Effects of Saline Water Irrigation on Litter Decomposition and Soil Organic Carbon Mineralization: Postprint

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Abstract

Saline water is the sole irrigation source for vegetation in the Tazhong Botanical Garden and desert highway shelterbelts in the Taklamakan Desert, which not only determines the normal physiological functioning of artificial vegetation in the Tazhong Botanical Garden and shelterbelts, but also influences material cycling between plants and soil. Investigating the effects of saline water irrigation on litter decomposition and soil organic carbon mineralization is of great significance for understanding material cycling and soil organic carbon sequestration in extreme environments. Using leaf litter of Populus euphratica and Pyrus betulifolia from the Tazhong Botanical Garden as research materials and combining laboratory incubation methods, this study dynamically investigated litter decomposition characteristics and soil organic carbon processes under saline water addition at different salt concentrations. The results showed that: (1) Compared with freshwater, saline water addition restricted litter decomposition rates by affecting soil physicochemical properties, with high-concentration saline water severely inhibiting litter decomposition. (2) During the cumulative mineralization process of soil organic carbon, the cumulative mineralization amount was maximal under freshwater treatment, while minimal under saline water addition at 15.0 g • L-1. (3) Litter addition increased soil organic carbon content, which was in a dynamic change process. In conclusion, appropriate concentrations of saline water limit litter decomposition and mineralization processes by affecting soil physicochemical properties and microbial activities, thereby facilitating soil organic carbon accumulation.

Full Text

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Effects of Saline Water Irrigation on Litter Decomposition and Soil Organic Carbon Mineralization

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Abstract: Saline groundwater serves as the sole irrigation water source for vegetation in the Taklimakan Desert Botanical Garden and desert highway shelterbelt, determining not only the normal physiological functioning of artificial vegetation but also influencing plant-soil material cycling. Investigating the effects of saline water irrigation on litter decomposition and soil organic carbon mineralization is crucial for understanding material cycling and soil organic carbon sequestration in extreme environments. Using leaf litter from Populus euphratica and Pyrus betulifolia from the Taklimakan Desert Botanical Garden, we conducted indoor incubation experiments to dynamically examine litter decomposition characteristics and soil organic carbon processes under different saline water concentrations. The results demonstrated that: (1) Compared with freshwater, saline water addition restricted litter decomposition rates by altering soil physicochemical properties, with high-concentration saline water severely inhibiting litter decomposition. (2) During the cumulative mineralization of soil organic carbon, the freshwater treatment produced the maximum cumulative mineralization, while the 15.0 $g \cdot L^{-1}$ saline water treatment yielded the minimum. (3) Litter addition enhanced soil organic carbon content, which exhibited dynamic changes throughout the incubation period. In summary, appropriate concentrations of saline water limited litter decomposition and mineralization processes by influencing soil physicochemical properties and microbial activities, thereby promoting soil organic carbon accumulation.

Keywords: litter decomposition; saline water irrigation; soil organic carbon; mineralization rate

Introduction

Litter represents a critical hub for material cycling and energy flow in ecosystems and constitutes an important source of soil carbon [1]. Litter decomposition significantly influences soil microbial activity, alters soil respiration rates, and affects soil organic carbon mineralization processes, consequently impacting soil carbon pool dynamics [2]. In desert ecosystems where vegetation is sparse and external nutrient inputs are scarce, nutrients released from litter decomposition serve as vital nutrient sources that can effectively modify soil organic carbon content and quality [3]. Litter decomposition also represents a crucial life cycle process in arid regions, determining subsurface ecosystem material cycling and energy flow. This biochemical process is primarily controlled by the combined effects of climate, soil physicochemical environment, litter chemical properties, and soil biological communities [4]. In arid zones, moisture acts as a key limiting factor [5], affecting not only soil microbial quantity and activity but also subsurface biogeochemical cycling processes [6]. Xie Tingting et al. [7] found that drought stress significantly reduced corn straw decomposition rates, exerting pronounced inhibitory effects on litter decomposition in arid regions. Due to unique geographical and climatic factors, subsurface saline water serves as a double-edged sword, providing water sources for plant growth and soil material cycling [8], yet high-concentration saline water reduces litter decomposition rates, affecting nutrient release and consequently influencing soil carbon mineralization and organic carbon accumulation [9]. Saline water irrigation affects mineralization in aeolian sandy soils. Mineralization is a complex biochemical process through which microorganisms convert organic carbon and release CO_2. Previous studies have found that saline water irrigation inhibits CO_2 emissions, with freshwater addition increasing cumulative CO_2 emissions [10]. Wang Weiqi et al. [11] observed that litter decomposition was inhibited by 1.9%-29.1% as salinity increased. Saline-alkali soils affect microbial life activities, thereby influencing soil respiration and organic carbon mineralization processes [12].

Soil moisture significantly influences litter decomposition, with changes in soil water content altering soil structure and physicochemical properties that affect microbial activity [13], consequently impacting litter decomposition and soil organic carbon mineralization [14]. Litter decomposition rates increase with soil water content [15], while moisture changes also affect organic carbon mineralization in forest ecosystems. A ^{13}C-labeled litter decomposition experiment demonstrated that litter addition promoted organic carbon mineralization, with greater mineralization observed in soil at 60% water-holding capacity compared to 30% [16]. Indoor experiments revealed larger CO_2 emissions under high temperature and humidity conditions, with excessive moisture not inhibiting soil organic carbon mineralization [17].

The Taklimakan Desert Botanical Garden, located in the hinterland of the Taklimakan Desert, contains over 400 desert plant species. Populus euphratica and Pyrus betulifolia are typical deciduous plants that grow well under saline water irrigation. Previous research has analyzed changes in soil physicochemical properties in desert ecosystems under saline water addition [18], but studies on soil CO_2 emissions and litter decomposition under saline water irrigation remain limited. Therefore, this study employed indoor incubation experiments to investigate the decomposition processes of P. euphratica and P. betulifolia leaf litter and the CO_2 emissions and soil organic carbon accumulation in aeolian sandy soil under different saline water concentrations, providing a reference for carbon cycling research in desert ecosystems.

1.1 Soil and Litter Characteristics

Soil and litter samples were collected from the Taklimakan Desert Research Station of the Chinese Academy of Sciences (83°36 E, 39°01 N). The site is located in the hinterland of the Taklimakan Desert on the southern slope of the Tianshan Mountains, characterized by a warm temperate arid climate at 1,100 m elevation, with mean annual precipitation of 24.6 mm and mean annual temperature of 12.4°C [19]. The incubation experiment began in March 2023. Prior to the experiment, initial quality parameters of P. euphratica and P. betulifolia leaf litter were determined (Table 1).

1.2 Experimental Design

1.2.1 Litter Decomposition Leaf litter of P. euphratica and P. betulifolia was cleaned to remove impurities and oven-dried at 65°C for 48 hours. After drying, the litter was cut into 2–3 cm segments and stored for later use. Fresh soil samples (100.00 g) were weighed and evenly spread at the bottom of 250 mL Erlenmeyer flasks. The soil moisture content was adjusted to 60% of field capacity using ultrapure water, then sealed and incubated in a dark 25°C incubator for 7 days of pre-cultivation. After pre-cultivation, 2.00 g of broken litter was added to each flask, ensuring thorough mixing with the soil. A control group without litter addition was also established. The experiment included five treatments: ultrapure water (control) and saline water at four concentrations ($7.5\ \text{g} \cdot \text{L}^{-1}$, $15.0\ \text{g} \cdot \text{L}^{-1}$, $22.5\ \text{g} \cdot \text{L}^{-1}$, and $30.0\ \text{g} \cdot \text{L}^{-1}$), with three replicates per treatment. Samples were recovered at days 0, 15, 30, 60, 90, 120, 150, and 180 days of decomposition, with three samples recovered per concentration at each time point (three samples per recovery). Flasks were sealed with plastic wrap perforated with small holes to maintain air exchange. Soil moisture was regularly corrected using the weighing method throughout the incubation period.

1.2.2 Soil Organic Carbon Mineralization Concurrently with the litter decomposition experiment, 100.00 g of fresh soil was evenly placed in 500 mL incubation bottles. After the same pre-cultivation treatment, 2.00 g of P. euphratica or P. betulifolia leaf litter was added and thoroughly mixed with the aeolian sandy soil. Each treatment had three replicates, and a blank group without litter addition was included. Soil moisture was readjusted after litter addition.

CO_2 release rates were measured using the alkali absorption method: centrifuge tubes containing 10 mL of 0.6 $\text{mol} \cdot \text{L}^{-1}$ NaOH solution were suspended in the incubation bottles, which were then sealed and placed in a 25°C incubator. The NaOH solution was replaced at days 1, 2, 3, 5, 7, 10, 15, 20, 30, 40, 60, 90, 120, 150, and 200 days. The collected NaOH solution was poured into 250 mL Erlenmeyer flasks, 2 mL of 1 $\text{mol} \cdot \text{L}^{-1}$ $BaCl_2$ solution and phenolphthalein indicator were added, and the solution was titrated with 0.2 $\text{mol} \cdot \text{L}^{-1}$ HCl until the red color disappeared completely. After each sampling, bottles were opened for 30 minutes of aeration, reweighed, replenished with water, and fresh NaOH solution was added before returning to the incubator. Soil moisture was regularly corrected using the weighing method.

1.2.3 Soil Analysis Soil pH and electrical conductivity were measured using a pH meter and conductivity meter. Soil organic carbon and litter total carbon were determined by digestion with concentrated potassium dichromate solution. Plant total nitrogen and total phosphorus were measured using a continuous flow analyzer after digestion with concentrated sulfuric acid and hydrogen peroxide. Litter lignin and cellulose contents were determined using the acid detergent method [20].

1.2.4 Calculation of Relevant Indicators The litter mass residual rate was calculated using the formula:

$$Y = \frac{M_t}{M_0} \times 100\%$$

where Y is the mass residual rate (%), *M_t* is the litter mass at decomposition time t, and *M_0* is the initial litter mass.

Litter decomposition processes were fitted using the negative exponential decay model:

$$M_t = ae^{-kt}$$

where a is a correction coefficient, t is decomposition time, k is the decomposition constant, $t_{0\cdot5}$ = ln0.5/(-k) is the time required for 50% decomposition, and $t_{0\cdot95}$ = ln0.05/(-k) is the time required for 95% decomposition.

Soil organic carbon mineralization amount was calculated as:

$$C_{\text{min}} = \frac{(V_0 - V) \times C_{\text{HCl}} \times M}{m} \times 1000$$

where C is soil organic carbon mineralization amount ($\text{mg} \cdot \text{kg}^{-1}$), V_0 is the HCl consumption in the blank titration, V is the HCl consumption in the sample titration, C is HCl concentration ($\text{mol} \cdot \text{L}^{-1}$), M is molar mass, and m is soil mass in the incubation bottle (kg).

Soil organic carbon mineralization rate was calculated as:

$$R = \frac{C_{\text{min}}}{t}$$

where R is the soil organic carbon mineralization rate ($\mathrm{mg \cdot kg^{-1} \cdot d^{-1}}$).

Soil organic carbon mineralization was fitted using a first-order kinetic equation:

$$C_t = C_0(1 - e^{-kt})$$

where C_t is cumulative mineralization at time t ($\mathrm{mg \cdot kg^{-1}}$), C_0 is potentially mineralizable organic carbon ($\mathrm{mg \cdot kg^{-1}}$), t is incubation time (days), and k is the turnover rate constant ($\mathrm{d^{-1}}$).

Data were analyzed using SPSS 26.0 software for one-way ANOVA and Pearson correlation analysis, with Duncan' s test for significance. Figures were prepared using Origin 2023 software.

Results

2.1 Soil pH and Electrical Conductivity

Soil pH in the P. euphratica litter group ranged from 7.57 to 7.96, with no significant differences among treatments at the same incubation time. In the P. betulifolia litter group, pH ranged from 7.46 to 8.01, with significant differences appearing under high-concentration saline water addition, though no differences were observed among treatments at 180 days (Figure 1 [Figure 1: see original paper]). Electrical conductivity in the P. euphratica group ranged from 0.34 to 3.88 $\mathrm{mS \cdot cm^{-1}}$, while in the P. betulifolia group it ranged from 0.13 to 3.65 $\mathrm{mS \cdot cm^{-1}}$. Except for the P. euphratica litter addition group at 180 days, soil electrical conductivity increased with saline water concentration (Figure 2 [Figure 2: see original paper]).

2.2 Litter Decomposition of P. euphratica and P. betulifolia Under Different Saline Water Concentrations

Litter mass residual rates decreased over time under all saline water concentrations. The lowest mass residual rates for both species occurred during 0-15 days, when mass loss was rapid, with decreasing rates as decomposition progressed. Under the same concentration, P. euphratica decomposed faster than P. betulifolia, requiring 5.44-12.37 months for 50% decomposition and 23.50-53.47 months for 95% decomposition. In contrast, P. betulifolia required 6.44-19.03 months for 50% decomposition and 27.82-95.06 months for 95% decomposition (Table 2). After 180 days, P. euphratica litter residual rates were 48.3%-67.6%, while P. betulifolia residual rates were 52.3%-78.5%. At the same saline concentration, P. euphratica had lower mass residual rates than P. betulifolia (Figure 3 [Figure 3: see original paper]).

The decomposition index (k) of P. betulifolia litter showed a significant negative correlation with saline water concentration ($P < 0.05$), whereas no significant negative correlation was observed for P. euphratica ($P > 0.05$) (Table 3). The negative exponential model explained 62%-84% of the variation in litter decomposition ($R^2 = 0.62$-0.84).

2.3 Soil Organic Carbon Mineralization Rate Characteristics Under Different Saline Water Concentrations

During the 200-day incubation, soil organic carbon mineralization rates under different saline water concentrations showed similar dynamic patterns for both litter types (Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper]). The initial mineralization rate was higher in the P. betulifolia group than in the P. euphratica group. Mineralization rates decreased rapidly during the first 4-15 days, then gradually slowed, with no significant differences among treatments in later stages.

Cumulative soil organic carbon mineralization increased gradually over time under all saline water concentrations (Figure 6 [Figure 6: see original paper]). After 200 days, the maximum cumulative mineralization occurred in freshwater treatments, slightly higher in P. euphratica (7,374.55 $mg \cdot kg^{-1}$) than in P. betulifolia (7,083.56 $mg \cdot kg^{-1}$). The minimum cumulative mineralization occurred in the 15.0 $g \cdot L^{-1}$ saline water treatment, with 6,706.33 $mg \cdot kg^{-1}$ in the P. euphratica group and 6,035.19 $mg \cdot kg^{-1}$ in the P. betulifolia group.

First-order kinetic modeling revealed that potentially mineralizable organic carbon (C_0) in the P. euphratica group ranged from 6,543.21 to 7,108.67 $mg \cdot kg^{-1}$ across saline water concentrations, while in the P. betulifolia group it ranged from 5,735.28 to 6,613.02 $mg \cdot kg^{-1}$ (Table 4). For both litter types, the ranking of cumulative mineralization was S4 > S0 > S3 > S2 > S1.

2.4 Soil Organic Carbon Content Dynamics Under Different Litter Additions

Litter addition promoted soil organic carbon accumulation. Soil organic carbon content in the P. euphratica and P. betulifolia addition groups ranged from 1.13-2.35 $g \cdot kg^{-1}$ and 0.85-2.23 $g \cdot kg^{-1}$, respectively, compared to 0.44-1.27 $g \cdot kg^{-1}$ in soils without litter addition. Soil organic carbon content exhibited dynamic changes under different saline water concentrations (Figure 7 [Figure 7: see original paper]). At day 15, soil organic carbon content was relatively high, particularly in the P. euphratica group. At day 60, the S2 group showed significantly higher soil organic carbon content ($P < 0.05$). At day 90, the S4 group had higher soil organic carbon content ($P < 0.05$), while both litter addition groups had significantly lower soil organic carbon than other concentrations ($P < 0.05$). At day 180, the P. euphratica group under S2 treatment had significantly higher soil organic carbon content than other concentrations ($P < 0.05$), and the P. betulifolia group under S2 treatment also had significantly higher soil organic carbon content than other concentrations ($P < 0.05$).

Discussion

3.1 Effects of Saline Water Concentration on Litter Decomposition

Saline water addition affected basic soil physicochemical properties [35]. In this indoor incubation experiment, saline water addition had minimal effect on soil pH, particularly in the P. euphratica litter addition group. However, saline water addition significantly altered soil electrical conductivity, which increased markedly with saline water concentration. These changes in soil physicochemical properties subsequently affected soil microbial activities, potentially influencing litter decomposition [36]. The decomposition processes of different litter types under saline water addition were similar (Figure 3 [Figure 3: see original paper]). Salinity significantly inhibited P. betulifolia litter decomposition ($P < 0.05$), consistent with previous findings that saline water significantly reduced litter decomposition rates compared to freshwater [11, 12]. As the primary carbon source in aeolian sandy soils, saline water addition may have inhibited their mineralization and decomposition. However, saline water concentration did not significantly affect P. euphratica decomposition rates, suggesting that litter decomposition may be related to other factors [37]. As decomposition progressed, litter mass continuously decreased and available substrates became limited, causing decomposition rates to decline—a difference between indoor experiments and field decomposition where continuous external litter input cannot be guaranteed.

3.2 Effects of Saline Water Concentration on Soil Organic Carbon Mineralization

Saline water concentration affected soil and microbial respiration, thereby influencing soil organic carbon mineralization [38]. During the indoor incubation, high initial mineralization rates that declined rapidly indicated intense mineralization activity in the early decomposition stage, particularly during days 4–15, likely related to rapid mass loss of easily decomposable substances. Litter addition initially stimulated soil microbial respiration, enhancing microbial activity and releasing higher CO_2 concentrations [39]. Simultaneously, easily decomposable compounds in litter were rapidly lost [40], and organic matter was converted to CO_2 through strong mineralization. Fresh litter entering the soil also stimulated decomposition of older soil organic matter through priming effects [41]. The combined effects of these three processes resulted in strong soil organic carbon mineralization in the early stage. Later, as substrate quantity and quality for microorganisms declined, CO_2 release gradually decreased. Previous studies found that CO_2 release rates from litter decreased over time and eventually stabilized [42]. Zhang Shaolei et al. [10] conducted indoor incubation experiments with Calligonum mongolicum litter in aeolian sandy soil and observed that CO_2 emission rates were initially rapid, then declined and eventually stabilized.

Soil organic carbon mineralization is related to both biological factors (soil fauna respiration, microbial respiration, plant root respiration) and abiotic chemical oxidation of carbon [43]. Indoor experiments primarily involve microbial respiration. Previous indoor experiments found that as irrigation water concentration increased, microbial utilization of carbon sources in aeolian sandy soil decreased [44]. Cumulative CO_2 emissions under freshwater addition were higher than under saline water irrigation, possibly due to saline water inhibiting soil microbial activity [45]. The lowest cumulative mineralization occurred under 15.0 $g \cdot L^{-1}$ saline water irrigation, likely related to microbial activity at this concentration. Some studies found that saline water irrigation did not significantly affect microbial abundance and diversity but altered microbial community structure [46], with high concentrations potentially being more suitable for salt-tolerant microorganisms. Therefore, further research on microbial community structure under different saline water concentrations is needed.

3.3 Effects of Saline Water Concentration on Soil Organic Carbon Accumulation

Litter decomposition promoted soil organic carbon accumulation and improved soil quality [47], particularly in desert ecosystems lacking external nutrient inputs. Litter itself is the primary source of plant-derived carbon in soil [48], while microorganisms can complete their life cycles through feeding and decomposition, ultimately contributing to microbial-derived carbon accumulation [49]. During the 180-day decomposition process, soil organic carbon content under different saline water concentrations showed dynamic changes, likely reflecting the balance between litter conversion to soil organic carbon and mineralization to CO_2. Litter is transformed into soil organic carbon through microbial decomposition, while soil organic carbon is mineralized to CO_2 through microbial respiration—representing a balance between carbon input and output [50]. At day 180, soil organic carbon content was highest under the 15.0 $g \cdot L^{-1}$ treatment, while mineralization was lowest and some carbon remained in the litter, maximizing organic carbon retention in soil and litter rather than releasing it to the atmosphere. Further exploration of carbon turnover processes at this concentration could enhance the value of saline water utilization.

Since indoor incubation experiments lack external carbon input in later stages, microbial substrates become depleted over time, potentially leading to more microbial residues entering the soil as important components of organic carbon. Therefore, strengthened analysis of soil organic carbon sources at different stages is needed [41, 46]. Saline water concentration affects soil respiration and microbial activity [51], and thus its effects on soil carbon sequestration in the Taklimakan Desert Botanical Garden and desert highway shelterbelt require further investigation.

Conclusion

Analysis of litter decomposition characteristics, soil organic carbon mineralization rates, and accumulation from indoor incubation experiments revealed that freshwater addition produced the fastest decomposition rates and highest mineralization for both litter types. Saline water concentration affected both litter decomposition rates and soil organic carbon mineralization rates. Litter addition promoted soil organic carbon accumulation, with soil organic carbon content showing dynamic changes over time. The 15.0 $g \cdot L^{-1}$ saline water treatment was most conducive to soil organic carbon sequestration.

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