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The Impact of Long-Term Mulched Drip Irrigation on Soil Particle Composition and Salinity in Arid Northwest China

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Abstract: The evaluation of soil particle composition and salt dynamics is essential for promoting the sustainable development of oasis agriculture in arid regions under long-term mulched drip irrigation (MDI). In this study, we employed the space-for-time substitution method to investigate the long-term effects of MDI on soil particle composition and salinity. Additionally, seven fields, with MDI durations ranging from 0 to 16 years, were selected to represent the primary successional sequence though time in Northwest China. Soil samples were collected from three soil depths (0–30 cm, 30–60 cm, and 60–100 cm) and then analyzed in the laboratory for soil particle composition and salt content. Our findings demonstrated that influenced by the depth of mechanical cultivation and the maximum wetting front depth, the long-term application of MDI significantly altered both the structure of soil layers and the composition of soil particles after 8 years. Soil sand content and soil salinity gradually decreased, whereas the content of soil silt and clay increased with increasing MDI duration throughout 0–100 cm soil depth. Furthermore, the rates of soil desalination stabilized after 10 years of MDI application, with desalination levels exceeding 90% in the 0–100 cm soil layer. Additionally, the soil mass fractal dimension (Dm) exhibited an upward trend across 0–100 cm soil depth. The changes in soil particle composition indirectly influenced the variations in Dm and salt content. Our study demonstrated that long-term application of MDI effectively mitigated soil salinity, changed soil structure, and ultimately enhanced soil quality and cotton yield.

Keywords: oasis agriculture; mulched drip irrigation; soil particle composition; soil structure; soil salinization; cotton field

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1. Introduction

Soil salinization poses a pressing threat to global food security and sustainable agricultural development [1]. Recent reports by the Food Agriculture Organization of the United Nations (FAO) indicate that more than 1100 Mha of land worldwide have already been affected by soil salinization, with an alarming increase in recent decades [2]. This issue transcends national boundaries, with arid and semi-arid regions experiencing particularly severe consequences. Furthermore, the combined impacts of climate change and human activities are exacerbating soil salinization and degradation [3–5]. Future projections indicate that by 2050, approximately 50% of cultivated lands will be affected by soil salinization, leading to reduced agricultural productivity across numerous regions [6].

The challenge of salt stress in soil has gained significant attention as freshwater resources diminish and the global population rapidly grows [7,8]. Soil affected by salinization exhibits elevated levels of soluble salts, increased pH, compromised soil structure, and diminished organic matter content, all of which exert detrimental effects on soil ecology and crop growth [9]. Consequently, effective management for soil salinization is crucial. In semi-arid regions, crop yield is primarily determined by water availability within the root zone [10]. Hence, comprehensive research on irrigation methods that can conserve water while regulating soil salinity is imperative.

Mulched drip irrigation (MDI) has emerged as a promising water-saving approach that combines the benefits of drip irrigation and film mulching. Drip irrigation efficiently supplies water and nutrients in the root zone of crops, while the film cover reduces soil–water evaporation and provides insulation [11]. The widespread adoption of MDI technology in the arid regions of Xinjiang since the 1990s has transformed millions of hectares of salt-affected uncultivated lands into productive farmland [12].

Due to the low wetting front depth of MDI (usually 50–60 cm) and the restriction of water evaporation within the membrane (promoting water cycle in the membrane space), it exhibits significant differences compared to conventional irrigation methods [11]. Soil particle composition, serving as a pivotal gauge of soil texture [13] and hydraulic properties [14–16], significantly influences soil water–salt transport, erosion, degradation, and microbial community composition. Currently, a plethora of studies have scrutinized the impacts of MDI on diverse crop varieties [17,18], film mulching materials [19,20], soil water–salt distribution [21,22], and optimal irrigation schedules tailored to specific regions and crops [23]. Given the severe water scarcity in arid regions, local farmers prioritize partial soil physical and chemical properties, such as texture and salinity, directly impacting crop yields, over hydraulic conditions. However, a critical research gap persists as there is an absence of studies analyzing the long-term temporal and spatial dynamics of soil texture and salinity, particularly under the influence of MDI.

Consequently, this study aimed to (1) assess the impact of prolonged MDI application on soil particle composition and textural structure; (2) evaluate the long-term effects of MDI application on soil salinity; and (3) scrutinize the relationship between soil particle composition and soil salinity under long-term MDI conditions. This comprehensive analysis provides valuable insights into the long-term application of MDI on soil properties, specifically shedding light on the interplay between MDI, soil structure, and salinity levels. The study's methodology and findings contribute significantly to our understanding of sustainable agricultural practices, particularly in the context of long-term MDI applications in cotton fields.

2. Materials and Methods

2.1. Experimental Site

This investigation delved into an oasis agroecosystem characterized by a continental arid climate. The study site is located in the 121st Regiment (85°33′–85°35′ E, 44°48′–44°50′ N, 337 m a.s.l.) near the city of Shihezi, Xinjiang, China. The average annual air temperature ranges from 6.5 to 7.2 °C. The climate conditions are marked by abundant sunshine, with annual averages ranging from 2318 to 2732 h. The area also records extreme temperature fluctuations, reaching highs of up to 43.1 °C and lows of −42.8 °C.

This region has been one of the earliest adopters of MDI in Xinjiang, and MDI has become the primary irrigation technique in all cotton fields. Originally, the soil in these fields was categorized as chloride-sulfate saline soil [24]. In the 0–30 cm tillage layer, the average bulk density is about 1.37 g/cm^3, with a pH of 7.83 and a field water holding capacity of 34.08% (m/m of soil). During the cotton growing season, crop evapotranspiration is estimated at 538 mm, with the average annual irrigation amount reaching 816.15 mm. The irrigation water is primarily sourced from a nearby reservoir with a salinity level of around 0.4 g/kg. The groundwater level in this region fluctuates 3–4.5 m throughout the year and has a salinity ranging from 10 to 50 g/kg.

2.2. Experimental Design

In this study, a space-for-time substitution approach was utilized to assess the effectiveness and sustainability of long-term MDI in a typical oasis agricultural ecosystem. The studied cotton fields were initially saline-alkali uncultivated lands with similar soil structure and physical properties before the implementation of MDI. Seven fields, comprising six cotton fields subjected to varying durations of MDI application (2, 6, 8, 10, 12, and 16 years), and an adjacent saline-alkali uncultivated land serving as the control, were selected to represent distinct stages in the soil successional process through time.

The experimental site, affiliated with Shihezi University, is specifically designated to explore the effects of different durations of MDI use and various irrigation practices on soil quality and crop yields in oasis environments. It is noteworthy that all studied fields began as uniform saline-alkali uncultivated lands regarding their soil structure and physicochemical properties before their reclamation for agricultural use. To maintain uniformity in the climatic and environmental conditions across the experimental plots, all plots representing different successional stages were positioned closely together. Throughout the cultivation period after land reclamation, MDI was the sole irrigation method applied across the cotton field plots, with consistent planting patterns and identical irrigation and fertilizer applications from the outset.

Hence, the variations noted in soil physical and chemical properties across the experimental plots can largely be attributed to the varying lengths of MDI application, along with the distinct agricultural practices employed. This strategic approach allows for a clearer understanding of the long-term impacts of MDI on soil rehabilitation and cotton productivity within saline-alkali uncultivated lands that were transformed into productive agricultural lands.

In the field, a systematic planting pattern was implemented, involving the use of a single mulch film and two drip tape lines for every six rows of cotton (Figure 1). On 17 August 2014, three distinct sampling areas within each cotton field, reflecting varying durations of practicing MDI, were randomly selected for soil sampling using a 5.0 cm diameter soil auger. To ensure accuracy and eliminate the impact of planting patterns and soil heterogeneity, three specific sampling points were chosen within each sampling area: directly below the drip line, at the middle of a narrow row, and at the midpoint of the bare land. The depth for soil sampling was established across three different soil layers: the cultivation layer (0–30 cm), the layer corresponding to the maximum wetting extent in MDI (30–60 cm), and the deep leaching layer (60–100 cm). Soil samples were collected at 10 cm intervals from surface down to a depth of 100 cm. Soil samples from the same soil layers at each sampling point were aggregated to form a composite. The soil samples from each plot of different durations of MDI were then partitioned into two parts. These samples were carefully transported to the laboratory for separate analysis of soil salinity and soil particle composition.

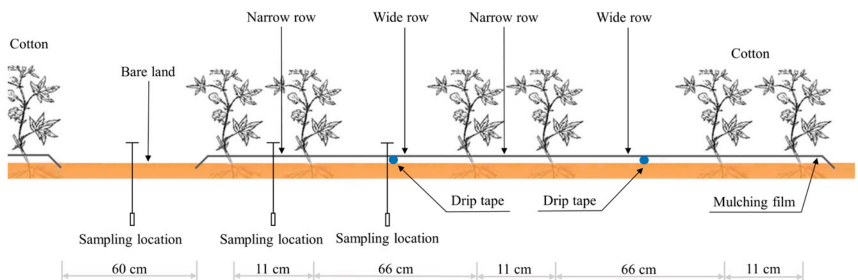

Figure 1. The layout of the design of MDI and three sampling points in each replicated sampling area.

2.3. Experimental Methods

2.3.1. Soil Salinity and Desalinization Rate

To prepare the soil samples for analysis, plant remains and debris were first removed, followed by oven drying. Each sample was then milled to a fine consistency and sieved through a 2 mm mesh. An extraction ratio of soil to water of 1:5 was used, and the mixtures were shaken for 15 min before filtration. The electrical conductivity (EC) value of each filtrate was measured using a conductivity meter (DDS-11A, Shanghai Leici Ltd., Shanghai, China). Subsequently, the EC values were converted into soil salinity values (g/kg) according to the calibration equation described by Wang [25]:

$$S = 0.008EC + 0.876 \tag{1}$$

where S is soil salinity (g/kg), and EC is the soil electrical conductivity (μS/cm).

The contrast in soil salinity before and after MDI application (ΔS; g/kg) and the desalinization rate (R; %) were calculated based on the salinity balance equations:

$$\Delta S = S_1 - S_2 \tag{2}$$

$$R = \frac{\Delta S}{S_1} \times 100\% \tag{3}$$

where S_1 is the soil salt content of the uncultivated land (g/kg), and S_2 is the soil salt content of cotton fields under different durations of MDI (g/kg).

2.3.2. Soil Particle Composition and Mass Fractal Dimension

Soil samples were transported to the laboratory and allowed to air-dry. After removing stones, roots, and debris, the samples underwent sieving through a 2 mm mesh. The classical sieve-pipette method, with guidelines followed as outlined in Gee and Or [26], was employed for the determination of sand, silt, and clay content. Soil particle classification was based on standards established by the United States Department of Agriculture (USDA) for soil texture [27]. Soil particles were classified in descending order of particle size as sand (0.05~2 mm), silt (0.002~0.05 mm), and clay (<0.002 mm). Then, D_m (soil mass fractal dimension) can be estimated [28]:

$$\frac{M(d < d_i)}{M_T} = \left(\frac{d_i}{d_{max}}\right)^{3-D_m} \tag{4}$$

where d is the mass of a particle of ith size class, d_i is the average particle size of ith size class, d_{max} is the mean size of the largest size class, M is the cumulative mass of particles of ith diameter less than d_i, and M_T is the total mass.

2.4. Statistical Analysis

IBM SPSS Statistics 27.0 software (IBM, Chicago, IL, USA) was utilized to perform a one-way analysis of variance (ANOVA). Post hoc multiple comparisons were conducted based on the Duncan test to determine the significance of differences between factors ($\alpha = 0.05$). A heatmap was employed to select and evaluate the variables that impact the soil particle composition and salt content and to thoroughly explore the relationship among drip irrigation years, soil particle composition, soil structure, and soil salt content. Heatmap analysis was performed with Origin 2023 (OriginLab, Northampton, MA, USA).

3. Results and Discussion

3.1. Comparison of Soil Particle Composition Characteristics for Different MDI Durations

The variations in soil particle composition in cotton fields with different MDI durations are presented in Table 1, which demonstrates a significant impact of long-term MDI on soil particle composition. As the MDI duration increases, the content of sand particles gradually decreases, while the content of clay particles increases. However, it was observed that the content of soil silt particles, which accounted for more than 50% of the total particles in all soil layers within the study area, did not exhibit significant differences. This phenomenon could be attributed to the location of the study site in the arid region, where the soil was highly susceptible to wind erosion and showed evident surface desertification [29].

Consequently, the initial content of sand particles in the soil was relatively high. Under the combined effects of long-term mechanical cultivation, irrigation, and root growth, soil particles tended to shift towards finer particle sizes. After 16 years of continuous MDI practice, however, the soil texture in the 0–100 cm soil layer remains predominantly silty loam (Figure 2). This indicates that long-term MDI facilitates the maintenance of stable water infiltration and a rhizosphere microbial community environment within the 0–100 cm soil layer.

Table 1. Soil particle composition of cotton fields with different durations of MDI.

Soil Depth (cm)	Durations of MDI (a)	Soil Particle Composition			Dm
		Sand (%)	Silt (%)	Clay (%)	
0–30	0	36.31 ± 2.96 [a]	47.39 ± 3.64 [a]	16.31 ± 0.78 [d]	2.74 ± 0.03 [a]
	2	31.53 ± 2.58 [ab]	48.74 ± 3.80 [a]	19.73 ± 1.46 [c]	2.77 ± 0.02 [a]
	6	28.47 ± 2.88 [bc]	50.08 ± 3.90 [a]	21.45 ± 1.39 [bc]	2.78 ± 0.03 [a]
	8	25.75 ± 3.04 [c]	50.82 ± 3.76 [a]	23.43 ± 1.22 [ab]	2.79 ± 0.03 [a]
	10	24.54 ± 3.16 [c]	51.92 ± 3.88 [a]	23.54 ± 1.12 [ab]	2.79 ± 0.03 [a]
	12	24.00 ± 3.19 [c]	52.52 ± 3.85 [a]	23.49 ± 0.99 [ab]	2.79 ± 0.03 [a]
	16	23.47 ± 3.17 [c]	52.81 ± 3.83 [a]	23.72 ± 1.04 [a]	2.80 ± 0.03 [a]
30–60	0	27.48 ± 3.05 [a]	52.91 ± 4.27 [a]	19.61 ± 1.23 [d]	2.77 ± 0.04 [d]
	2	24.20 ± 2.69 [ab]	54.20 ± 3.99 [a]	21.60 ± 1.33 [cd]	2.78 ± 0.04 [d]
	6	23.13 ± 2.98 [abc]	53.54 ± 4.39 [a]	23.33 ± 1.43 [c]	2.79 ± 0.03 [c]
	8	20.60 ± 3.10 [bc]	53.65 ± 4.51 [a]	25.75 ± 1.41 [b]	2.81 ± 0.03 [b]
	10	19.07 ± 3.25 [bc]	53.37 ± 4.26 [a]	27.56 ± 1.03 [ab]	2.82 ± 0.03 [ab]
	12	18.63 ± 3.39 [bc]	53.69 ± 4.75 [a]	27.68 ± 1.40 [ab]	2.82 ± 0.03 [ab]
	16	17.88 ± 3.26 [c]	52.81 ± 4.40 [a]	29.31 ± 1.17 [a]	2.83 ± 0.02 [a]
60–100	0	19.41 ± 3.26 [a]	57.00 ± 5.65 [a]	23.59 ± 2.41 [b]	2.79 ± 0.02 [b]
	2	18.13 ± 2.55 [ab]	58.61 ± 4.10 [a]	23.26 ± 1.59 [b]	2.79 ± 0.01 [b]
	6	17.74 ± 2.91 [ab]	57.65 ± 4.98 [a]	24.61 ± 2.13 [ab]	2.80 ± 0.02 [ab]
	8	16.39 ± 3.30 [ab]	58.34 ± 5.98 [a]	25.27 ± 2.68 ab	2.80 ± 0.02 [ab]
	10	15.50 ± 3.43 [ab]	58.77 ± 6.53 [a]	25.74 ± 3.10 [ab]	2.81 ± 0.02 [ab]
	12	14.17 ± 3.50 [ab]	58.26 ± 6.35 [a]	27.57 ± 2.88 [ab]	2.82 ± 0.02 [ab]
	16	11.88 ± 3.49 [b]	59.21 ± 6.14 [a]	28.91 ± 2.66 [a]	2.82 ± 0.02 [a]

Note: Means followed by different letters were shown to differ statistically by Duncan's test at the 5% significance level.

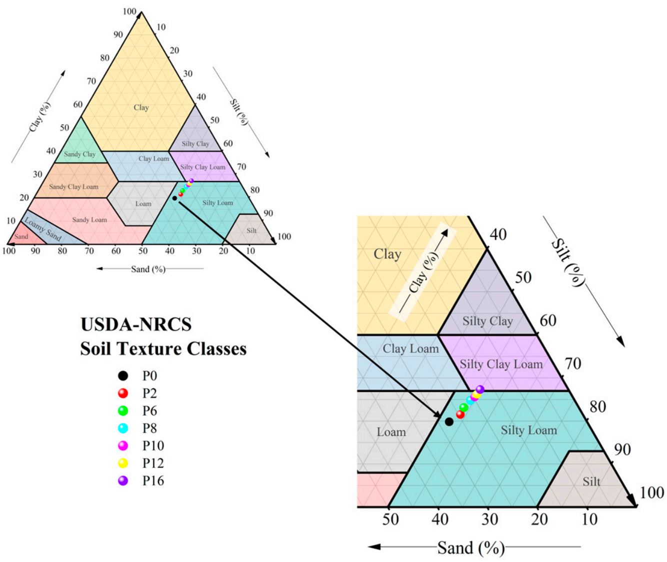

Figure 2. Average soil texture of plots with different durations of MDI at 0–100 cm depth. Durations of MDI were coded as 0 (i.e., uncultivated land), 2, 6, 8, 10, 12, and 16.

3.2. Long-Term Characteristics of Soil Salinity in Cotton Field with Different MDI Durations

As the duration of MDI increased, cotton fields underwent three distinct stages of desalination based on desalination rate: rapid desalination, slow desalination, and stable desalination (Figure 3). The initial phase of MDI (0–8 years) was characterized by a substantial decrease in soil salinity. In the eighth year of MDI application, the soil salinity in each soil layer was below 5 g/kg (Figure 3a). Additionally, in the 8-year drip irrigation cotton field, the desalination rate exceeded 80% when compared to the 0-year drip irrigation cotton field, with an average desalination rate of 84.01% across all soil layers (Figure 3b). This stage signifies a rapid desalination process, which is consistent with the past results of Li et al. [30]. Numerous studies have indicated that excessive soil salinity can significantly impede crop production, potentially transforming arable land into unproductive soil [31]. In oasis agroecosystems, where soil salinization and drought coexist, reducing soil salt content often correlates with enhancements in crop yield and agricultural sustainability [32,33]. Li et al. [30] reported that cotton growth is almost unaffected by salinity at a soil salt content of 2.49 g/kg. However, when soil salinity increases to 8.57 g/kg, the survival rate of cotton and yield per unit area decrease by approximately 53.49% and 43.05%, respectively. Therefore, the application of MDI in arid oasis regions holds paramount significance for improving both the quality of saline-alkali soil and crop yield.

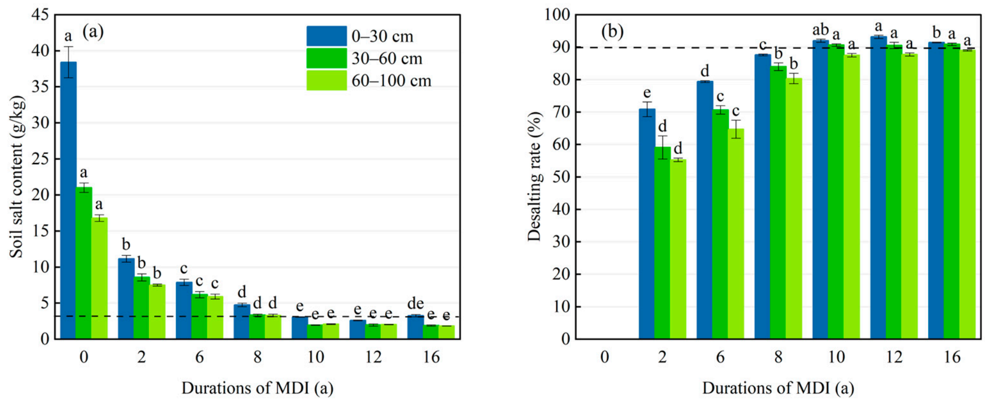

Figure 3. (**a**) Characteristics of soil salt content with MDI durations; (**b**) characteristics of desalting rate with MDI durations. Different superscripted letters (a, b, c, d and e) indicate that there are statistically significant differences between treatments ($p \leq 0.05$).

Throughout 8–10 years of practicing MDI, the reduction in soil salinity became less pronounced. By the end of the 10th year, the desalination rate exceeded 90%, with an average rate of 90.07% across all soil layers. This stage represented a slow desalination process, displaying a 6.06% increase compared to the rapid desalination stage. From years 10–16, there was a stabilization of changes in soil salinity, and the overall desalination rate in the 16-year drip-irrigated cotton field reached more than 90%, with an average rate of 90.47% across all soil layers. During this stage, there was a slight increase (0.4%) compared to the rapid desalination stage. Our research aligns with previous observations, attributing these phenomena to the interplay between salt and water movement during irrigation events [34]. Previous studies indicate that post-reclamation, the soil porosity gradually increases, and bulk density decreases due to mechanical disturbance and the accumulation of organic matter [35,36]. In the initial stages of reclamation, this fosters dynamic shifts in soil moisture and salinity transport. Artificial oases, characterized by significant potential evapotranspiration, lead to the primary accumulation of soil salts in the surface layer of reclaimed land, with lower concentrations in deeper layers [37]. Thus, the early adoption of high-quality reservoir water for irrigation, coupled with an increase in the irrigation amount to boost the leaching fraction and the application of mulching to reduce severe soil evaporation in arid oasis regions, initiates a rapid desalination phase [38]. This holistic strategy ensures that soluble salt accumulation is effectively transported to deeper soil layers subsequent to irrigation events. However, with an increase in the duration of MDI application, the accumulation of soil salinity in the surface soil diminishes, leading to a gradual reduction in desalination rates.

3.3. The Response of Soil Particle Composition and Salinity to Long-Term MDI

In this study, principal component analysis (PCA) was employed to analyze the correlation among the soil physicochemical properties with durations of MDI and to identify the differences and fundamental clustering patterns in samples. The first two principal components (PC1 and PC2) were obtained, accounting for 79% and 13.11% of the total variation in the original variables, respectively (Figure 4). Together, these two components collectively explain more than 92% of the total variation. Table 2 presents the correlation between the observed variables and principal components.

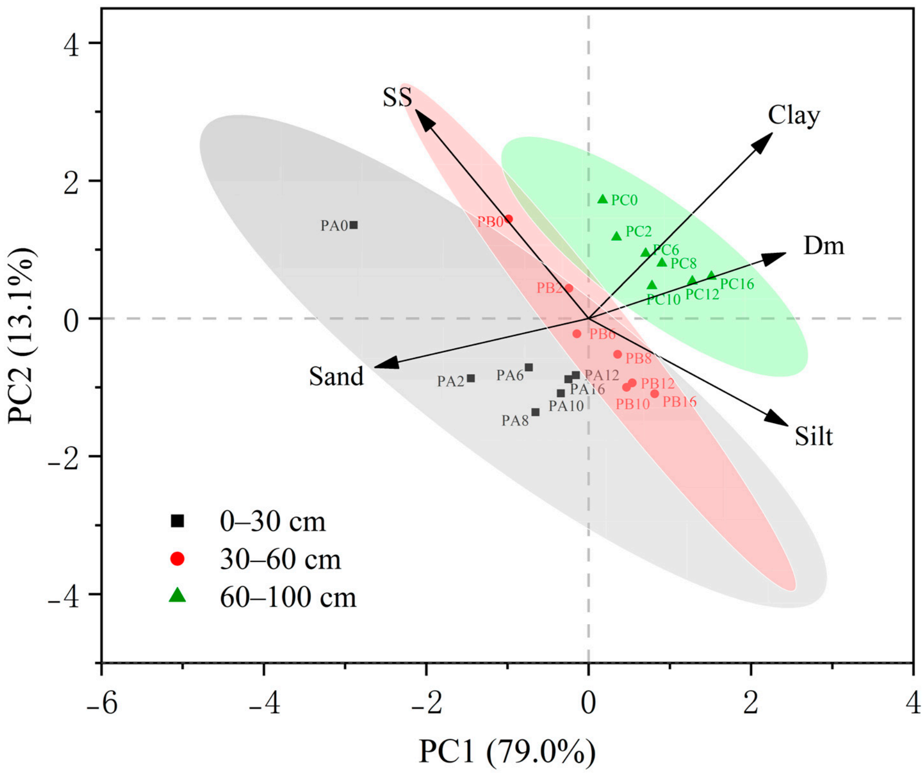

Figure 4. PCA result of 21 soil sequences of three soil layers under long-term MDI. Soil layers were coded as PA for 0–30 cm, PB for 30–60 cm, and PC for 60–100 cm. Durations of MDI were coded as 0 (i.e., uncultivated land), 2, 6, 8, 10, 12, and 16. SS refers to soil salinity.

Table 2. Correlation coefficient between soil variables and principal components.

Variable	PC1	PC2
Sand	−0.49353	−0.15788
Silt	0.45943	−0.34616
Clay	0.42367	0.59845
SS	−0.39918	0.67262
Dm	0.45443	0.2114

Silt, clay, and Dm were the most influential variables in explaining the overall variability of the data set, as evidenced by their correlations with PC1. This suggests that the variability described by PC1 was primarily related to soil texture. The most influential variables in PC2 were soil salinity and clay, which were negatively correlated with each other. This indicates that PC2 was associated with some solutes (e.g., finer soil particles and soil salt) that are more easily transported by irrigation water.

The oasis agricultural system represents a relatively enclosed spatial domain, within which alterations in soil properties are predominantly attributable to the practices of cultivation and irrigation [39]. The study site is situated in a temperate continental climate, amid an oasis environment that was substantially affected by surface desertification prior to being cultivated. After reclamation into cotton fields, larger soil particles tend to be more actively engaged by cultivation tools and the growth of crop roots, which results in their gradual diminution in particle size [40]. Yao et al. [41] demonstrated that water flow possesses enhanced transport capability for finer soil particles which, in turn, facilitates localized modifications in the soil texture. Therefore, the adoption of MDI, through its practice of minimal but frequent irrigation, leaches some solutes (such as soil salts and clay) to deeper soil along with the wetting front. Simultaneously, the phenomena of clay flocculation and the differential settling rates during irrigation contribute to the accumulation of finer clay particles in the upper layers of the soil, notably within the 0–60 cm soil layer. Consequently, the extended application of MDI manifested significant variances in the soil properties within the 0–60 cm and 60–100 cm layers (Figure 4), which are closely linked with the duration through which MDI has been employed.

However, residue plastic film accumulation in the cotton field under MDI requires special attention. Through column experiments, Wen et al. identified significant effects of plastic film residues on soil properties [42]. They observed that when the quantity of residual plastic film, primarily located in the topsoil layer (0–15 cm), exceeded 396 kg/ha, it considerably impaired the soil's infiltration capacity [42]. This, in turn, could influence soil texture and structure. The inability to manage plastic film residues as the duration of MDI extends could result in the accumulation of plastic film in deeper soil layers due to tillage practices, further exacerbating changes in soil texture and structure.

3.4. The Interactive Effect of Soil Particle Composition and Salinity with Different MDI Durations on Soil Structure

Figure 5 presents the variability of five specific soil physical and chemical indicators under different durations of MDI. The horizontal clustering in the heatmap reflects the strength of correlations among the five soil physical indicators under different MDI durations, while the vertical clustering reveals the associations between MDI durations and soil depths. The vertical clustering analysis shows two evident categories. The first category corresponds to clay, silt, and Dm, which increases proportionally with MDI duration, while sand content and soil salinity decrease inversely. These findings align with the results observed in PCA results.

The horizontal clustering analysis categorized the 21 soil samples with different MDI durations and soil depths into five groups. The first group (Class I) encompassed soil information from the 0–60 cm depth without MDI application, including PA0 and PB0. The second group (Class II) comprised the 0–60 cm soil layer with MDI durations of less than six years, incorporating PA2 to PA6 and PB2 to PB6. This indicates that during the initial six years of MDI application, there were significant and rapid alterations in the soil properties of both soil particles and salinity levels. Furthermore, given that the mechanical tillage depth in Xinjiang is approximately 30–40 cm, with a maximum wetting front depth of 60 cm, the primary changes in soil physical and chemical properties at the initial stages of MDI application can be attributed to the disruption of coarse soil particles such as sand, due to mechanical tillage, coupled with the leaching effect of MDI on high-level soil salinity [43,44]. The stratification effect of the soil, however, was not pronounced during this stage, resulting in a consistent and pronounced trend of changes in the soil properties of the 0–60 cm soil layer.

The third group (Class III) consisted of soil data from the 0–30 cm depth with MDI durations ranging from 8 to 16 years, including PA8 to PA16. The fourth group (Class IV) consisted of data from the 30–60 cm soil depth with MDI durations ranging from

8 to 16 years, including PB8 to PB16. This indicates that after MDI durations exceeded 8 years, noticeable stratification effects in the soil properties of the 0–30 cm and 30–60 cm soil layers became apparent. This phenomenon can be attributed to the gradual reduction in desalination rates in the soil after 8 years of MDI application. Concurrently, the mechanical tillage depth and cotton root system were primarily concentrated in the underground layer of approximately 0–30 cm [44]. Consequently, the rate of change in the soil particle composition of the 0–30 cm soil layer gradually exceeded that of the 30–60 cm soil layer.

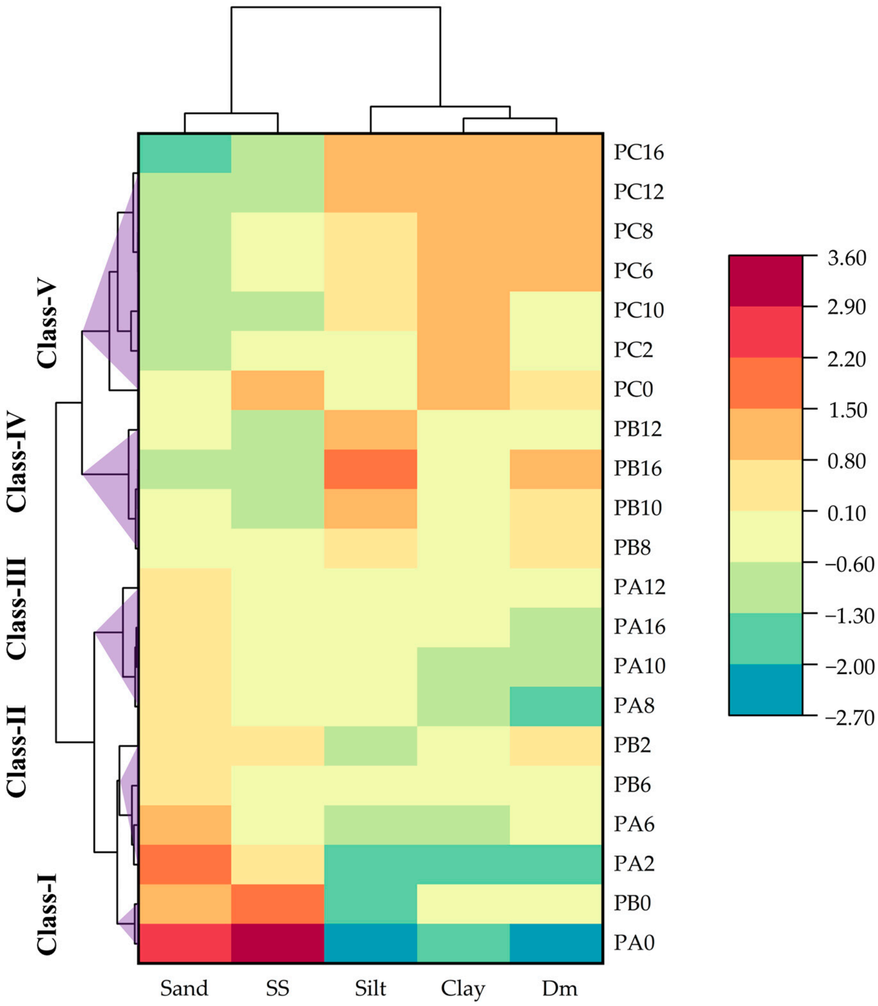

Figure 5. Heatmap depicting the Pearson correlation coefficient between specific soil properties and MDI durations. Colors leaning towards red signify stronger positive correlations, whereas those leaning towards blue indicate stronger negative correlations. Soil layers are coded as PA for 0–30 cm, PB for 30–60 cm, and PC for 60–100 cm. Durations of MDI are coded as 0 (i.e., uncultivated land), 2, 6, 8, 10, 12 and 16. SS refers to soil salinity.

The fifth group (Class V) presents soil data from the 60–100 cm soil layer, ranging from PC0 to PC16. This is because the 60–100 cm soil layer was relatively less affected by MDI, resulting in less pronounced changes compared to the 0–60 cm soil layer. Notably, variations in this deeper layer were primarily affected by finer particles like silt and clay (Figure 5). The phenomenon can be elucidated by the downward movement facilitated by MDI, which facilitates the transportation of finer particles and solutes towards deeper soil layers. The increased presence of fine particles promoted the development of clay and loam textures, facilitating the formation of soil aggregates and enhancing water-holding capacity.

As widely acknowledged, MDI enabled precise moisture delivery, optimizing water utilization by delivering water directly to the crop root zone while minimizing evapotranspiration [45]. However, the findings from this study suggested that MDI's restriction of deep percolation may lead to the accumulation of certain detrimental solutes (e.g., clay particles and salt ions) in the shallow soil layers, thereby increasing the risks of soil compaction and declining soil quality. To enhance the sustainable development potential of MDI in oasis agriculture, the implementation of appropriate desalination measures and timely increases in irrigation volumes are essential.

4. Conclusions

This study provides significant insights into soil particle composition and salinity dynamics in oasis cotton fields under MDI. The results showed a clear trend towards finer soil particle sizes with prolonged MDI application. The Dm was an effective indicator for assessing the dynamic impact of long-term MDI on soil particle composition, with a positive correlation observed between the abundance of fine particles and Dm. Furthermore, a marked reduction in soil salinity was observed with prolonged MDI duration, resulting in desalination rates exceeding 90% across all soil layers after 10 years of practicing MDI, which can greatly benefit crop growth. Notably, the long-term use of MDI indirectly influenced soil salinity migration through modifications in soil particle composition and soil structure. Compared to the uncultivated land, the implementation of MDI in cotton fields can regulate soil salinity and improve soil moisture retention capacity by modifying soil structure, thus creating more favorable conditions for cotton cultivation in saline-alkali soils. However, it is crucial to acknowledge potential risks, such as soil compaction, clay particle aggregation, and soil degradation, which may arise from long-term cotton cultivation under MDI. Future research should aim to address these concerns to promote sustainable agricultural practices in oasis agricultural systems.

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