level. Each data point is the mean ± SD (n = 3).

Overall, there was a notable increase in IWP, transitioning from 2.39 kg/m^3 (CK) to 2.85 kg/m^3 (M4) in 2021 and from 2.72 kg/m^3 (CK) to 3.30 kg/m^3 (M4) in 2022. This substantial improvement in IWP signifies enhanced water and nutrient use efficiency facilitated by MOF application.

The productivity of partial fertilizer N witnessed commendable growth, advancing from 18.85 kg/kg (CK) to 20.28 kg/kg (M4) in 2021 and from 21.44 kg/kg (CK) to 23.48 kg/kg (M4) in 2022. These figures correspond to increases of 7.59% and 9.51%, respectively, under MOF treatment. A parallel trend was observed for the productivity of P and K fertilizers in 2021, where MOF application elevated their productivity from 45.95 kg/kg and 34.15 kg/kg (CK) to 54.77 kg/kg and 40.71 kg/kg (M4), respectively, indicating a substantial improvement of 19.21%. These data suggest that MOF application enhances the efficiency of water and nutrient utilization, possibly by optimizing plant water and nutrient absorption mechanisms.

In summary, the quantitative analyses presented here unequivocally demonstrate that MOF application significantly enhances water and nutrient productivity, resulting in improved water and nutrient use efficiency. These findings emphasize the potential of MOF to enhance sustainable agricultural practices by maximizing resource utilization.

3.6.2. Economic Benefits Analysis

To evaluate the economic benefits of MOF application, a comprehensive assessment was conducted considering income, outcome, and net income. Income was mainly derived from jujube fruit sales, while outcome included expenses for fertilizers, labor, drip irrigation materials, water charges, and MOF costs. As shown in Table 6, MOF application significantly increased jujube income and investment costs ($p < 0.05$), with investment costs being proportional to the MOF application rate. In 2021, net income increased by 1340–6960 CNY/ha for MOF application rates from M1 to M4. In 2022, net income increased by 4000–10,080 CNY/ha for MOF application rates from M1 to M5. Both years showed that M4 had the highest net income. This reaffirms the positive impact of MOF application on jujube's economic benefits.

3.7. Comprehensive Evaluation

3.7.1. Correlation Analysis

Figure 6 depicts the influence of MOF treatment on various aspects of jujubes, including hydraulic and physical properties, enzyme activity, physiological growth, yield, quality, and economic benefits. Mean SWC, mean SWC, SPV, CE, SE, and FL content showed extremely significant positive correlations ($p < 0.01$). These factors also positively correlated with RCC, yield, SS, and S/A ($p < 0.05$). Negative correlations were observed between Ks and BD ($p < 0.01$) with some soil properties. These relationships emphasize that creating a suitable root zone soil environment offers adequate nutrients and water for jujube growth. Jujube yield positively correlated with mean SWC, mean SWS, SPV, UE, CE, and SE ($p < 0.05$). It also significantly correlated with SS, FL, S/A, and NI ($p < 0.01$). NI was only significantly correlated with yield and quality indicators ($p < 0.01$).

In summary, SWC, SWS, SPV, and enzyme activity in the jujube root zone effectively promoted yield and quality improvement. UE, CE, SE, and FL appeared to exhibit inhibitory effects on titratable acidity increase while promoting soluble sugar content increase. Encouragingly, the applied regulatory measures improved the soil environment in the root zone while substantially enhancing jujube fruit yield and quality. This was achieved by MOF enhancing soil water retention and fertility in desert soils and improving enzyme activity, creating an optimal soil environment for jujube growth.

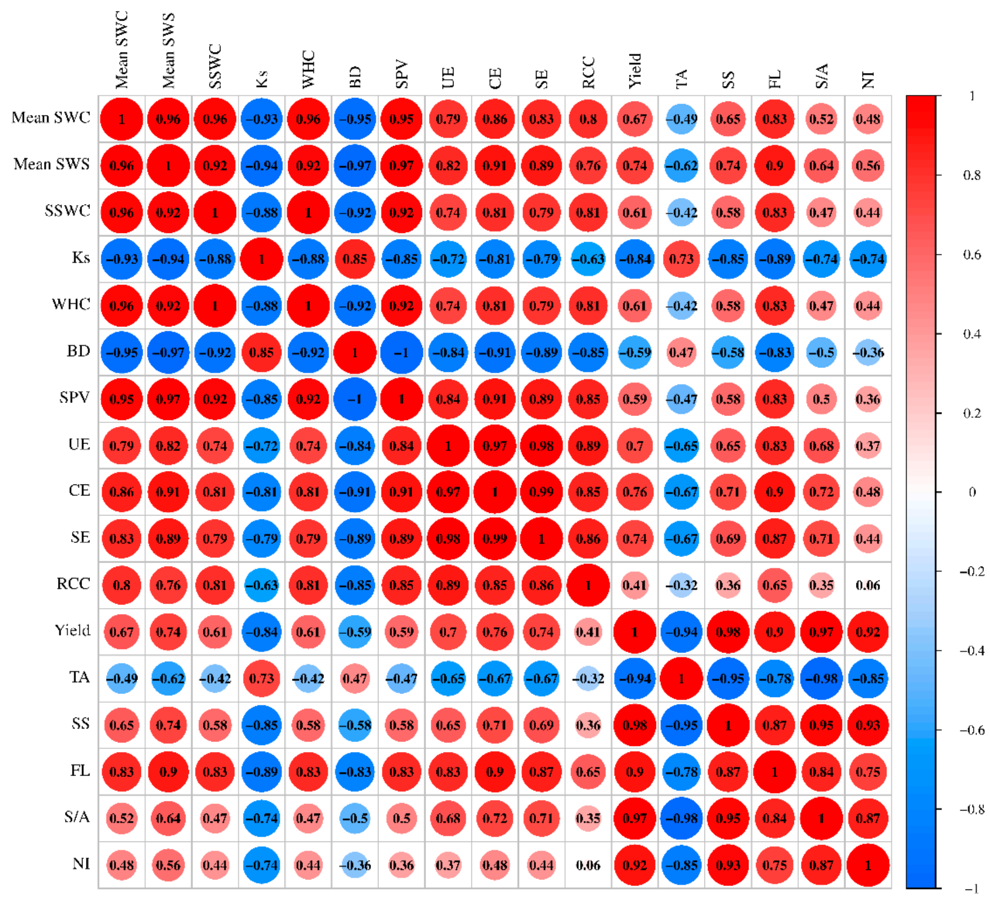

Figure 6. Correlations among the soil's hydraulic and physical properties, enzyme activity, physiological growth, yield, quality, and economic benefits. Mean SWC, mean soil water content; mean SWS, mean soil water storage; SSWC, saturated soil water content; Ks, saturated hydraulic conductivity; WHC, water-holding capacity; BD, soil bulk density; SPV, soil porosity volume; UE, urease activity; CE, catalase activity; SE, sucrose activity; RCC, relative chlorophyll content; TA, titrable acid; SS, soluble sugar; FL, flavone; S/A, sugar–acid ratio; NI, net income.

3.7.2. Cluster Analysis

Based on the correlation analysis, hierarchical cluster analysis was applied to the 17 indicators representing jujubes, including hydraulic and physical properties, enzyme activity, physiological growth, yield, quality, and economic benefits (Figure 7). Cluster relationships between 10 treatments and 17 indicators for both 2021 and 2022 were compared. Overall, TA, BD, and Ks were distinct characteristics separating from other indicators. Notably, an increase in TA, BD, and Ks was associated with inhibitions observed in other indicators, including soil enzyme activity and jujube yield. The clustering relationship between treatments revealed that in 2021 and 2022, M4, M2, and M5 in 2022 were the top three treatments, followed by M4 and M3 in 2021. This might be attributed to better jujube yield and quality in 2022, as M2 and M5 rankings improved compared to M4 in 2021. In both years, M4 consistently ranked among the top. This implies that M4 treatment comprehensively improved the soil's hydraulic characteristics and enzyme activity, and substantially increased jujube fruit yield and quality, showcasing the best overall performance. Based on this limited two-year study (2021 and 2022), the recommended most economical and efficient MOF application rate for jujube cultivation in this region is 2.4 t/ha.

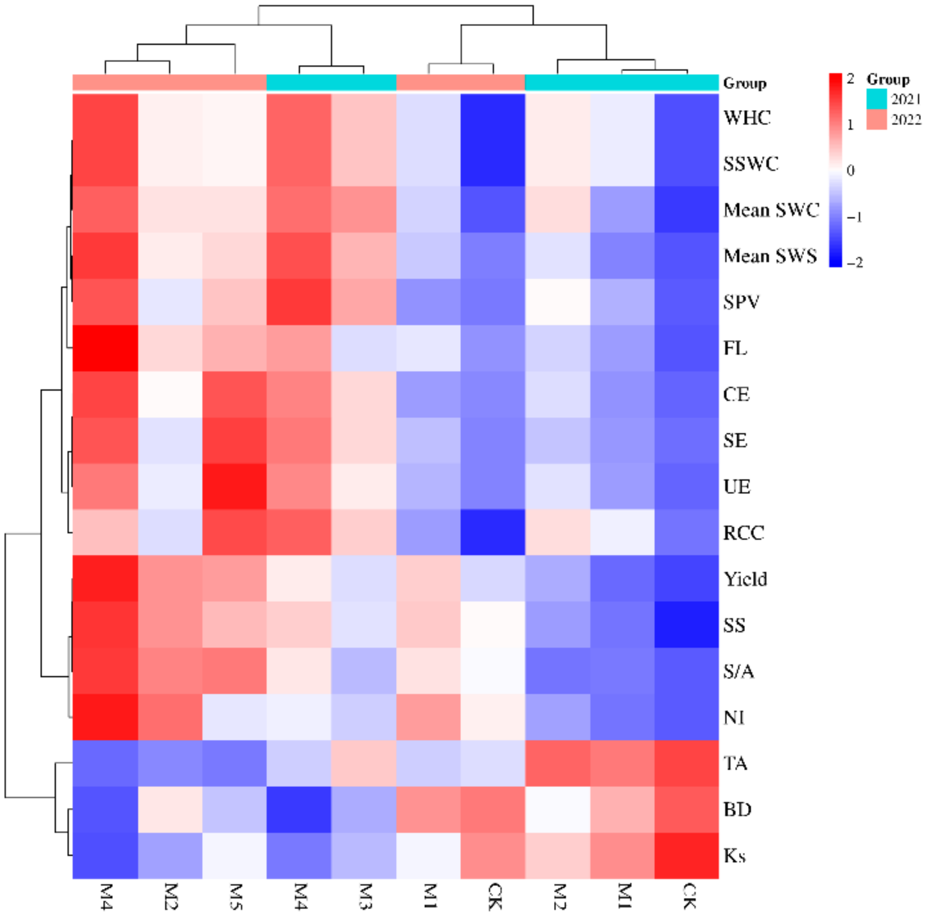

Figure 7. Cluster analysis of the soil's hydraulic and physical properties, enzyme activity, physiological growth, yield, quality, and economic benefits. Mean SWC, mean soil water content; mean SWS, mean soil water storage; SSWC, saturated soil water content; Ks, saturated hydraulic conductivity; WHC, water-holding capacity; BD, soil bulk density; SPV, soil porosity volume; UE, urease activity; CE, catalase activity; SE, sucrose activity; RCC, relative chlorophyll content; TA, titrable acid; SS, soluble sugar; FL, flavone; S/A, sugar–acid ratio; NI, net income.

3.7.3. TOPSIS Ranking

To ensure the objectivity of our evaluation, we employed a combination of the entropy weight method and the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method. This approach allowed for a comprehensive and effective assessment of various aspects of jujube cultivation, including the soil's hydraulic and physical properties, enzyme activity, physiological growth, yield, quality, and economic benefits under MOF application.

The Euclidean distance metric between the positive ideal solution and the negative ideal solution was used to quantify the degree of difference between each experimental treatment and the best- and worst-case scenarios, considering multiple indicators. Subsequently, we utilized the relative closeness (C-value) to determine the relative superiority or inferiority of each experimental treatment in the comprehensive evaluation. A higher C-value indicated that the treatment's soil hydraulic and physical properties, enzyme activity, physiological growth, yield, quality, and economic benefits were closer to the optimal MOF regulation strategy.

As presented in Table 7, the relative closeness values in 2021 ranked from high to low as follows: M4, M3, M2, M1, CK. In 2022, the order was M4, M5, M2, M1, CK. Overall, the relative closeness values ranked from high to low were M4 (2022), M5 (2022), M4 (2021), M2 (2022), M3 (2021), M2 (2021), M1 (2022), CK (2022), and CK (2021). This analysis underscores that the M4 treatment consistently outperformed other treatments in creating an optimal soil environment for jujube growth, resulting in enhanced jujube yield and quality.

Table 7. TOPSIS comprehensive score.

Year	Treatment	Positive Ideal	Negative Ideal	Relative Proximity C	Ranking
2021	CK	3.649434798	1.747229901	0.323761063	10
	M1	2.980332995	1.696047983	0.362683877	8
	M2	2.48513116	1.971813370	0.442413711	6
	M3	2.149913006	2.235547603	0.509763467	5
	M4	1.897100524	2.978171607	0.610872896	3
2022	CK	3.232117645	1.553216327	0.324578459	9
	M1	2.537163879	1.876340944	0.425136262	7
	M2	2.148392696	2.281330431	0.515005197	4
	M4	1.735140415	3.578581976	0.673460469	1
	M5	1.811858201	2.847133158	0.611105052	2

In conclusion, our assessment highlights the effectiveness of the M4 treatment in promoting favorable soil conditions and improving jujube cultivation outcomes, making it the recommended strategy for achieving optimal results in jujube production.

4. Discussion

4.1. Mechanisms of the Soil's Hydraulic Properties and Enzyme Activity Enhancement by MOF Amendment

The study area for this investigation is situated at the southern fringe of the Taklamakan Desert, a geographically unique region exposed to various influences, including sandstorms, scorching temperatures, high evaporation rates, and distinctive parent materials for soil formation. Within this complex and variable environment, irrigation water quickly moves downward through the soil profile to the subsoil layer where jujube roots grow, resulting in significant water loss. Notably, desert soils exhibit astonishingly high rates of water movement, up to 0.29 cm/min, with infiltrative wetting fronts vertically advancing at an even more remarkable rate of up to 1.5 cm/min [7]. These findings highlight the limited water retention capacity of desert soils, often leading to conditions of "physiological drought" for jujube trees. Before this investigation, we hypothesized that the application of MOF could have multiple positive effects on desert soils. Firstly, we postulated that MOF might enhance the water retention capacity of desert soils, thus reducing rapid water loss [23,24]. Additionally, MOF might decompose organic matter, releasing essential nutrients for plant uptake [22]. Moreover, the microorganisms within MOF could establish symbiotic relationships with plant root systems, enhancing nutrient absorption and utilization, and thereby improving soil fertility [25]. Furthermore, through various ecological and physiological mechanisms, MOF could enhance the efficiency of water and nutrient uptake by jujube trees, ultimately increasing yield and quality.

Fortunately, the research findings strongly support these hypotheses. Following the application of MOF, the average soil moisture content and profile water storage in the 0–50 cm soil profile increased by 10.98% to 36.42% and 1.8% to 26.8%, respectively. Furthermore, experiments conducted in both 2021 and 2022 consistently indicated that MOF application increased saturated soil water content (SSWC) and water holding capacity (WHC) by 6.25% to 15.98%, while hydraulic conductivity (Ks) and bulk density (BD) were reduced by 2.91% to 9.88% and 0.63% to 8.08%, respectively. These outcomes can be primarily attributed to five underlying mechanisms:

(a) The microbial components in MOF, such as microbial rhizomes and microbial cell bodies, contribute by secreting cohesive substances that bind soil particles and organic matter [22,27,38]. The adhesive substances generated by these microorganisms form microscopic aggregates, consolidating soil particles and resulting in more stable soil aggregates [21,28]. This cohesive action increases soil porosity and permeability, thereby enhancing water retention and permeability [39].
(b) Microorganisms in MOF have a positive impact on soil structure. Metabolic by-products, secretions, and microbial community activities alter interactions between soil particles, promoting aggregate formation. Such structural enhancements contribute to the development of larger stable pores, thereby increasing soil hydraulic conductivity and air permeability [29,30,40].
(c) The application of MOF promotes the accumulation of organic matter. Microbial decomposition of organic matter generates metabolic by-products that become part of the organic matter, ultimately raising soil organic matter content. Organic matter can adsorb and retain water, increasing soil water retention capacity [33,37].
(d) MOF application enhances the diversity and abundance of soil microbial communities. These rhizospheric microorganisms establish complex root-associated ecosystems with jujube roots. Activities of these rhizosphere microorganisms modify soil eco-chemical properties, facilitating organic matter breakdown and transformation and ultimately improving soil structure and water retention [41,42].
(e) During growth and metabolism, microorganisms generate bio-cellular and colloidal substances. These substances form microscopic aggregates in the soil, assisting in binding soil particles together. This cohesive action enhances soil cohesion, reducing water loss [15,39].

However, our findings also reveal that excessive MOF application does not invariably yield beneficial promotion. In 2022, the M5 treatment displayed inferior effects compared to M4 in terms of soil moisture and porosity augmentation. This disparity could stem from an excessive accumulation of viscous substances produced by microbial bodies after extensive MOF application, leading to excessive particle cohesion, compact structure formation, and an increased proportion of ineffective pores, ultimately reducing the number of effective pores [43].

Similarly, enzymes serve as catalytic agents for nutrient transformation in soil and crucially influence the root zone environment for plant growth [32,33,44]. Soil enzyme activity is regarded as an indicator of soil health. In this study, MOF application significantly enhanced the activities of urease, peroxidase, and invertase enzymes, which was attributed to the copious spore-forming bacteria and organic matter present in MOF. There were notable enhancements in invertase and peroxidase activity after the application of silicon fertilizer and microbial spore-forming bacteria [31,40]. Organic fertilizer addition increased urease activity, positively correlating with soil nitrogen availability [30,39]. Elevated soil enzyme activity signifies the restoration of soil ecological health by organic fertilizer, which is congruent with our findings. Additionally, increased soil moisture due to MOF application in turn accelerates reactant mobility, providing an optimal reaction environment for enzyme catalysis, consequently boosting invertase activity [28,44]. Other studies also affirm that soil moisture is a decisive factor in enzyme activity, as enzyme activity increases with augmented soil moisture content [41,45]. Likewise, our research underscores a highly significant correlation between increased soil moisture and enhanced enzyme activity (Figure 5).

4.2. Mechanisms of MOF-Induced Yield and Quality Enhancement in Jujubes

MOF has demonstrated superior efficacy compared to chemical fertilizers [23,43]. The growth-promoting effect of MOF can be attributed to increased root activity in the rhizosphere, which activates hormone functions, thereby enhancing nutrient uptake by plants [46,47]. Numerous studies have reported the supportive role of biofertilizers in plant growth. For instance, the application of *Bacillus subtilis* microbial fertilizer effectively delayed the coloring of blood orange peel and pulp, increased leaf nitrogen and potassium concentrations, and reduced titratable acidity (TA) [15]. Additionally, *Bacillus subtilis* microbial fertilizer enhanced single plant and market yields, fruit weight, and length of tomatoes. Similar outcomes were observed in this study, with jujube yield increasing by 3.66% to 21.38%. In 2021, TA decreased from 19.12 g/kg to 12.71 g/kg and SS and FL significantly increased the S/A by over 47.24%. These improvements can be attributed to MOF enhancing water and nutrient retention capacities in desert soils, reducing deep water and nutrient leaching, and providing ample support for jujube tree growth [24]. Furthermore, MOF increased soil enzyme activity, promoting metabolic processes, such as sugar decomposition and organic compound synthesis in plants, consequently elevating the synthesis of SS and FL [27,29,30]. Notably, correlation analysis demonstrates that soil moisture content and enzyme activity are the predominant factors driving jujube yield increase (Figure 5). This study also found that MOF significantly enhanced irrigation water productivity and improved the efficiency of nitrogen (N), phosphorus (P), and potassium (K) fertilizers, which was attributed to MOF's reduction in Ks and increased SPV [20,21]. Additionally, microorganisms such as Bacillus subtilis in MOF accelerated fertilizer transformation and absorption, thereby enhancing jujube yield. As evidenced by previous studies, improved nutrient consumption fosters tree growth, concurrently augmenting fruit yield [29,42].

4.3. Limitations and Future Directions

This study primarily aimed to regulate the habitat of jujube trees in the arid regions of southern Xinjiang to enhance jujube yield, quality, and local environmental conditions, thereby improving economic gains for local farmers. Considering soil improvement, yield, quality, and economic benefits, we recommend an MOF application rate of 2.4 t/ha, which could result in a net income increase of 10,080 CNY/ha. However, our study remains incomplete as MOF was used solely as a basal fertilizer, and chemical fertilizer application was not reduced. Consequently, future research should consider substituting MOF for chemical fertilizers to achieve sustainable agricultural development in this region. Increased expenditure mainly results from MOF. Exploring the possibility of MOF replacing or reducing chemical fertilizer application could decrease production costs, further boosting economic benefits, a facet deserving attention in future research.

5. Conclusions

The outcomes of this study strongly confirm the positive effects of MOF on jujube cultivation in arid regions. MOF treatment notably improves soil moisture distribution, soil hydraulic properties, and enzyme activity in the root zone, creating a more favorable growth environment for jujube trees. This enhancement is also validated in physiological growth and yield improvement, manifested as increased relative chlorophyll content, enhanced yield, and improved quality. The economic analysis underscores the significant economic potential of MOF treatment, effectively increasing jujube net income. Comprehensive evaluation results support an application rate of 2.4 t/ha as yielding optimal comprehensive benefits, which holds significant application value in arid region jujube cultivation. These findings not only present innovative strategies for agricultural production but also offer crucial insights for improving soil's ecological conditions in arid regions.

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